Application of Unified Smith Predictor for Load Frequency Control with Communication Delays

ASHU AHUJA[1], S. K. AGGARWAL[2]

[1,2]Electrical Engineering Department, Maharishi Markandeshwar University, Mullana, INDIA

ashu.valecha.ahuja@gmail.com, vasusanjeev@yahoo.co.in

Abstract:-

The presence of communication delay in modern load frequency control (LFC) systems complicates the design and implementation of the controller to achieve robust performance of the system. In this work, the performance of proportional-integral (PI) controller, H_∞ state feedback controller using linear matrix inequality (LMI) and Unified Smith Predictor (USP) has been analyzed in case of LFC with time delays. USP approach is used to design the state feedback controller. An equivalent representation of the augmented plant is designed, which consists of original time delayed plant and USP. Linear Matrix Inequality (LMI) is used for designing H_∞ controller for the augmented plant designed from two area LFC scheme. A robust controller is found out that ensures stable dynamic performance despite of delay.

Keywords: - Communication delay, Unified Smith Predictor, Linear Matrix Inequality, load frequency control.

1 Introduction

The main objective of load frequency control (LFC) is to automatically adjust the generation levels in response to load changes and deviations in scheduled interchanges in the multi-area power system [1]. As it responds automatically, it reduces the response time, as compared to that of manual control [2]. The conventional controller used for this task is proportional-integral (PI) controller, which achieves zero steady state error and adequate dynamic response considering stability requirements [3]. However, a large amount of literature has been devoted to this subject [4-6], and many conventional and artificial intelligence (AI) based controllers have also been investigated by the various researchers like proportional-integral and derivative (PID) controller [7-15], fractional

Order PID (FOPID) controller [16], decentralized controllers such as sliding mode control [17-20], artificial neural network (ANN) controller [21], fuzzy logic (FL) controller [22-24], and neuro-fuzzy controller [25]. Many researchers have employed optimal and robust control theory in an effort to achieve optimal performance based on the minimization of a performance index [26]. Some of the techniques which have been studied are: state feedback control such as linear quadratic regulator (LQR) control [27], internal model control (IMC) [28-29] and H_∞ state feedback controller in linear matrix inequalities (LMI) framework [30-33].

In a power system, while governors control individual generators, automatic generation control (AGC) or LFC system simultaneously control many governors to balance generation to load. An AGC system has components in the control center and in the power system. The control center components include the computer equipment that both calculates the area control error (*ACE*) signal and distributes the signal to controlled generators. A new control signal may be calculated and new set-points are distributed to controlled generators every few (2-6) seconds. ACE equation for the most commonly used tie line bias control is:

ACE = (Actual Interchange–Scheduled Interchange) – 10*B_f*(Actual frequency–Scheduled frequency)

Where, B_f is the frequency bias setting. Conventional LFC was a centralized activity; which is now being treated as an ancillary service under new deregulated environment. In traditional LFC schemes, the control actions are usually determined for each control area in the control center and ACE signals are transmitted via the dedicated communication channels to the generating units on AGC [30]. These signals suffer from negligible time delays. However, in interconnected power systems, LFC needs an open communication infrastructure so as to support its decentralized property. In this case, generators on LFC or AGC may receive control signals from either a control center (scheduling through market clearing) or from the customer side directly (bilateral contract). In this case, there may be uncertain and large time delay may be involved in the ACE signal.

The issue of time delay is very significant as it complicates the design and implementation of the controller and also it may create instability in the system [34].Traditionally, time delays in control systems are handled by approximations [35]. The issue of time delay in LFC has been studied by many researchers. They used PI controller, converted the problem to state output feedback control [30, 33], mixed H_2/H_∞ control technique [31] and Lyaponuv theory based delay dependent criteria [32] and minimization of a performance index is achieved using LMI. The Smith Predictor (SP) [36-37] and Modified Smith Predictor (MSP) are commonly used methods of controlling time delayed systems. To handle the time delay in transmitting the remote signal a controller is being designed by USP based approach [41] solving the problem using linear matrix inequalities (LMIs) with additional pole-placement constraints to ensure minimum damping ratios for all dominant inter-area modes[42]. However, these controllers have not been studied for handling time delay issues in LFC problem and are the main focus of the present work.

In this work, initially, an augmented plant has been formed by combining original time delayed plant with USP. Then, H_∞ state feedback controller has been designed using LMI such that infinity norm of closed loop system is minimized (MATLAB LMI toolbox has been used to solve LMI). This methodology has been applied to two area interconnected power system model with communication delay. Delay independent one term controller using LMI has also been considered [30]. It has been observed that, though more damped response is obtained with delay independent controller design; yet design of the controller using USP is more realistic as the controller has been designed for the augmented plant, which is the combination of delayed plant and USP. This paper is organized as follows: Section 2 explains USP approach. Model development of the plant and H∞ controller design using LMI approach has been explained in section 3. Simulation results are presented in section 4 and section 5 concludes the paper.

