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論 文

Decentralized Robust Adaptive Controller Design

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ABSTRACT

This paper deals with the decentralized robust adaptive controller design for large-scale interconnected systems. We consider an arbitrary interconnection of subsystems with unkown parameters and bounded disturbances. When the disturbance and uncertain interconnections are present, the stability of the controlled large-scale system is ensured if there exists a positive definite M-matrix which is related to the bound of the interconnections. The possible bound of the interconnections is assumed to be known P_{th} order polynomials for the decentralized adaptive controller. A modified adaptive law is proposed guaranteeing the existence of a region of attraction from which all signals converge to a residual set D_0, which contains the equilibrium.

要 約

본 논문에서는 서로 다른 유계된 외란이 부시스템 간에 존재하는 상호 연계된 시스템의 강건한 분할 적응제어기를 설계한다. 외란과 미지차수의 상호연계가 존재할때, 전체 시스템의 안정도는 시스템의 연계정도를 제한하는 양 확정 M-행렬의 크기로 결정된다. 부 시스템의 상대 차수의 범위가 P_{th}로 제한될 때, 시스템을 제어영역별로 분할하여 제어기를 설계한다. 수정된 제어기를 사용하여 각 부시스템의 기준입력을 적분편차로 적용하여 정상상태의 오차가 잔류집합 D_o에 수렴하고, 제어기의 파라미터를 설계할 수 있는 분할적응제어기에 적용해 보였다.

I. INTRODUCTION

We have attempted to address the problem of controlling large-scale systems which are interconnected. The overall system may be considered to be a set of small interconnected subsystems. For such systems, with possibly many interconnected components, the dynamics of each subsystem may be individually determined but the interconnection terms are harder to identify. A drawback of most centralized adaptive schemes is that they

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are concerned with the dynamic structure of the processes they are controlling because they require parametrization of the dynamics of the system in linear paramatric form. They cannot handle structural changes in the system. Our approach is to decouple complex systems from control by using appropriate simplified linear reference models. Traces generated by these models are tracked using decentralized controllers which must be robust so that they perform well under lack of parameteric uncertainties and variable dynamics. The fundamental uncertainties encountered in decentralized controller design are the strength of the interconnections among the subsystems. Most of the previous works in decentralized control of large-scale systems can be found in [1][3][7][8] and their works are based on the assumptions that the interconnections are either bounded by known or unknown P_{th} order polynomials in states [2]. The standard M-matrix conditions have been used by Ioannou[5] and Ossman[9] for decentralized adaptive controller designs. The stability of the controlled large-scale sysetm is ensured if there exists a positive definite M-matrix which is related to the bound of the interconnections. In this paper, we investigate robust adaptive controller design when the strength of the interconnections among for subsystems is bounded by a known polynomial in states. We consider the decentralized adaptive control for the interconnected subsystems with unknown parameters, nonlinearity and bounded disturbances. The stability of the overall adaptive decentralized controller is analyzed through the Lyapunov direct method and Kalman-Yacubovich lemma[3]. The robust adaptive decentralized controller is proposed to drive the uncertain subsystems to track the local reference models [6][12][13] as closely as possible with improving a steady state deviation.

II. INTERCONNECTED LINEAR SYSTEMS

We consider a large-scale systems S which is composed of N interconnected linear subsystems S_i. Each subsystems S_i of control area may be represented as

$$S_i : \dot{x}_i = A_i x_i + b_i U_i + D_i + \sum_{j=0}^{N} f_{ij}(t, x_j) \quad (1)$$

$$y_i = h_i^T x_i \quad (2)$$

where $x_i(t) \in R^{n_i}$ is the state vector, $U_i(t) \in R$ is the control input, $A_i \in R^{n_i} \times R^{n_i}$ is the unknown constant matrix, and $b_i \in R^{n_i}$ is the unknown constant vector. The unknown function $f_{ij}(t, x_i) \in R^n$, where $n = \sum_{j=0}^{N} n_j$ is the strength of interconnections from other subsystems. It should be noted that the interconnections are assumed to satisfy the following formular.

