Load Frequency Control of Interconnected Power Systems by Considering Self-Component of Area Control Error

R. Sahoo D. Das J. Pal

Abstract— **The paper presents study of load frequency control of two area interconnected power systems. Area control error (ACE) is decomposed into self-component and mutual component. Self-component of ACE is used to control the frequency and tie-power deviations following a step load disturbance. Advantage of using self-component of ACE is that it corrects the time deviation in addition to correcting frequency and tie-power deviations. Based on the self-component of ACE, a modified area control error (MACE) is proposed for reducing the inadvertent interchange accumulation in the steady state.**

Index Terms—**Load frequency control, area control error, integral squared error.**

I. INTRODUCTION

IN the last three decades, the problem of load frequency control (LFC) has been one of the most accentuated topics in the operation of interconnected power systems. The LFC of an interconnected power system has two principal aspects: the maintenance of frequency and power exchange over inter area tie lines on scheduled values. At the same time, it should minimize the time error and inadvertent interchange accumulations. The objective of LFC is to maintain the area generation –demand balance by adjusting the outputs of regulating units in response to deviations of frequency tie-line exchange.

A large number of controllers are used to maintain a power system in a normal state of operation. As demand fluctuates from its normal operating value, the state of the system changes. To maintain the system at a normal operating state, different types of controllers based on optimal control theory [1- 4], variable structure control strategy [5,8] robust control [9,10] and fuzzy logic control [11,12] have been developed in the past. Despite powerfulness of these control strategies, these controllers have failed to appeal to the industry because the practical realization of such controllers for LFC is difficult, cumbersome and costly. On the other hand, simple classical (tie-line bias) controls for LFC are still popular with the industry because of its inherent simplicity, easy realization, low cost and because of the decentralized nature of the control strategy. Most load frequency controllers are primarily composed of integral or proportional integral controller .The controller gains are set to a level that compromises between fast transient recovery and low overshoot in the dynamic response of the overall system .The literature survey shows that, researchers have used classical control strategy [13-17] for LFC using area control error (ACE) as an input signal to the controller.

Area control error is a signal, which is a function of frequency and tie-power deviation. When this signal is used as input signal to the controller, frequency and tie-power deviations are corrected to zero following a step load disturbance. However, time deviation and inadvertent interchange accumulations, which is time integral of tie-power deviation, show steady state errors. To compute area control error, measurement of frequency and tie-power deviations are required.

In the present work, area control error (ACE) is decomposed into self and mutual components. It is shown that, self-component of area control error is a function of frequency and time deviation. Self-component of ACE is used as an input signal to the controller to correct the frequency deviation, tie-power deviation and time deviation following a step load disturbance.

II. SYSTEM INVESTIGATED

The LFC system investigated is composed of an interconnection of two-area power system shown in Fig1. In area-1, one reheat (RH) and one hydro unit are there and in area–2, two non-reheat (NRH) units are there.Fig.2 shows the transfer function block diagram of Fig.1. The generation rate constraints are not considered. Nominal parameters of the systems are given in the Appendix,

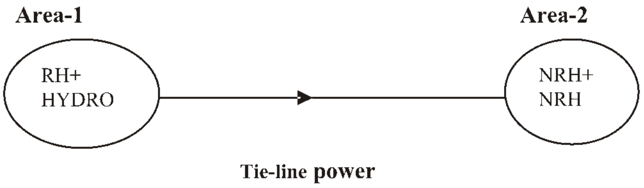

Fig.1: Two area interconnected power system

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III. DYNAMIC MODEL

The dynamic behaviour of the LFC system is described by the linear vector differential equation:

$$\dot{X} = AX + BU + \gamma P \qquad (1)$$

where X, U and P are the state, control and disturbance vectors, and A, B and γ are real constant matrices of appropriate dimensions. The state, control and disturbance vectors are defined as:

$$X' = \left[\Delta F_1, \Delta P_{g1}, \Delta P_{R1}, \Delta X_{E1}, \Delta P_{tie12}, \Delta F_2, \Delta P_{g2}, \right.$$
$$\left. \Delta P_{R2}, \Delta X_{E2}, \Delta P_{g3}, \Delta P_{g4}, \Delta P_{R3}, \Delta P_{R4}\right] \qquad (2)$$

$$U' = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \qquad (3)$$

$$P' = \begin{bmatrix} \Delta P_{d1} & \Delta P_{d2} \end{bmatrix} \qquad (4)$$

where ′ stands for transpose.