2 Unified Smith Predictor (USP)

The SP enables control engineers to design a controller for the equivalent delay free process and apply that control law in conjunction with Smith predictor to control the time-delayed process [36-37]. However, traditional SP gives poor robustness and it is difficult to ensure a minimum damping ratio of the close-loop system when the open-loop system has poorly damped poles. Consequently, modifications to SP have been proposed [38-40]; but, in case of systems having fast stable Eigen values, the Modified Smith Predictor (MSP) algorithms may be numerically unstable. Then USP was proposed [41], which does not require matrix exponential computation for fast stable poles. Usually, the system can be represented in transfer function form as:

$$G(s) = P(s).e^{-s\tau} \tag{1}$$

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. 1. $K(s)$ is a stabilizing controller for $G(s)$.

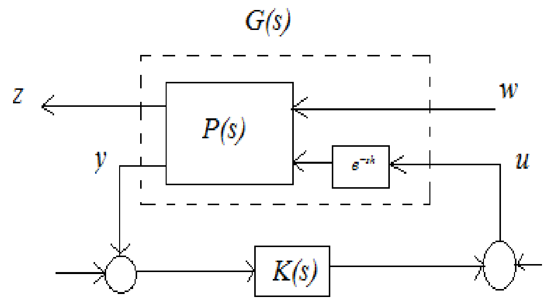

Fig. 1 Control system comprising time delayed plant G and controller K

In state space form,

$$P(s) = \begin{bmatrix} A & \vdots & e^{-A\tau}B_1 & B_2 \\ \cdots & \vdots & \cdots & \cdots \\ C_1 & \vdots & 0 & 0 \\ C_2 e^{-A\tau} & \vdots & 0 & 0 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \tag{2}$$

The delay free plant is decomposed in stable and unstable parts $P(s) = P_s(s) + P_u(s)$. Transformed augmented delay free plant between input $u(t)$ and output $y(t)$ is given as

$$P_{22}(s) = \begin{bmatrix} V^{-1}AV & \vdots & V^{-1}B_2 \\ \cdots\cdots\cdots & \vdots & \cdots\cdots \\ C_2 V & \vdots & 0 \end{bmatrix} = \begin{bmatrix} A_u & 0 & \vdots & B_u \\ 0 & A_s & \vdots & B_s \\ \cdots\cdots\cdots & & \vdots & \cdots\cdots \\ C_u & C_s & \vdots & 0 \end{bmatrix} \tag{3}$$

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(A)*. 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 after transforming into Jordan canonical form. This decomposition is made by splitting 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 λ of A with $Re(\lambda) > \alpha$, while A_s has remaining eigen values of A. The generalized plant $\tilde{P}(s)$ shown in Fig. 2 is realized as plant $G(s)$ together with USP and controller $K(s)$ in Fig. 1 has been decomposed into USP $Z(s)$ and compensator $K_{USP}(s)$ so that $K = K_{USP}(1 - ZK_{USP})^{-1}$. K_{USP} With $\tilde{P}$ ensures the same performance as controller K with original time delayed plant G.

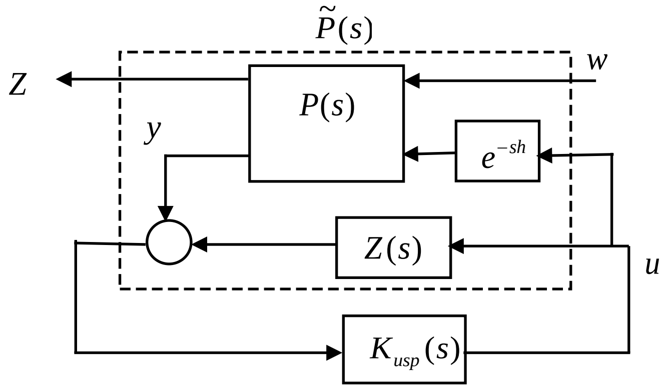

Fig. 2 Plant $G(s)$ together with USP and controller $K_{usp}(s)$

$$\tilde{P} = \begin{bmatrix} A & 0 & \vdots & E_\tau^{-1}B_1 & B_2 \\ 0 & A_s & \vdots & \begin{bmatrix} 0 & e^{A_s\tau} - I_s \end{bmatrix} V^{-1}B_1 & 0 \\ \cdots & \cdots & \vdots & \cdots & \cdots \\ C_1 & C_1V\begin{bmatrix} 0 \\ I_s \end{bmatrix} & \vdots & 0 & 0 \\ C_2E_\tau & 0 & \vdots & 0 & 0 \end{bmatrix} = \begin{bmatrix} P_a & \vdots & P_f & P_b \\ \cdots & \vdots & \cdots & \cdots \\ P_{c1} & \vdots & 0 & 0 \\ P_{c2} & \vdots & 0 & 0 \end{bmatrix} \tag{4}$$

$$E_\tau = V \begin{bmatrix} e^{-A_u\tau} & 0 \\ 0 & I_s \end{bmatrix} V^{-1} \tag{5}$$

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

$$Z(s) = P_{22}^{aug}(s) - P_{22}(s)e^{-s\tau} \tag{6}$$

Where, $$P_{22}^{aug}(s) = \begin{bmatrix} A & \vdots & B \\ \cdots & \vdots & \cdots \\ CE_\tau & \vdots & 0 \end{bmatrix} \tag{7}$$

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

$$u(t) = K_{usp}x(t) \tag{8}$$

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

$$T_{zw} = P_{c1}\left(sI - (P_a + P_b.K_{usp})\right)^{-1}P_f \tag{9}$$

Where s is the Laplace operator. The design of H_∞ controller stabilizes the system if the infinity norm of T_{zw} is bounded by γ.