$$\| f_{ij}(t, x_i) \| \leq \alpha_{ij} \| x_j \| \quad (3)$$

where α_{ij} describes the unknown arbitrary positive definite constant. The overall systems S can be written in a compact form.

$$S : \dot{X} = AX + BU + D + F(t, x) \quad (4)$$

$$Y = CX \quad (5)$$

where $X = [X_1^T, X_2^T, \ldots, X_N^T]^T$ are states, $D = [D_1^T, D_2^T, \ldots, D_N^T]$ are disturbances and $F(t, x)$ is interconnections of subsystems. The constant block matrices $A \in R^n \times R^n$ and $B \in R^n \times R^N$ are represented by $A = diag[A_1, \ldots, A_N]$, $B = diag[B_1, \ldots, B_N]$. We now investigate the formular of the problem. The objective is to track a reference tragectory x_{mi} generated by a linear reference model M_i, $i \in N$

$$M_i : \dot{x}_{mi} = A_{mi} x_{mi} + b_{mi} r_i \quad (6)$$

$$y_{mi} = C_{mi}^T x_{mi} \quad (7)$$

where A_{mi} is a stable constant matrix. Therefore, it satisfies the Lyapunov matrix equation. i.e., for any positive definite matrix Q_i, there exists a unique positive matrix P_i such that

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$$A_{mi}^T P_i + P_i A_{mi} = -Q_i \tag{8}$$

The overall reference model M for the systems can also be written in a compact form

$$M : \dot{X}_m = A_m X_m + B_m r \tag{9}$$

$$Y = C_m X_m \tag{10}$$

where $r \in R^N$ is the reference input vector and $A_m = diag[A_{m1}, \ldots, A_{mN}]$, $B_m = diag[B_{m1}, \ldots, B_{mN}]$. when there is no disturbances, and non-interconnections, i.e., in the case of $D=0$ and $F(t, x)=0$, the above formulation describes the single input single output adaptive control systems. But the term $F(t, x)$ has nonlinearity for interconnections.

Ⅲ. DECENTRALIZED ADAPTIVE CONTROLLER

We consider the transfer function of the plant is given by

$$W_p(s) = h_p^T (SI - A_p)^{-1} b_p = K_p \frac{N_i(s)}{D_i(s)} \tag{11}$$

where $N_i(s)$ is the $n_i - 1$ order monic Hurwitz polynomials, and $D_i(s)$ is the n_i order monic polynomials. The reference model is assumed to be order n with a strictly positive real transfer function

$$W_{mi}(s) = C_{mi}^T (SI - A_m)^{-1} b_{mi} = K_{mi} \frac{Z_m(s)}{R_m(s)} \tag{12}$$

where $Z_m(s)$ and $R_m(s)$ are monic Hurwitz polynomials of degree $n-1$ and n respectively and K_{mi} is positive.

The controller structure is completely described by the differential equation.

$$\dot{V}_i^{(1)} = A_i V_i^{(1)} + g_i U_i \tag{13}$$

$$W_i^{(1)} = C_i^T(t) V_i^{(1)} \tag{14}$$

$$\dot{V}_i^{(2)} = A_i V_i^{(2)} + g_i Y_i \tag{15}$$

$$W_i^{(2)} = d_{oi}(t) Y_i + d_i^T V_i^{(2)} \tag{16}$$

$$V_i \triangleq [r(t), V_1^T(t), Y_p(t), V_2^T(t)]^T \tag{17}$$

$$\theta_i \triangleq [K_{oi}(t), C_i^T(t), d_{oi}^T(t), d_i^T(t)]^T \tag{18}$$

$$U(t) = \theta^T(t) W(t) \tag{19}$$

where A is an asymptotically stable matrix and $det[SI - A] = \lambda(s)$. It follows that when the control parameters $K(t)$, $\theta_1(t)$, $\theta_0(t)$ and $\theta_2(t)$ assume constant values K_c, θ_{1c}, θ_{0c} and θ_{2c} respectively, the transfer functions of the feedforward and the feedback controllers are respectively