IV. DECOMPOSITION OF AREA CONTROL ERROR (ACE)

The area control error of area-1 and area-2 are given as

$$ACE_1 = B_1 \Delta F_1 + \Delta P_{tie12} \qquad (5)$$

$$ACE_2 = B_2 \Delta F_2 + a_{12} \Delta P_{tie12} \qquad (6)$$

where,

ΔF_1 = Frequency deviation in area-1

ΔF_2 = Frequency deviation in area-2

ΔP_{tie12} = Tie-power deviation

a_{12} = Area capacity ratio

B_1 = Frequency bias in area-1

B_2 = Frequency bias in area-2

From Fig.2, the tie-line power deviation can be written as:

$$\Delta P_{tie12} = \frac{2\pi T_{12}}{s}(\Delta F_1 - \Delta F_2) \qquad (7)$$

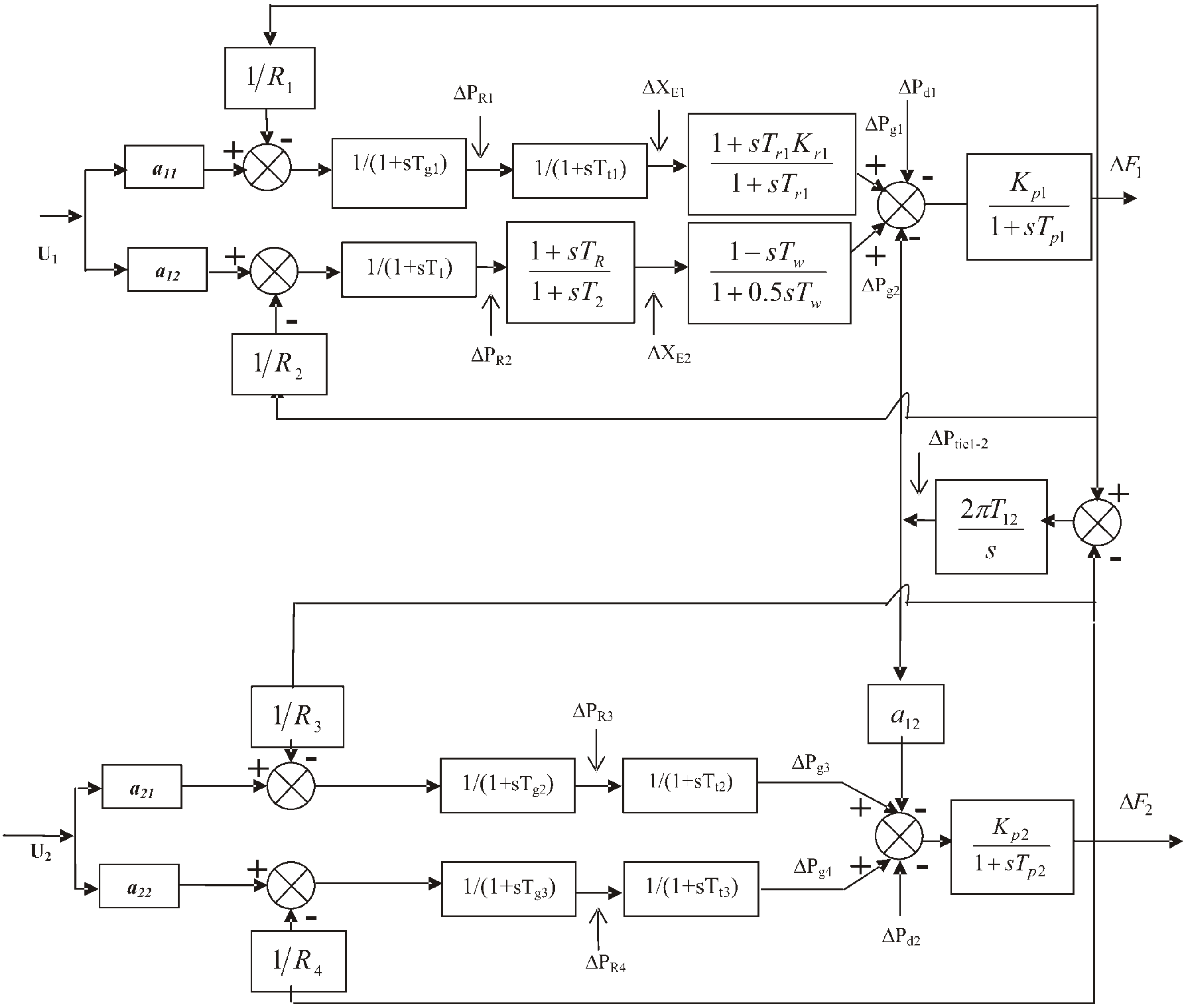

Fig.2: Transfer Function block diagram of Fig.1

$$\therefore \quad \Delta P_{tie12} = 2\pi T_{12}\left(\int \Delta F_1 dt - \int \Delta F_2 dt\right)$$

$$\therefore \Delta P_{tie12} = \frac{2\pi T_{12} f_0 \left(\int \Delta F_1 dt - \int \Delta F_2 dt\right)}{f_0} \tag{8}$$

where f_0 = nominal system frequency

$$\therefore \ \Delta P_{tie12} = 2\pi T_{12} f_0 (\varepsilon_1 - \varepsilon_2) \tag{9}$$

where $\varepsilon_1 = \frac{1}{f_0}\left(\int \Delta F_1 dt\right)$ = Time- deviation in area-1

$\varepsilon_2 = \frac{1}{f_0}\left(\int \Delta F_2 dt\right)$ = Time- deviation in area-2

From equation (9), substituting the expression of ΔP_{tie12} into equations (5) & (6), we obtain

$$ACE_1 = B_1 \Delta F_1 + 2\pi T_{12} f_0 (\varepsilon_1 - \varepsilon_2) \tag{10}$$

$$ACE_2 = B_2 \Delta F_2 + 2\pi T_{12} f_0 a_{12} (\varepsilon_1 - \varepsilon_2) \tag{11}$$