$$\|T_{zw}\|_\infty \le \gamma, \qquad \gamma > 0 \tag{10}$$

3 Model development and control design

3.1 State space description of LFC problem

To introduce the concept of communication delay, two area LFC model has been modified to include communication network delays in the respective *ACE* signals. Fig. 3shows the block diagram of the system in detail. In each area, all generators are assumed to be coherent group. Each area including steam turbine contains governor and reheater stage of steam turbine. The parameters for Area 1 and Area 2 have been taken from [21, 33]. The dynamics of the model can be represented in the form of equations (11) to (21).

$$\dot{x}_1(t) = -\frac{1}{T_{p1}}x_1(t) + \frac{K_{P1}}{T_{P1}}x_2(t) - \frac{K_{P1}}{T_{P1}}x_5(t) - \frac{K_{P1}}{T_{P1}}w_1(t) \tag{11}$$

$$\dot{x}_2(t) = -\frac{x_2(t)}{T_{RH1}} + \left(\frac{1}{T_{RH1}} - \frac{K_{RH1}}{T_{ch1}}\right)x_{2r}(t) + \frac{1}{T_{ch1}}.x_3(t) \tag{12}$$

$$\dot{x}_{2r}(t) = -\frac{1}{T_{ch1}}x_{2r}(t) + \frac{1}{T_{ch1}}x_3(t) \tag{13}$$

$$\dot{x}_3(t) = -\frac{1}{R_1T_{g1}}x_1(t) - \frac{1}{T_{g1}}x_3(t) - \frac{1}{T_{g1}}x_4(t-\tau_1) + \frac{1}{T_{g1}}u_1(t) \tag{14}$$

$$\dot{x}_4(t) = K_{I1}.K_{PR1}.x_1(t) + K_{I1}x_5(t) \tag{15}$$

$$\dot{x}_5(t) = 2\pi.T_{12}.x_1(t) - 2\pi.T_{12}.x_6(t) \tag{16}$$

$$\dot{x}_6(t) = -\frac{1}{T_{p1}}x_6(t) + \frac{K_{P1}}{T_{P1}}x_7(t) + \frac{K_{P1}}{T_{P1}}x_5(t) - \frac{K_{P1}}{T_{P1}}w_2(t) \tag{17}$$

$$\dot{x}_7(t) = -\frac{1}{T_{RH2}}x_7(t) + \left(\frac{1}{T_{RH2}} - \frac{K_{RH2}}{T_{ch2}}\right)x_{7r}(t) + \frac{K_{RH2}}{T_{ch2}}x_8(t) \tag{18}$$

$$\dot{x}_{7r}(t) = -\frac{1}{T_{ch2}}x_{7r}(t) + \frac{1}{T_{ch2}}x_8(t) \tag{19}$$

$$\dot{x}_8(t) = -\frac{1}{R_2T_{g2}}x_6(t) - \frac{1}{T_{g2}}x_8(t) - \frac{1}{T_{g2}}x_9(t-\tau_2) + \frac{1}{T_{g2}}u_2(t) \tag{20}$$

$$\dot{x}_9(t) = K_{I2}.K_{PR2}.x_6(t) - K_{I2}x_5(t) \tag{21}$$

The symbols used for state and other variables are given in Table 1.

Table 1 Symbols used in two area LFC model

$x_1, x_6 = \Delta f_1, \Delta f_2$	Frequency deviation in area 1 and 2
$x_2, x_7 = \Delta P_{m1}, \Delta P_{m2}$	Mechanical power output of generator in area 1 and 2
$x_{2r}, x_{7r} = \Delta P_{m1r}, \Delta P_m$	Mechanical power input to reheater of generator in area 1 and 2
$x_3, x_8 = \Delta P_{v1}, \Delta P_{v2}$	Governor valve position in area 1 and 2
$x_4, x_9 = \Delta E_1, \Delta E_2$	Area control error (ACE) in area 1 and 2
$x_5 = \Delta P_{12}$	Tie-line power flow from area 1 to 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 in area 1 and 2
$K_{PR1} = B_1,\ K_{PR2} = B_2$	Proportional gain of PI controller in area 1 and 2
$K_{I1} = 0.7, K_{I2} = 0.65$	Integral gain of PI controller in area 1 and 2
$T_{g1} = 0.1, T_{g2} = 0.4$	Governor time constant in area 1 and 2 (in s)
$T_{ch1} = 0.3, T_{ch2} = 0.17$	Turbine time constant in area 1 and 2 (in s)
$K_{RH1} = 0.5,\ K_{RH2} = 0.75$	Gain of reheater in area 1 and 2
$T_{RH1} = 10,\ T_{RH2} = 20$	Time constant of reheater in area 1 and 2 (in s)
$D_1 = 1, D_2 = 1.5$	Sensitivity of load w.r.t. frequency in area 1 and 2 ($D = \partial P / \partial f$ in pu MW/Hz)
$K_{p1} = 1/D_1, K_{p2} = 1/D_2$	Power system gain of area 1 and 2 (in Hz/pu MW)
$M_1 = 10, M_2 = 12$	Inertia constant of area 1 and 2
$T_{p1} = M_1/D_1, T_{p2} = M_2/D_2$	Power system time constant of area 1 and 2 (in s)
$R_1 = R_2 = 0.05$	Governor speed droop in area 1 and 2 respectively ($R = \Delta f / \Delta P$ in Hz/pu MW)
$T_{12} = 0.7$	Stiffness coefficient of tie-line connecting area 1 and 2
$B_1 = \frac{2}{R_1} + D_1$ and $B_2 = \frac{4}{R_2} + D_2$	Automatic load frequency characteristics (ALFC) of area 1 and 2
τ_1, τ_2	Time delay in ACE signal of area 1 and area 2 respectively (in s)