$$\frac{\lambda(s)}{\lambda(s) - C(s)} \quad \text{and} \quad \frac{D(s)}{\lambda(s)} \tag{20}$$

and overall transfer function of the plant together with the controller can be expressed as

$$W_0(s) = \frac{K_c K_p N_i(S) \lambda(s)}{[\lambda(s) - C(s)] D_i(s) - K_p N_i(s) D(s)} \tag{21}$$

where $\lambda(s)$ is a monic polynomial of degree $n-1$ and $C(s)$ and $D(s)$ are polynomials of degree $n-2$ and $n-2$ respectively. The parameter vector θ_1 determines the coefficient of $C(s)$ while θ_0 and θ_2 together determine those of $D(s)$. Fig 1. shows the decentralized adaptive controller structure which used in this paper.

Let $C^*(s)$ and $D^*(s)$ be polynomials in S such that

$$\lambda(s) - C^*(s) = N_i(s), \; D_i(s) - K_p D^*(s) = R_m(s) \tag{22}$$

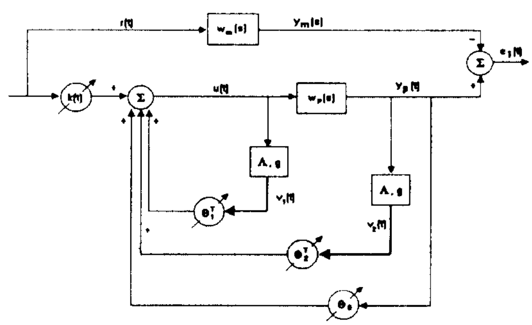

Fig. 1. The decentralized adaptive controller.

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Futher let $\lambda(s)=Z_m(s)$, then scalars K^*, θ_0^* and θ_1^* and θ_2^* exist such that $K^*=\frac{K_m}{K_p}$, $\theta_1^{*T}(SI-\Lambda)^{-1}g_i=\frac{C^*(s)}{\lambda(s)}$ and $\theta_0^*+\theta_2^{*T}(sI-\Lambda)^{-1}g_i=\frac{D^*(s)}{\lambda(s)}$ choosing $\theta(t)\equiv\theta^*$, where θ^* is defined as

$$\theta^* \triangleq [k^*, \theta_1^{*T}, \theta_0^*, \theta_2^{*T}]^T \tag{23}$$

The transfer function $W_0(s)$ in Eq.(21) becomes

$$W_0(s)=k_m\frac{N_i(s)Z_m(s)}{N_i(s)[D_i(s)-k_pD^*(s)]}=W_m(s) \tag{24}$$

The overall system equation describing the plant together with the controller can be expressed as

$$\begin{bmatrix} \dot{x}_i \\ \dot{v}_i^{(1)} \\ \dot{v}_i^{(2)} \end{bmatrix}=\begin{bmatrix} A_i & 0 & 0 \\ 0 & \Lambda & 0 \\ g_ih_i^T & 0 & \Lambda \end{bmatrix}\begin{bmatrix} x_i \\ v_i^{(1)} \\ v_i^{(2)} \end{bmatrix}+\begin{bmatrix} b_i \\ g_i \\ 0 \end{bmatrix}[\theta_i^T(t)\ w_i] \tag{25}$$

$$y_p=h_i^Tx_i \tag{26}$$

where we define the following parameter errors :

$$\phi(t)=k(t)-k^*,\quad \varphi_i(t)=\theta_i(t)-\theta_i^*,$$
$$\varphi(t)\triangleq[\phi(t), \varphi_1^T(t), \varphi_0^T(t), \varphi_2^T(t)]^T$$

then eq(25) can be written as

$$\dot{x}=A_{ci}x+b_{ci}[k^*r+\varphi_i^T(t)v_i] \tag{27}$$

where

$$A_{ci}=\begin{bmatrix} A_i+b_i\theta_0^*h_i^T & b_i\theta_0^{*T} & b_i\theta_2^{*T} \\ g_i\theta_0^*h_i^T & \Lambda+g_i\theta_1^{*T} & g_i\theta_2^{*T} \\ g_ih_i^T & 0 & \Lambda \end{bmatrix} \tag{28}$$