ACE_1 as given in equation (10) is decomposed into two components, i.e. equation (10) can be written as:

$$ACE_1 = ACE_{11} + ACE_{12} \tag{12}$$

where, ACE_{11} is called self-component and ACE_{12} is called mutual component and can be given as:

$$ACE_{11} = B_1 \Delta F_1 + 2\pi T_{12} f_0 \varepsilon_1 \tag{13}$$

$$ACE_{12} = -2\pi T_{12} f_0 \varepsilon_2 \tag{14}$$

Note that self-component ACE_{11} is function of frequency and time deviations of area-1 and both are measurable quantities. Similarly, ACE_2 as given in equation (11) can be decomposed into two components, i.e.

$$ACE_2 = ACE_{22} + ACE_{21} \tag{15}$$

$$ACE_{22} = B_2 \Delta F_2 - 2\pi T_{12} f_0 a_{12} \varepsilon_2 \tag{16}$$

$$ACE_{21} = 2\pi T_{12} f_0 a_{12} \varepsilon_1 \tag{17}$$

In the present work self-component ACE_{11} and ACE_{22} are used as an input signal to the controllers. Note that equations (13) & (16) are functions of frequency and time deviations. Advantages of using this scheme are that it corrects the frequency, tie-power and time deviations without much deteriorating the dynamic performances.

V. CONVENTIONAL AREA CONTROL ERROR (ACE) AS AN INPUT SIGNAL TO THE INTEGRAL CONTROLLER

Emphasis has been laid on conventional integral controller. The integral control law is described as,

$$U_i = -K_{Ii} \int ACE_i dt \tag{18}$$

Where K_{Ii} is the integral gain setting of area i and ACE_i is the area control error of area i.