The state vector is $\bar{x} = [x_1\ x_2\ x_{2r}\ x_3\ x_4\ x_5\ x_6\ x_7\ x_{7r}\ x_8\ x_9]^T$; the control vector is $\bar{u} = [u_1\ u_2]^T$; the disturbance vector is $\bar{w} = [w_1\ w_2]^T$; and the measured output vector is $\bar{y} = [y_1\ y_2]^T$.

The equations from (11) to (21) can be represented in the state space form of a time delay linear control system:

$$\dot{x}(t) = Ax(t) + A_{d1}x(t-\tau_1) + A_{d2}x(t-\tau_2) + Bu(t) + Fw(t) \quad (22)$$

$$y(t) = Cx(t) \quad (23)$$

where, $A \in \Re^{11\times 11}$ is the system state matrix corresponding to normal states, $A_{d1}, A_{d2} \in \Re^{11\times 11}$ are the system matrices corresponding to delayed states $x_4(t-\tau_1)$ and $x_9(t-\tau_2)$ respectively, $B \in \Re^{11\times 2}$ is the system input matrix, $F \in \Re^{11\times 2}$ is the disturbance matrix, and $C \in \Re^{2\times 11}$ is the output matrix. (23)

3.2 USP implementation

A numerical problem with the modified Smith predictor when the plant has fast stable poles has been pointed out and the unified Smith predictor has been proposed as a solution. An equivalent representation of the augmented plant consisting of a time delayed plant and a unified Smith predictor is derived. However, delay is taken as $\tau = \max(\tau_1, \tau_2)$ where $\tau_1\ and\ \tau_2$ are delay in area 1 and 2 respectively. In the designed problem $\tau = \tau_2$ .Using this representation, a parameterization of the (exponentially) stabilizing controllers for the augmented plant (with the USP connected to it) is derived and the H^∞ control problem is solved using LMI.

3.3H∞ Controller Design Using Linear Matrix Inequalities

The state feedback controllers in the proposed work are designed using following LMI's.

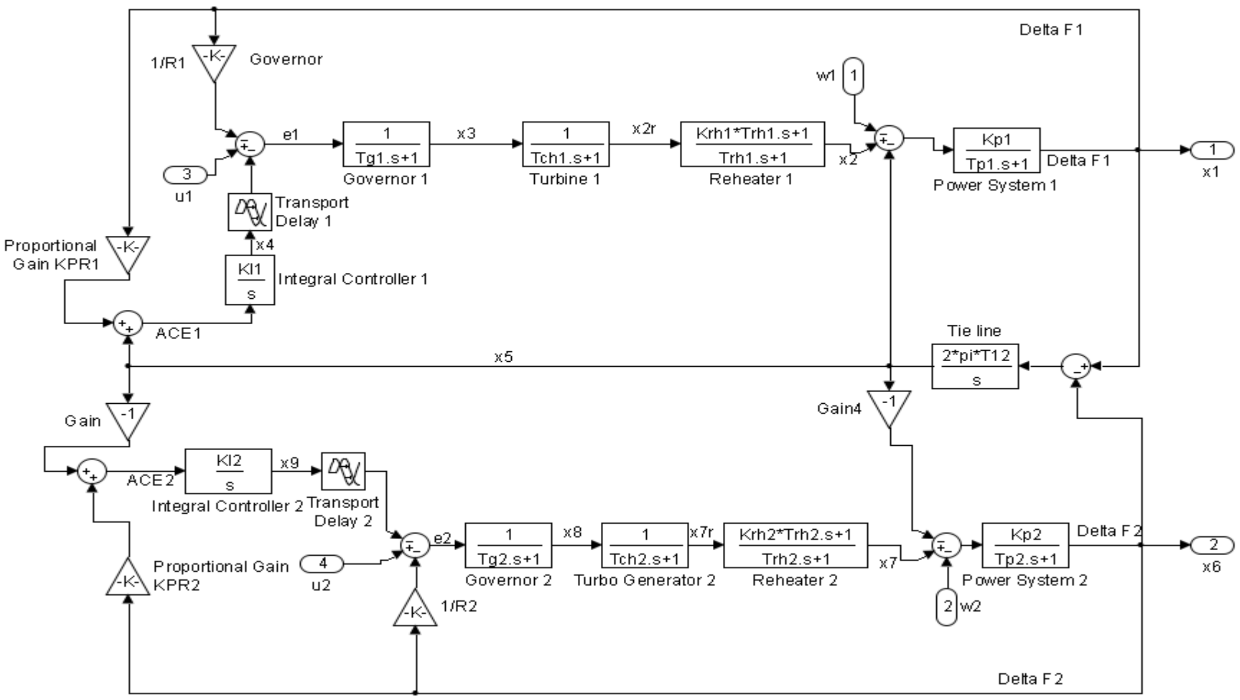

Fig. 3 Two Area Load Frequency Control Model

3.3.1 Delay independent H∞ one term controller design

H∞ controller design using delay independent analysis for LFC has been considered in [30] in which the controller is designed with the objective to minimize the performance index γ as given in (24) and the corresponding controller is called H_∞ controller with a norm bounded performance measure γ.