$$b_{ci}=\begin{bmatrix} b_i \\ g_i \\ 0 \end{bmatrix},\ h_i=[h_1, 0, 0]^T,\ x\triangleq[x_i^T, v_1^T, v_2^T] \tag{29}$$

since $W_0(s)\equiv W_m(s)$ when $\theta(t)\equiv\theta^*$, it follows that the reference model can be described by the $(3n-2)^{th}$ order differential equation

$$\dot{X}_{mi}=A_{mi}X_{mi}+b_{mi}k^*r_i,\quad Y_{mi}=h_i^TX_{mi} \tag{30}$$

Where $X_{mi}=[X_i^{*T}, v_1^{*T}, v_2^{*T}]^T$.

$X_i^*(t)$, $v_1^*(t)$ and $v_2^*(t)$ can be considered as signals in the reference model corresponding to $x_i(t)$, $v_1(t)$ and $v_2(t)$ in the overall system.

Therefore, the error equation for the overall system may be expressed as

$$\dot{e}_i=A_{mi}e_i+b_{mi}\varphi_i^Tv_i+D_{ci}+F_i \tag{31}$$

$$e_{oi}=h_{mi}^Te_i=[1, 0, 0, \cdots]e_i \tag{32}$$

where $\dot{e}_i=x-x_{mi}$, $e_{oi}=y_i-y_{mi}$, $D_{ci}=[D_i^T, 0, 0]^T$
$F_i=[\sum_{i=1}^{N} f_{ij}^T(t, x_i), 0, 0]^T$

Equation (31) is of dimension 3n−1 while the corresponding $W_m(s)$ is order n. The models remaining 2n−1 poles are uncontrollable and/or unobservable but asymptotically stable since $N_i(s)$ is Hurwitz.

Ioannou[2] proposed a decentralized adaptive controller for computing the parameters of each subsystem ;

$$\dot{\theta}_i=-\delta_i\Gamma_i\theta_i-\Gamma_ie_{oi}v_i \tag{33}$$

where $\delta_i=\begin{cases} \delta_{oi} & \text{if } \|\theta_i\|>\theta_{oi} \\ 0 & \text{if } \|\theta_i\|\le\theta_{oi} \end{cases}$

Γ_i is a positive definite matrix of appropriate dimension.

Ⅳ. DECENTRALIZED ADAPTIVE SYSTEM STABILITY

It is shown that the equilibrium stable ($e=0$, $\varphi=0$) of Eqs (31) and (32) is uniformly stable in the large and $\lim_{t\to\infty}e(t)=0$.

Let $V(e_i, \varphi_i)$ be a Lyapunov function candidate of the form

$$V(e_i, \varphi_i)=\frac{1}{2}(e_i^TP_{ci}e_i+\varphi_i^T\Gamma_i\varphi_i) \tag{34}$$

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From the Kalman-Yacubovich lemma, it is known that if $h^T(SI-A)^{-1}b$ is strictly positive real, a matrix P exists such that $A^TP+PA=-qq^T-\varepsilon L$, $Pb=h$ for some vector q, matrix $L=L^T>0$ and $\varepsilon>0$. It is clear that $V(e_i, \varphi_i)\geq 0$. The derivative of this function (34) using the adaptation law (33) is

$$\dot{V}(e_i, \varphi_i)=-\frac{1}{2}\ e_i^T(q_i q_i^T+\varepsilon L_i)e_i\leq 0 \qquad (35)$$

Hance, the equilibrium state ($e_i=0$, $\varphi_i=0$) of Eqs (31) and (32) is globally stable. Also $e\in\mathcal{L}^2$ and $\dot{e}$ is bounded.