VI. SELF-COMPONENT OF AREA CONTROL ERROR AS AN INPUT SIGNAL TO THE INTEGRAL CONTROLLER

In this case, integral control law is described as,

$$U_i = -K_{si} \int ACE_{ii} dt \tag{19}$$

where K_{si} is the integral gain setting of area i when self-component of area control error is used as an input signal to the controller.

VII. OPTIMIZATION OF INTEGRAL GAIN SETTING USING INTEGRAL SQUARED ERROR (ISE) TECHNIQUE

Integral squared error (ISE) technique is used for obtaining the optimum gain settings of integral controllers. A performance index

$$J = \int_0^t (\Delta F_1^2 + \Delta F_2^2 + \Delta P_{tie12}^2) dt \tag{20}$$

is minimized for 1% step load disturbance in either of the areas for obtaining the optimum values of integral gain settings. It is proposed in [16], that the optimum value of gain settings can be obtained on an individual basis by considering other area uncontrolled.

In the present work, the optimum values of integral gain settings of two-area interconnected power systems are also obtained by keeping other area uncontrolled.

Fig.3 shows the plot of J Vs KI1 for 1% step load disturbance in area –1 keeping the other area uncontrolled. From Fig.3, it is seen that $K_{I1}=K_{I1opt}=0.5$

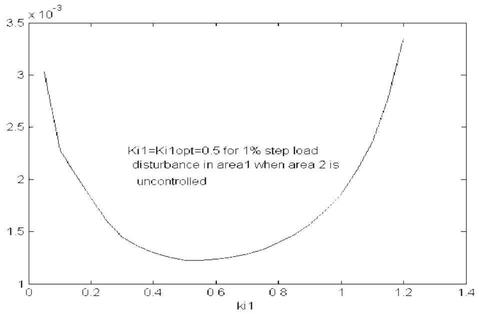

Fig.3: Plot of J Vs K_{I1} (K_{I2}=0) for ΔP_{d1}=0.01&ΔP_{d2}=0.0

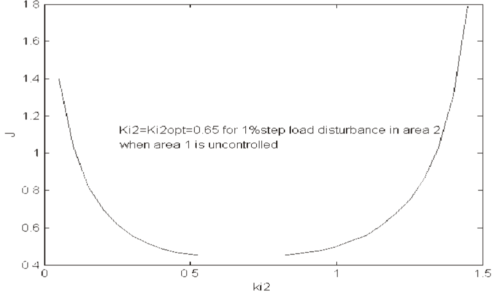

Fig.4: Plot of J Vs K_{I2} (K_{I1}=0) for ΔP_{d1}=0.0 &ΔP_{d2}=0.01

Similarly, Fig.4 shows the plot of J Vs KI2 for 1% step load disturbance in area-2 keeping the other area uncontrolled. From Fig.4,it is seen that $K_{I2}=K_{I2opt}$= 0.65.

VIII. Optimization of Integral Gain Settings Considering Self-Component of Ace (SACE)

When self-component of *ACE* (*SACE*) is used the same performance index (eqn-20) is minimized for 1% step load disturbance in either of the areas for obtaining the optimum values of integral gain settings $K_{s1}=K_{s1opt}$ and $K_{s2}=K_{s2opt}$.

Fig.5 shows the plot of J Vs Ks1 for 1% step load disturbance in area-1 by keeping the other area uncontrolled. From Fig.5, it is seen that $K_{s1}=K_{s1opt}= 0.4$

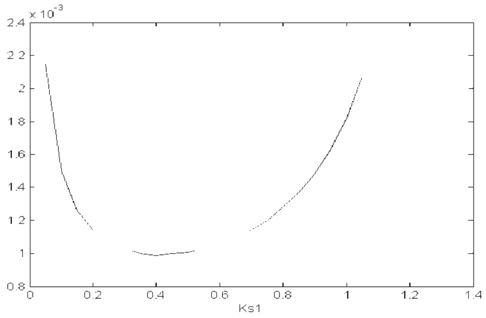

Fig.5: Shows the plot of J Vs K_{s1} (K_{s2}=0) for $\Delta P_{d1}=0.01$& $\Delta P_{d2}=0.0$ considering self-component of ACE.