$$\|T_{wy}\|_\infty = \frac{\|y\|_2}{\|w\|_2} = \frac{\sqrt{\int_0^\infty y^T(t)y(t)dt}}{\sqrt{\int_0^\infty w^T(t)w(t)dt}} \le \gamma \quad (24)$$

The control law considered for designing this one term controller is

$$u(t) = Kx(t) \quad (25)$$

Where, $K \in R^{2\times 11}$ for the system (22). Design of this one term controller K has been applied in [30] for LFC problem using lemma1:

Lemma 1. System (22) with the feedback control law (25) satisfies the H_∞ performance (24), if there exist symmetric positive definite matrices *Y*, P_i, *i*=1, 2, and an arbitrary matrix *X* such that following LMI holds:

$$\begin{bmatrix} AY + Y^TA^T + BX + X^TB^T + P_1 + P_2 & A_{d1}Y & A_{d2}Y & YC^T & F \\ Y^TA_{d1}^T & -P_1 & 0 & 0 & 0 \\ Y^TA_{d2}^T & 0 & -P_2 & 0 & 0 \\ CY^T & 0 & 0 & -I & 0 \\ F^T & 0 & 0 & 0 & -\gamma^2 I \end{bmatrix} < 0 \quad (26)$$

The corresponding H∞ one term controller may be obtained as $K = XY^{-1}$.

3.3.2 H_∞ state feedback controller design for augmented plant

A H_∞ state feedback controller is designed for USP based augmented plant (4) such that infinity norm of the closed loop system is minimized [43] using lemma 2:

Lemma 2: There exists a state feedback controller that stabilizes the system (4) if there exists a symmetric and positive definite matrix $S>0$, an arbitrary matrix Q and appositive scalar γ that satisfies the following LMI:

$$\begin{bmatrix} P_aS+S^TP_a^{\,T}+P_bQ+Q^TP_b^{\,T} & SP_{c2}^{\,T} & P_b \\ P_{c2}S^T & -\gamma I & 0 \\ P_b^T & 0 & -\gamma I \end{bmatrix}<0 \quad (27)$$

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

Simulation and discussion

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 [30]. The system shown in Fig. 3 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.

Simulation is performed using MATLAB R2013a. The plant parameters in p.u. are given Table 1:

The system represented by (22) and (23) with $u(t)=0$ includes a local PI controller. Results for step change of 0.05 p.u. in the load $w(t)$ at t=10 sec and time delay in both control areas $(\tau_1=0.1,\tau_2=2)$ 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.

The performance of the PI controller is severely limited by the long time delay. This is because the PI controller has no knowledge of the delay time and reacts too "impatiently" when the actual output y does not match the desired set point. Everyone has experienced a similar phenomenon in showers where the water temperature takes a long time to adjust. There, impatience typically leads to alternate scolding by burning hot and freezing cold water. A better strategy consists of waiting for a change in temperature setting to take effect before making further adjustments. And once we have learnt what knob setting delivers our favorite temperature, we can get the right temperature in just the time it takes the shower to react. This "optimal" control strategy is the basic idea behind the Smith Predictor scheme.

Fig. 5 shows the responses with the technique of state feedback controller design by LMI [30] and Fig. 6 with the USP technique. Results show that with the USP techniques frequency deviation dies out and stable system is obtained. Though settling time is large in case of USP technique than [30] but the results are more realistic as the time delay really comes in the picture while in [30] H_∞ controller is designed for delay independent plant. Therefore, the stable transient response is obtained by USP technique. With the USP technique K_{usp} is given in (28) and with the technique proposed by Yu and Tomsovic [30] controller K is given in (29).

$$K_{usp}=\begin{bmatrix} 14.5548 & -0.2539 & -0.4390 & 1.0492 & 0.9058 & -0.0391 & 0.8127 & 0.0120 & -0.0181 & 0.0340 & 0.1350 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -5.6169 & -0.2808 & 0.1809 & -0.2553 & 0.2654 & -5.9216 & -108.0876 & -8.1269 & -0.2439 & 0.8484 & -1.5898 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (28)$$

$$K=\begin{bmatrix} -80.7216 & -4.2182 & 0.4006 & 0.4442 & -10.6881 & -2.4670 & 3.0334 & 0.0148 & 0.0007 & 0.0046 & -0.0033 \\ -4.1115 & -0.1599 & 0.0306 & -0.0228 & 0.1447 & -7.5729 & -514.2934 & -14.3051 & 2.3253 & -1.4923 & -16.9788 \end{bmatrix} \quad (29)$$