In eq (35), we consider the asymptotic stable and convergence to get the following equation.

$$V=\sum_{i=1}^{N}\ \alpha_i[\,e_i^T P_{ci}e_i+\varphi_i^T\Gamma_i^{-1}\varphi_i\,] \qquad (36)$$

where $\alpha_i=[\,\alpha_1,\ \alpha_2,\ \ldots,\ \alpha_N\,]^T$ is positive elements with dimension N. The standard M-matrix can be written in a form

$$M_{ij}=\begin{cases}\alpha_i(\lambda_i-2g_{ij}) & i=j\\ r-(\alpha_i g_{ij}+\alpha_i g_{ij}) & i\neq j\end{cases} \qquad (37)$$

M_{ij} is positive definite matrix which is ensured if there exists. The derivative of eq (36) is

$$\dot{V}=\sum_{i=1}^{N}\ \alpha_i[\,-e_i^T q_i q_i^T e_i-\varepsilon_i e_i^T L_i e_i+2e_i^T P_{ci}D_{ci}$$
$$+2e_i^T P_{ci}F_i-2\sigma_i\varphi_i^T\theta_i\,] \qquad (38)$$

where $\lambda_i=\frac{1}{2}\ \varepsilon_i\min\lambda(L_i)$

$g_{ij}=\|P_{ci}\|\alpha_{ij}$, $\quad P_i=\max\lambda(P_{ci})$

$r_i=\max\lambda(\Gamma_i^{-1})$, $\quad d_{oi}=sup\|P_{ci}D_{ci}(t)\|$

$x_{oi}=sup\sum_{i=1}^{N}g_{ij}\|x_{mi}(t)\|$, $\quad x_m=\min\lambda(M)$

The local interconnected function F_i is satisfied as

$$\|F_i\|\leq\sum_{\lambda=1}^{N}\ \alpha_{ij}(\|e_i\|+\|x_{mi}\|) \qquad (39)$$

The derivative of eq (38) can be rewritten

$$\dot{V}\leq-b_0V-\sum_{i=1}^{N}[\,\|e_i\|^2(\lambda_m-b_0\alpha_i P_{ci})+\alpha_i(\sigma_{oi}-b_0 r_i)\|\varphi_i\|^2]+\overline{k_0}$$
$$+\sum_{i=1}^{N}\alpha_i[\,(\sigma_{0i}-\sigma_i)\|\varphi_i\|^2-\sigma_i(\|\theta_i\|^2-\|\theta_i^*\|^2)\,] \qquad (40)$$

where $\overline{k_0}=\sum_{i=1}^{N}\ \frac{\alpha_i}{\lambda_i(D_{0i}+x_{0i})^2}$

$b_0=\min[\,\min(\frac{\lambda_m}{\alpha_i P_{ci}}),\ \min(\frac{\sigma_{0i}}{r_i})\,]$

In this case, we conclude that the derivative of eq (36) is adaptively estimated using

$$(\sigma_{0i}-\sigma_i)\|\varphi_i\|^2\leq\ \sigma_{0i}(\theta_{0i}+\|\theta_i^*\|)^2$$
$$-\sigma_i(\|\theta_i\|^2-\|\theta_i^*\|^2)\leq\ \sigma_{0i}\|\theta_i^*\|^2 \qquad (41)$$
$$\dot{V}\leq-b_0V+k_0$$

where $k_0=\sum_{i=1}^{N}\ \alpha_i[\,\frac{(D_{0i}+x_{0i})^2}{\lambda_i}+\sigma_{0i}(\theta_{0i}+\|\theta_i^*\|^2)+\sigma_{0i}\|\theta_i^*\|^2\,]$

Let us consider a Lyapunov function candidate

$$V(t)\leq e^{-b_0t}V(0)+(1-e^{-b_0t})\frac{k_0}{b_0},\quad \forall t\geq 0 \qquad (42)$$