Fig.6 shows that plot of J Vs Ks2 for 1% step load disturbance in area-2, keeping the other area uncontrolled. From Fig.6, it is seen that $K_{s2}=K_{s2opt}=0.6$

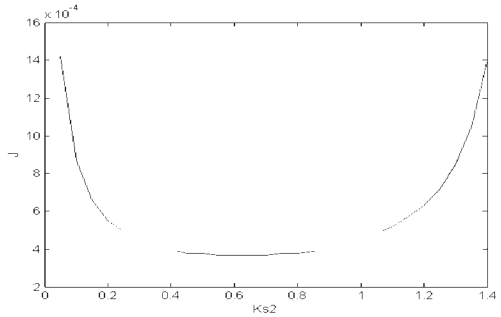

Fig.6: Plot of J Vs K_{s2} (K_{s1}=0) for $\Delta P_{d1}=0.0$ & $\Delta P_{d2}=0.01$ considering self-component of ACE.

Table –1 gives optimum integral gain settings considering conventional ACE and SACE. From Table-1, it is seen that the optimum integral gain settings considering self-component of ACE and conventional ACE are very close to each other.

TABLE 1

Optimum values of integral gains settings

CONVENTIONAL ACE		SELF-COMPONENT OF ACE	
K_{I1}	K_{I2}	K_{s1}	K_{s2}
0.5	0.65	0.4	0.6

IX. DYNAMIC RESPONSES

Fig.7 shows the dynamic responses for 1% step load disturbance in area –1 considering *ACE* and Self-component of *ACE*.

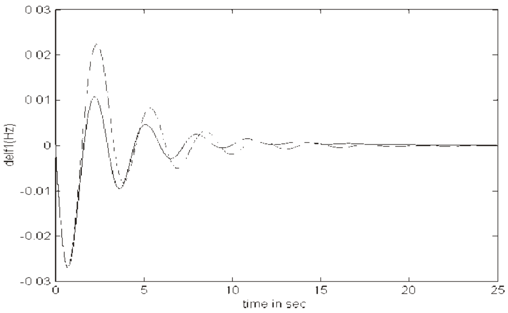

Fig.7 (a)

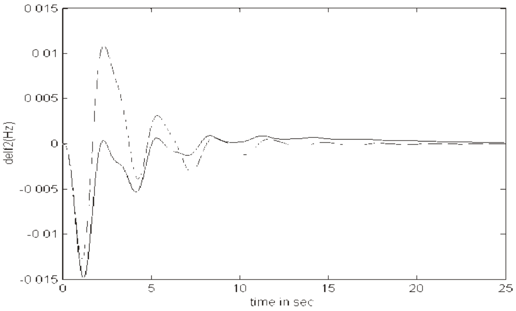

Fig. 7 (b)

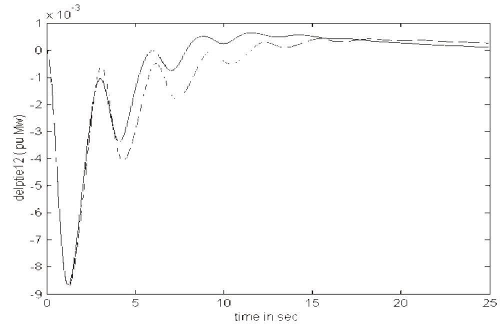

Fig.7(c)

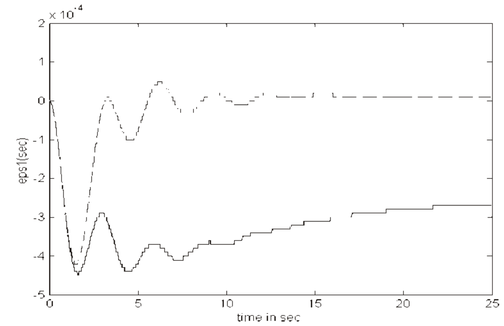

Fig.7 (d)