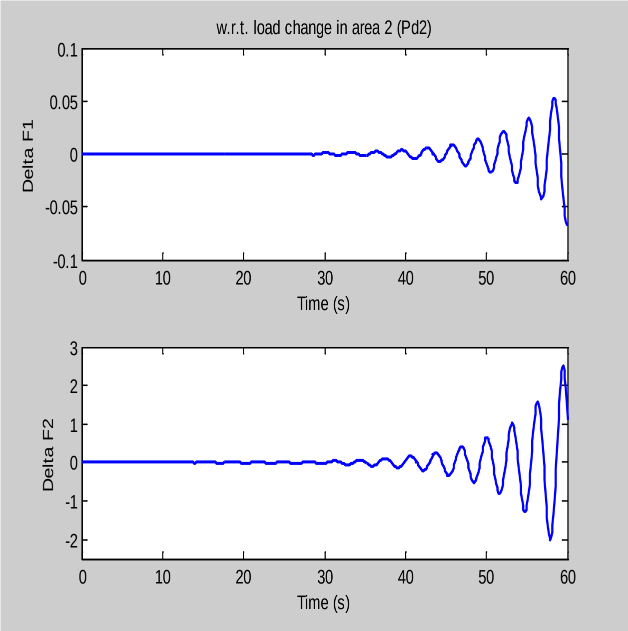

Fig. 4 Frequency deviation *(Δf_1,Δf_2)* using conventional PI controller with step load change of 0.05 pu in area 2

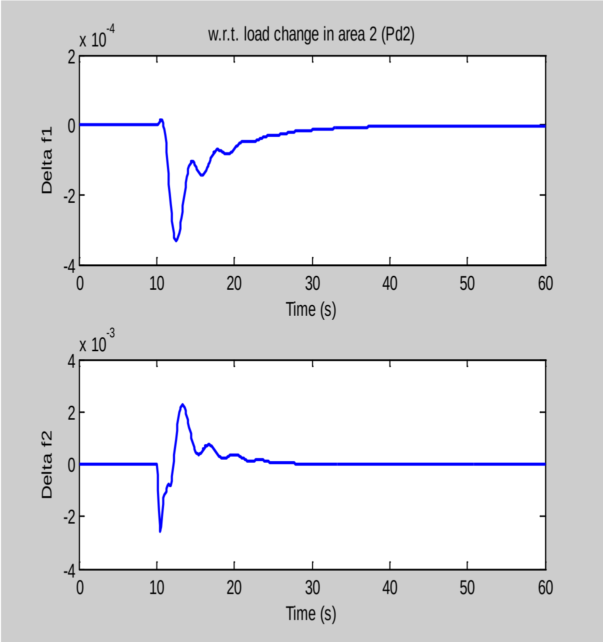

Fig. 6 Frequency deviation *(Δf_1,Δf_2)* using USP with step load change of 0.05 pu in area 2

$(\tau_1 = 0.1s, \tau_2 = 2s)$

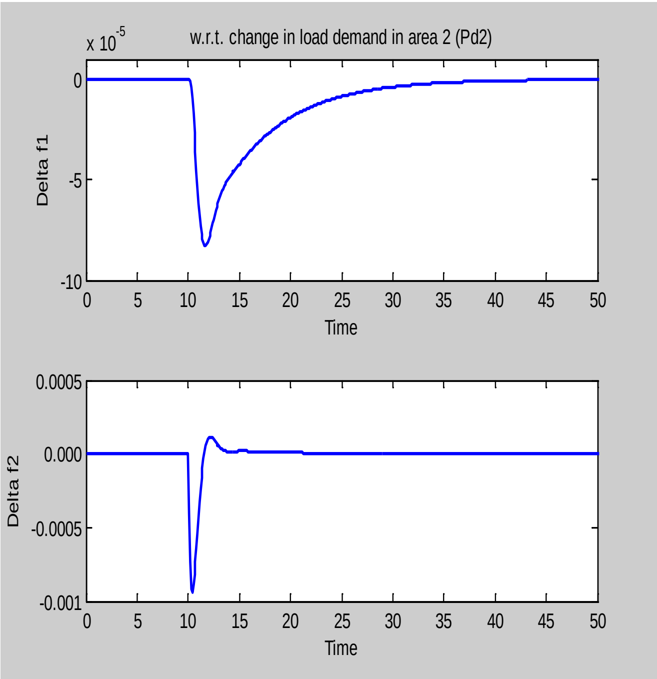

Fig. 5 Frequency deviation *(Δf_1,Δf_2)* using [30] with step load change of 0.05 pu in Area 2

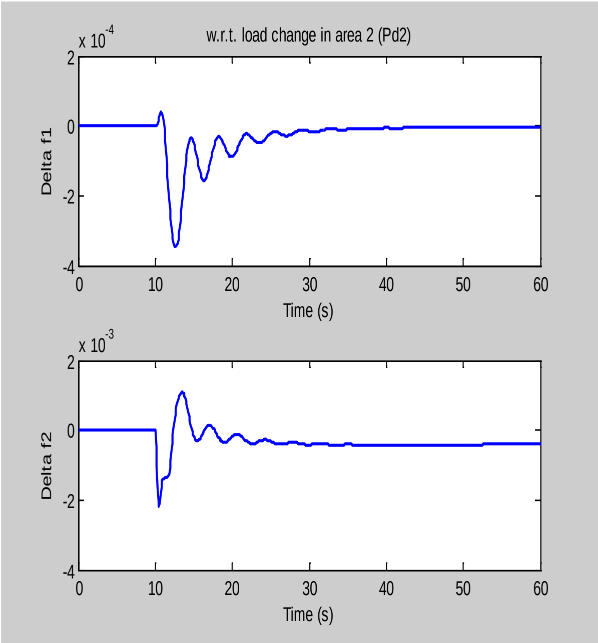

Fig. 7 Frequency deviation *(Δf_1,Δf_2)* using USP with step load change of 0.05 pu in area 2