By choosing $e_i(t)$ and $\theta_i(t)$ are bounded, the residual finite constants b_0 and q_0 exist. Therefore, overall parameter adaptive errors $\varphi_i=[\,\varphi_1^T,\ \varphi_2^T,\ \ldots,\ \varphi_N^T\,]^T$ and tracking errors $e_i=[\,e_1^T,\ e_2^T,\ \ldots,\ e_N^T\,]$ are globally converge to a residual set D_0.

where $D_0=\{(\varphi,\ e):\|\varphi\|^2+\|e\|^2\leq\frac{k_0}{b_0q_0}\}$

V. AN ILLUSTRATIVE EXAMPLE

We consider power systems of multivariable dynamic system consisting of two generators in a power grid[4]. A power system has to maintain a constant frequency and, hence two generators connected to it must be in synchronism. For this example we specify the control objectives of the overall power system ensure system stability and maintain the desired frequency and power balance

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with changing load conditions.

Two respects in adaptive power system control that have received considerable attentions are (1) adaptive load-frequency control and (2) adaptive generator exciter control. In this paper, we investigate the problem(1) from an MRAC point of view. In a power system, coherent groups of generators(called areas) are connected by tie lines. Each area meets its load changes according to a characteristic that relates area normal value whenever changes in frequency occur due to changing load, while maintaining interchange with other areas within prescribed limits. If constant controller parameters are used, they are, at best, compromises between values that give good damping at light loads and values needed for heavy load conditions. Hence, for improved performance, the parameters of the controller must be varied with time.

Defing the state vectors $x_i = (\int \Delta f_i\, dt, \Delta f_i, \Delta x_{ei}, \Delta p_i)^T$, output vector $y_i = \Delta f_i$ and input vector $r_i = \int \Delta f_i\, dt$, the adaptive law of the interconnected power system can be described as

$$\dot{\theta}_i = -\delta_i \Gamma_i \theta_i - \Gamma_i e_{0i} v_i \qquad (43)$$

$$\delta_i = \begin{cases} \delta_{0i}, & \|\theta_i\| > \theta_{0i} \\ 0, & \|\theta_i\| \le \theta_{0i} \end{cases}$$

where δ_{0i} and θ_{0i} are design parameters and $\Gamma_i = \Gamma_i^T > 0$. e_{oi} is frequency deviation Δf_i and Δx_{ei} is governer speed regulation deviation, and ΔP_i is generating power deviation. For simulations, we can be described as the following linear equations with 8th orders.

$$\dot{x}_1 = A_1 x_1 + b_1 U_1 + D_1 + E_1 x_{21}$$

$$\dot{x}_2 = A_2 x_2 + b_2 U_2 + D_2 + E_2 x_{11} \qquad (44)$$

where state vectors and interconnections as

$$x_1 = [\int \Delta f_1\, dt,\ \Delta f_1,\ \Delta x_{e1},\ \Delta P_1]^T$$

$$x_2 = [\int \Delta f_2\, dt,\ \Delta x_{e2},\ \Delta P_2]^T$$

$$x_{21} = \int \Delta f_2\, dt, \quad x_{11} = \int \Delta f_1\, dt$$

The system is in the form of comparing to (1), we obtain the subsystem matrices as

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -3.27 & 0 & 6 & 0 \\ 0 & 0 & -3.33 & 3.33 \\ 0 & -5.208 & 0 & -12.5 \end{bmatrix},$$

$$b_i = [0\ 0\ 0\ 12.5]^T$$

$$D_1 = [0\ -0.3\ 0\ 0]^T, \qquad D_2 = [0\ 0\ 0\ 0]^T$$

$$E_i = [0\ 3.27\ 0\ 0]^T$$

We choose the stable coefficient matrices as

$$\Lambda_i = \begin{bmatrix} -1 & -0.1 & 0 \\ -0.1 & -1 & -0.1 \\ 0 & -0.1 & -1 \end{bmatrix}$$