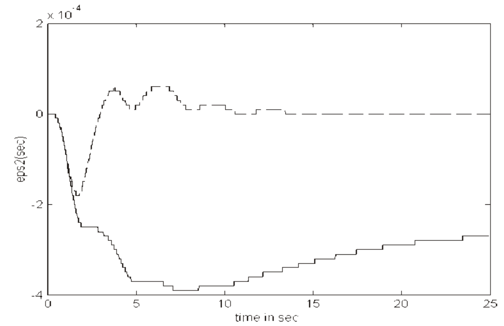

Fig. 7(e)

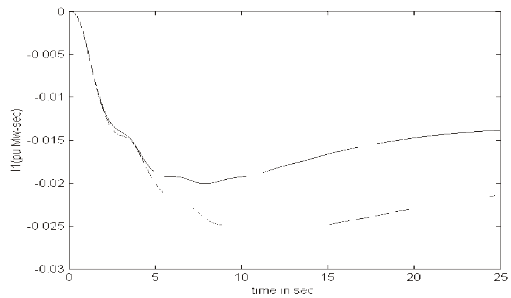

Fig.7 (f)

Fig.7 Dynamic responses for 1% step load disturbances in area-1

———— : Conventional ACE (K_{I1opt}=0.5 & K_{I2opt}=0.65)

------- : Self-component of ACE (K_{s1opt}=0.4 & K_{s2opt}=0.6)

From Fig.7, it is seen that frequency, tie-power and time deviations are corrected considering self-component of *ACE*, whereas with the use of conventional *ACE*, time deviation is showing steady-state errors. Note that with the use of self-component of *ACE*, frequency deviation is slightly deteriorated and this is obvious because it forces the steady state error of time deviation to zero. Also note that the tie-power deviation is corrected to zero because ΔPtie12 is function of ε_1 & ε_2 and time deviations in both the areas (ε_1 & ε_2) are corrected to zero. Also note that with the use of self-component of *ACE*, steady state values of inadvertent interchange accumulation is more than that obtained with conventional *ACE*. This is also obvious because mutual component of *ACE* is ignored. However, modifying the self-component of ACE can reduce steady state value of inadvertent interchange accumulation. Therefore, we define modified self-component of *ACE* (*MSACE*) as

$$MSACE_{11} = B_1 \Delta F_1 + K_{\varepsilon 1}\varepsilon_1 \quad (21)$$

$$MSACE_{22} = B_2 \Delta F_2 + K_{\varepsilon 2}\varepsilon_2 \quad (22)$$

In this case, integral control law for i-th area is given as:

$$\mathbf{U_i} = -\mathbf{K_{si}} \int MSACE_{ii}\,dt \quad (23)$$

Here the same optimum values of integral gain settings are used, i.e., K_{s1opt}=0.4 & K_{s2opt}= 0.6. It was also found that $K_{\varepsilon 1} = K_{\varepsilon 2} = 50$ gives better dynamic performances in terms of reducing the steady state value of inadvertent interchange accumulation. Fig.8 shows the dynamic responses considering self-component (S*ACE*) and MSACE. From Fig.8, it is seen that with the use of *MSACE*, accumulation of inadvertent interchange is less (Fig.8 (f)).

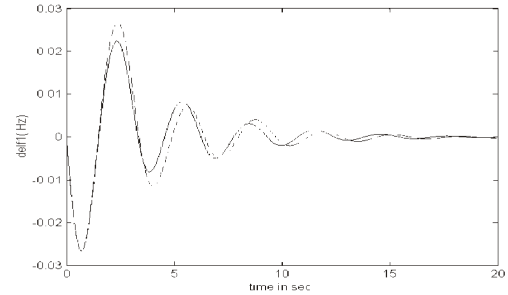

Fig. 8 (a)

