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Decentralized Robust Load Frequency Control: A PI-based Control Approach

Hassan Bevrani[*], Yasunori Mitani[**] and Kiichiro Tsuji[*]

[*]Department of Electrical Eng., Osaka University, 2-1 Yamada-Oka, Suita, Osaka 565-0871, Japan
[**]Department of Electrical Eng., Kyushu Institute of Technology, Kyushu, Japan

Abstract

This paper addresses a robust control method to decentralized PI-based load-frequency control (LFC) synthesis in a multi-area power system. The LFC problem is reduced to a static output feedback H_∞ control problem and then it is solved using a developed iterative linear matrix inequalities (ILMI) algorithm to get an optimal performance index. A three control area power system example with a wide range of load changes is given to illustrate the proposed approach. The obtained controllers are compared with full dynamic H_∞ controllers. The results show the proposed controllers guarantee the robust performance for a wide range of operating conditions as well as full-dynamic H∞ controllers.

Keywords: LFC, H_∞, LMI, Static out-put feedback control

1 INTRODUCTION

Load-frequency control (LFC) problem has been one of the major subjects in electric power system design/operation and is becoming much more significant today in accordance with increasing size, changing structure and complexity of interconnected power systems. In practice, LFC systems use simple proportional-integral (PI) controllers. However, since the PI controller parameters are usually tuned based on classical or trial-and-error approaches, they are incapable of obtaining good dynamical performance for a wide range of operating conditions and various load changes scenarios in a multi-area power system.

In the new power system structure, LFC acquires a fundamental role to enable power exchanges and to provide better conditions for the electricity trading. In the restructured power system, VIU no longer exist, however the basic concepts of conventional LFC structure are not changed, and that is why several LFC scenarios are recently proposed to adapt with well tested conventional LFC scheme to the changing environment of power system operation under deregulation.

In the last two decades, there has been continuing interest in designing LFC with better performance to maintain the frequency and to keep tie-line power flows within pre-specified values, using various decentralized robust and optimal control methods. But the most of them suggest complex state-feedback or high-order dynamic controllers, which are not practical for industry practices. Furthermore, some references have used the new and untested LFC frameworks, which may have some difficulties to implement in the real-world power systems. Usually, the existing LFC systems in the practical power systems use the proportional-integral (PI) type controllers that are tuned online based on classical and trial-and-error approaches. Recently, some control methods are applied to design the decentralized robust PI or low order controllers in order to solve the LFC problem [1-3]. A method for PI control design method is reported in [1], which used a combination of H∞ control and genetic algorithm techniques for tuning the PI parameters. [2] gives the sequential decentralized method based on μ-synthesis and analysis to obtain a set of low order robust controllers. [3] has used the Kharitonov's theorem and its results for solving the same problem.

In this paper, the decentralized LFC problem will be formulated as a H∞ control problem to obtain the proportional-integral (PI) controller via a static output feedback design. An iterative linear matrix inequalities (ILMI) algorithm is used to compute PI parameters. We applied the proposed strategy to a three control area example. The obtained robust PI controllers, which are useful for industry, will be compared with the H∞-based output dynamic feedback controllers (using standard LMI-based H∞ technique).

2 LFC: PRELIMINARIES

A large scale power system consists of a number of interconnected control areas. Fig. 1 shows the block diagram of control area-*i,* which includes *n* Gencos, from an *N*-control area power system. Where,

$$w_{1i} = \Delta P_{di} \quad (1)$$

$$w_{2i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j \quad (2)$$

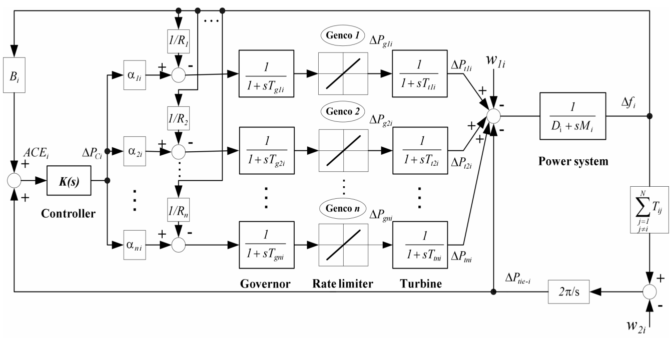


Figure 1. A general control area

and

Δf_i	frequency deviation,
ΔP_{gi}	governor valve position,
ΔP_{ci}	governor load setpoint,
ΔP_{ti}	turbine power,
ΔP_{tie-i}	net tie-line power flow,
ΔP_{di}	area load disturbance,
M_i	equivalent inertia constant,
D_i	equivalent damping coefficient,
T_{gi}	governor time constant,
T_{ti}	turbine time constant,
T_{ij}	tie-line synchronizing coefficient between area *i* & *j*,
B_i	frequency bias,
R_i	drooping characteristic,
α	ACE participation factor,
ΔP_{tie-i}	tie-line power changes.

Following a load disturbance within a control area, the frequency of that area, experiences a transient change and the feedback mechanism comes into play and generates appropriate rise/lower signal to the participated Gencos according to their participation factors to make generation follow the load. In the steady state, the generation is matched with the load, driving the tie-line power and frequency deviations to zero. The balance between connected control areas is achieved by detecting the frequency and tie line power deviations to generate the area control error (ACE) signal which is turn utilized in the (PI) control strategy as shown in Fig. 1.