with $\Gamma_{i(8\times8)}$ upper triangle nonzero elements

$$\Gamma_1(i,i) = \Gamma_2(i,i) = 0.1$$

$$\Gamma_1(i,i+1) = \Gamma_2(i,i+1) = 0.01$$

$$\Gamma_1(i,i+2) = \Gamma_2(i,i+2) = 0.01$$

Disturbance vector D_2 has all zero elements but D_1 has the nonzero element so that there is a load change in area 1. For 8th order interconnected system, the simulations are shown in Figs. 2. and 3. Fig.2 shows the frequency deviation and Fig.3 shows the parameters of decentralized adaptive controller. We observe that the frequency deviation of two controllers are similiar on the system transient states and both controlled systems are stable as expected. Now we increase the order of the one controlled area to 5th order. The simulation results are shown in Figs. 4 and 5, the frequency deviation is shown in Fig.4, which is bounded as we expected. We also see the decentralized adaptive controller parameters track as expected in Fig.5.

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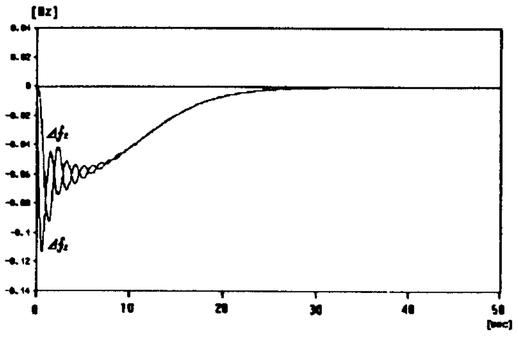

Fig. 2. Frequency Devlation of 8th order interconnected system

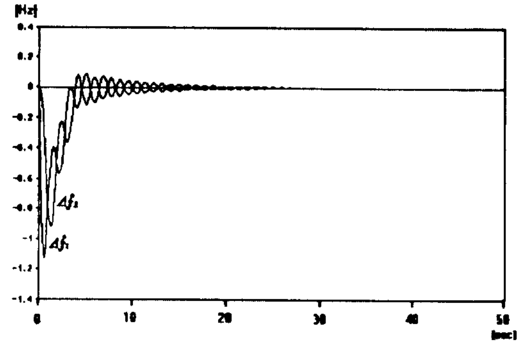

Fig. 4. Frequency Devlation of 9th order interconnected system

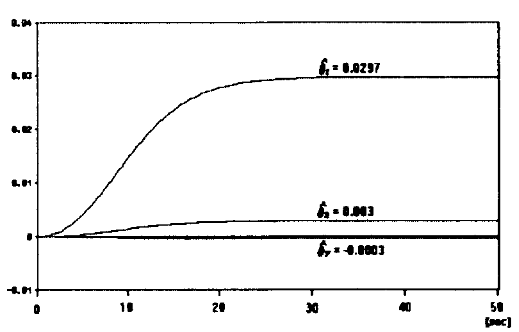

Fig. 3. Controller Parameters of 8th order interconnected system

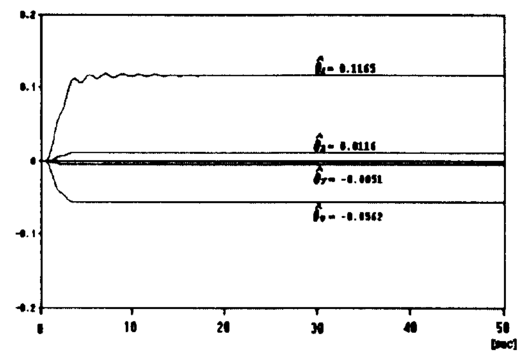

Fig. 5. Controller Parameters of 9th order interconnected system

Ⅵ. CONCLUSIONS

The design of decentralized adaptive controller for a class of large scale systems is investigated. Two areas which are connected by tie lines are controlled by adaptive load-frequency control. A decentralized adaptive controller is proposed to drive the unknown subsystems to track the local reference models as closely as possible with reducing residual output errors. A numerical simulations of adaptive power system are presented to demonstrate the possibility of the higher order interconnected systems.

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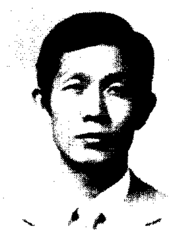

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