$(\tau_1 = 0.1s, \tau_2 = 1.5s)$

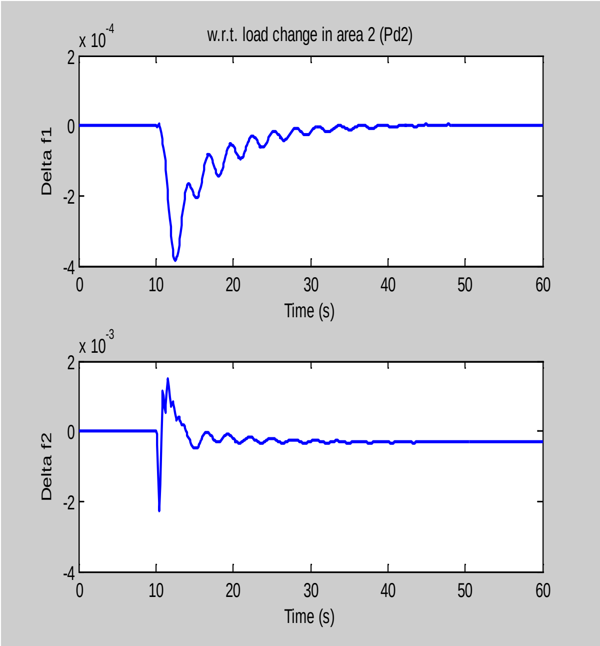

Fig.8 Frequency deviation (Δf_1,Δf_2) using USP with step load change of 0.05 pu in area 2

$$(\tau_1 = 0.1s, \tau_2 = 3.0s)$$

It is also shown from Figs. 6, 7 and 8 that for different time delays also the stable transient response with zero steady state error is obtained. Further, infinity norm of transfer function between unmeasured output 'z' and disturbances 'w' for τ_2= 1.5, 2 and 3 are 0.2978, 0.2889 and 0.3483 respectively. For all values of time delay, infinity norm is less than one which is the requirement of stable system. It is also concluded that with the increased values of time delay, infinity norm increased.

4. 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 in the plant. Simulations and comparative study show the validation of the proposed work. A stabilize system is obtained irrespective of the time delay in the system. Damping characteristics are comparable to the technique proposed by Yu and Tomsovic [30] and more realistic.

References

[1] P. Kundur, *Power System Stability and Control*, New York, McGraw Hill, 1994.

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

[3] H. Glavitsch and J. Stoffel, "Automatic generation control," *Electrical Power and Energy Systems*, vol. 2, no. 1, January 1980, pp. 21-28.

[4] H. Shayeghi, H. A. Shayanfar, A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher," *Energy Conversion and Management*, vol. 50, no.2, February 2009, pp. 344–353.

[5] S. K. Pandey, S. R.Mohanty, and N. Kishor, "A literature survey on load–frequency control for conventional and distribution generation power systems," *Renewable and Sustainable Energy Reviews*, vol. 25, 2013, pp. 318–334.

[6] Ibraheem, P. Kumar, and D. P. Kothari, "Recent Philosophies of Automatic Generation Control Strategies in Power Systems," *IEEE Transactions on Power Systems*, vol. 20, no. 1, February 2005, pp. 346-357.

[7] U. K. Rout, R. K. Sahu, and S. Panda, "Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system," *Ain Shams Engineering Journal*,vol. 4, issue 3, pp. 409-421, 2013.

[8] S. Panda and N. K.Yegireddy, “Automatic generation control of multi-area power system using multi-objective non-dominated sorting genetic algorithm-II,” *Electrical Power and Energy Systems*, vol. 43, pp. 54-63, 2013.

[9] A. K. Mahalanabis and G. Ray, “Modeling large power systems for efficient load frequency control,” *Mathematical Modelling*, vol. 7, pp. 259-272, 1986.

[10] E. Cam and I. Kocaarslan, “Load frequency control in two area power systems using fuzzy logic controller,” *Energy Conversion and Management*, vol. 46, pp. 233-243, 2005.

[11] W. Tan, “Unified tuning of PID load frequency controller for power systems via IMC,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, 2010.

[12] M. Farahani and S. Ganjefar, “Solving LFC problem in an interconnected power system using superconducting magnetic energy storage, *Physica C*, vol. 487, pp. 60-66, 2013.

[13] H. Gozde and M. C. Taplamacioglu, “Automatic generation control application with craziness based particle swarm optimization in a thermal power system,” *Electrical Power and Energy Systems*, vol. 33, pp. 8-16, 2011.

[14] A. M. Stankovic, G. Tadmor, and T. A. Sakharuk, “On robust control analysis and design for load frequency regulation,” *IEEE Transactions on Power Systems*, vol. 13, no. 2**,** 1998.

[15] H. Shabani, B. Vahidi, and M. Ebrahimpour, “A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems,” *ISA Transactions*, vol. 52, pp. 88-95, 2013.

[16] S. Debbarma, L. C.Saikia, and N. Sinha, “AGC of a multi-area thermal system under deregulated environment using a non-integer controller,” *Electric Power Systems Research*, vol. 95, pp. 175-183, 2013.