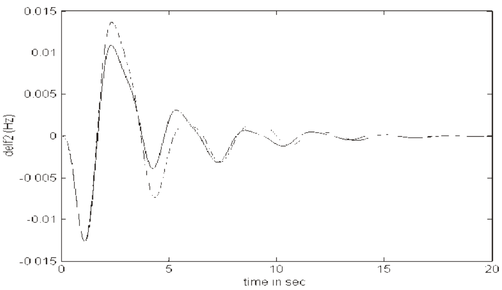

Fig.8 (b)

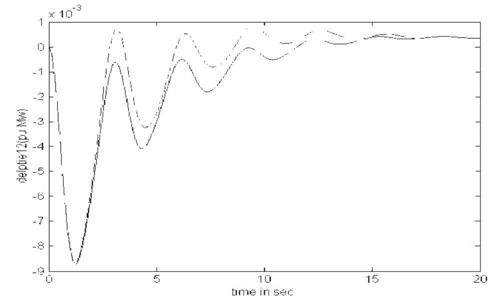

Fig. 8 (c)

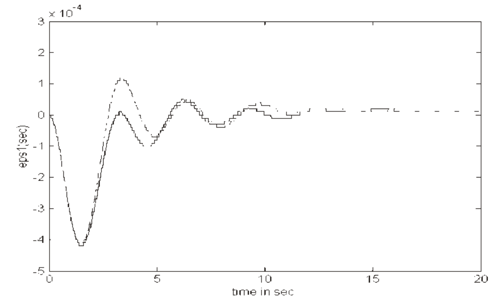

Fig. 8(d)

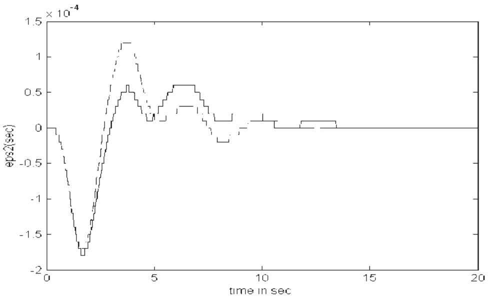

Fig. 8 (e)

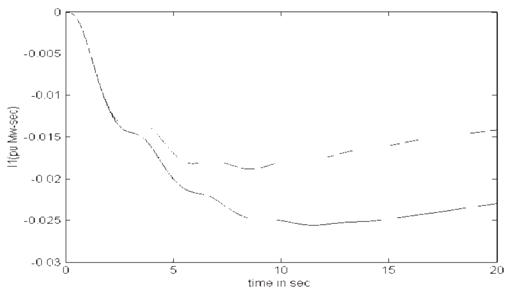

Fig. 8 (f)

Fig. 8: Dynamic Responses for 1% step load disturbance in area – 1 considering, K_{s1opt}=0.4 & K_{s2opt}= 0.6.

———— : SACE ------- : MSACE

X. CONCLUSIONS

In this paper, load frequency control of interconnected power system has been studied. It has been shown that the area control error (ACE) consists of a self-component and a mutual component. Self-component of ACE has been used as an input signal to the controller. Analysis reveals that the self-component of ACE is capable of correcting frequency, tie-power and time deviations. A modified self-component of ACE (MSACE) has also been proposed, which minimizes the inadvertent interchange accumulations in the steady state along with correcting the frequency, tie-power and time deviations. The study suggests that the proposed technique can be used for large interconnected power systems.

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APPENDIX

Data for power system

f_o = 60Hz, $P_{r1} = P_{r2}$ = 1000MW, $K_{p1} = K_{p2}$ = 120 Hz/pu MW, $T_{p1} = T_{p2}$ = 20.0 sec, sec, $R_1 = R_2$ = 2.4 Hz/pu MW, $B_1 = B_2$ = 0.425 pu MW/Hz, $T_{11} = T_{12}$ = 48.7secs, $T_{21} = T_{22}$ = 0.513sec, $T_{R1} = T_{R2}$ = 5.0secs, $T_{w1} = T_{w2}$ = 1.0sec. blishes scholarly the biography.