[17] T. C. Yang, Z. T. Ding, and H. Yu, “Decentralized Power System load frequency control beyond the limit of diagonal dominance,” *Electrical Power and Energy Systems*, vol. 24, pp. 173-184, 2002.

[18] M. Zribi, M. Al-Rashed, and M. Alrifai, “Adaptive decentralized load frequency control of multi-area power systems,” *Electrical Power and Energy Systems*, vol. 27, pp. 575-583, 2005.

[19] K.R. Sudha and R. VijayaSanthi, “Robust decentralized load frequency control of interconnected power system with Generation Rate Constraint using Type-2 fuzzy approach,” *Electrical Power and Energy Systems*, vol. 33, pp. 699-707, 2011.

[20] M. T. Alrifai , M. F. Hassan, and M.Zribi, “Decentralized load frequency controller for a multi-area interconnected power system,” *Electrical Power and Energy Systems*, vol. 33, pp. 198-209, 2011.

[21] H. Shayeghi and H.A. Shayanfar, “Application of ANN technique based on l-synthesis to load frequency control of interconnected power system,” *Electrical Power and Energy Systems*, vol. 28, pp. 503-511, 2011.

[22] E. Cam andI.Kocaarslan, “Application of fuzzy logic for load frequency control of hydro-electrical power plants,” *Energy Conversion and Management*, vol. 46, pp. 233-243, 2005.

[23] S.Pothiya, I.Ngamroo, “Optimal fuzzy logic-based PID controller for load–frequency

control including superconducting magnetic energy storage units," *Energy Conversion and Management*, vol. 49, pp. 2833-2838, 2008.

[24] K.R. Sudha, R. VijayaSanthi, "Load Frequency Control of an Interconnected Reheat Thermal system using Type-2 fuzzy system including SMES units," *Electrical Power and Energy Systems*, vol. 43, pp. 1383–1392, 2012.

[25] R. Farhangi, M. Boroushaki, and S. H.Hosseini, "Load–frequency control of interconnectedpower system using emotional learning-based intelligent controller," *Electrical Power and Energy Systems*, vol. 36, pp. 76-83, 2012.

[26] O.I. Elgerd, *Electric Energy Systems Theory: An Introduction*, Tata McGraw Hill, 1983, New Delhi.

[27] G. Ray, N. Yadaiah, and G. D. Parsad, "Design of load frequency regulator based on Schur approach," *Electric Power Systems Research*, vol. 36, pp. 145-149, 1996.

[28] W. Tan, "Unified Tuning of PID Load Frequency Controller for Power Systems via IMC," *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 341-350, 2010.

[29] S. Saxena and Y. V. Hote, "Load frequency control in power systems via Internal Model Control scheme and model order reduction," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2749-2757, 2013.

[30] X. Yu and K. Tomsovic, "Application of linear matrix inequalities for load frequency control with communication delay," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1508-1515, 2004.

[31] H.Bevrani and T.Hiyama, "Robust decentralized PI based LFC design for time delay power systems," *Energy Conversion and Management*, vol. 49, pp. 193-204, 2008.

[32] L. Jiang, W. Yao, Q. H. Wu, J. Y. Wen, and S. J. Cheng, "Delay-dependent stability for load frequency control with constant and time varying delay," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 932-941, 2012.

[33] R.Dey, S. Ghosh, G. Ray, and A. Rakshit, "H_∞ load frequency control of interconnected power systems with communication delays," *Electrical Power and Energy Systems*, vol. 42, pp. 672-684, 2012.

[34] Qing-Chang Zhong, *Robust Control of Time-delay Systems*, Springer-Verlag London Limited, 2006.

[35] Z. Gajic and M. Lelic, *Modern Control Systems Engineering*, Prentice Hall Europe, 1996.

[36] K. Watanabe and M. Ito, "A process model control for linear systems with delay," *IEEE Transactions on Automatic Control*, vol. 26, no. 6, pp. 1261-1269, 1981.

[37] Z. J. Palmor, "Time-delay compensation – Smith predictor and its modifications," *The Control Handbook*, S. Levine, Ed. CRC Press, pp. 224-237, 1996.

[38] M. R.Matausek and A. D. Micic, "On the modified Smith predictor for controlling a process with an integrator and long dead time", *IEEE Transactions on Automatic Control*, vol. 44, no. 8, pp. 1603-1606, 1999.

[39] S. Majhi and D. P. Atherton, "Modified Smith predictor and controller for processes with time delay", *IEE Proc. Control Theory Application*, vol. 146, no. 5, pp. 359-366, 1999.

[40] K. J. Astrom, C. C. Hang and B. C. Lim, "A new Smith predictor for controlling a process

with an integrator and long dead-time,"*IEEE Transaction on Automatic Control*, vol. 39, no. 2, pp. 343-345, 1994.

[41] Q. C. Zhong and G. Weiss, "A unified smith predictor based on the spectral decomposition of the plant," *International Journal of Control*, vol. 77, no. 15, pp. 1362-1371, 2004.

[42] R.Majumder, B.Chaudhuri, B. C. Pal and Q. C. Zhong, "A unified smith predictor approach for power system damping control design using remote signals," *IEEE Transactions on Control Systems Technology*, vol. 13, No. 6, pp. 1063-1068, 2005.

[43] S.Skogestad and I.Postlethwaite, *Multivariable Feedback Control Analysis and Design*, John Wiley and Sons Ltd., 2005.