3 DESIGN METHODOLOGY

3.1 Dynamic model

By augmenting the system description to include the ACE signal and its integral as the measured output vector, the PI control problem becomes one of finding a static output feedback that satisfied prescribed performance requirements. Using this strategy, the PI-based LFC design can be reduced to an H∞ static output feedback problem.
The proposed control framework in order to design of PI controller via the H∞ static output feedback problem for a given control area is shown in Fig. 2. $G_i(s)$ denotes the dynamical model corresponds to control area *i* (shown in Fig. 1). The state space model for each control area *i* can be obtained as

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_{1i} w_i + B_{2i} u_i \\ z_i &= C_{1i} x_i + D_{12i} u_i \\ y_i &= C_{2i} x_i \end{aligned} \quad (3)$$

where,

$$x_i^T = [\Delta f_i \quad \Delta P_{tie-i} \quad \int ACE_i \quad x_{ti} \quad x_{gi}]$$

$$x_{ti} = [\Delta P_{t1i} \quad \Delta P_{t2i} \quad \cdots \quad \Delta P_{tni}], \; x_{gi} = [\Delta P_{g1i} \quad \Delta P_{g2i} \quad \cdots \quad \Delta P_{gni}]$$

$$y_i^T = [ACE_i \quad \int ACE_i], \; u_i = \Delta P_{Ci}$$

$$z_i^T = [\eta_{1i}\Delta f \quad \eta_{2i}\int ACE_i \quad \eta_{3i}\Delta P_{tie-i} \quad \eta_{4i}\Delta P_{Ci}], \; w_i^{\mathrm{T}} = [w_{1i} \quad w_{2i}]$$

and,

$$A_i = \begin{bmatrix} A_{i11} & A_{i12} & A_{i13} \\ A_{i21} & A_{i22} & A_{i23} \\ A_{i31} & A_{i32} & A_{i33} \end{bmatrix}, \; B_{1i} = \begin{bmatrix} B_{1i1} \\ B_{1i2} \\ B_{1i3} \end{bmatrix}, \; B_{2i} = \begin{bmatrix} B_{2i1} \\ B_{2i2} \\ B_{2i3} \end{bmatrix}$$

$$C_{1i} = [c_{1i} \quad 0_{4\times n} \quad 0_{4\times n}] \;,\; c_{1i} = \begin{bmatrix} \eta_{1i} & 0 & 0 \\ 0 & 0 & \eta_{2i} \\ 0 & 0 & 0 \\ 0 & \eta_{3i} & 0 \end{bmatrix}, \; D_{12i} = \begin{bmatrix} 0 \\ 0 \\ \eta_{4i} \\ 0 \end{bmatrix}$$

$$C_{2i} = [c_{2i} \quad 0_{2\times n} \quad 0_{2\times n}] \;,\; c_{2i} = \begin{bmatrix} B_i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_{i11} = \begin{bmatrix} -D_i/M_i & -1/M_i & 0 \\ 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 & 0 \\ B_i & 1 & 0 \end{bmatrix}, \quad A_{i12} = \begin{bmatrix} 1/M_i & \cdots & 1/M_i \\ 0 & \cdots & 0 \\ 0 & \cdots & 0 \end{bmatrix}_{3\times n}$$

$$A_{i22} = -A_{i23} = diag[-1/T_{t1i} \quad -1/T_{t2i} \quad \cdots \quad -1/T_{tni}]$$

$$A_{i33} = diag[-1/T_{g1i} \quad -1/T_{g2i} \quad \cdots \quad -1/T_{gni}]$$

$$A_{i31} = \begin{bmatrix} -1/(T_{g1i}R_{1i}) & 0 & 0 \\ \vdots & \vdots & \vdots \\ -1/(T_{gni}R_{ni}) & 0 & 0 \end{bmatrix}, \quad A_{i13} = A_{i21}^{\mathrm{T}} = 0_{3\times n}, \quad A_{i32} = 0_{n\times n}$$

$$B_{1i1} = \begin{bmatrix} -1/M_i & 0 \\ 0 & -2\pi \\ 0 & 0 \end{bmatrix}, \quad B_{1i2} = B_{1i3} = 0_{n\times 3}$$

$$B_{2i1} = 0_{3\times 1}, B_{2i2} = 0_{n\times 1} \; B_{2i3}^{T} = [\alpha_{1i}/T_{g1i} \quad \alpha_{2i}/T_{g2i} \quad \cdots \quad \alpha_{ni}/T_{gni}]$$

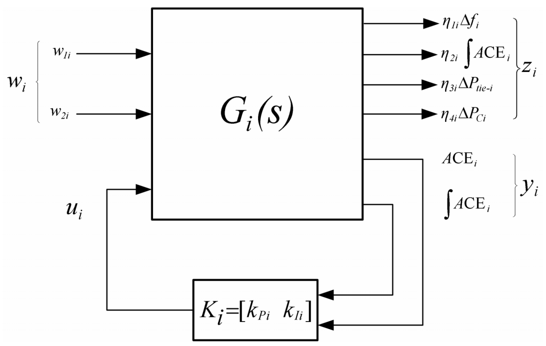


Figure 2. Proposed control framework

The η_{1i} , η_{2i} , η_{3i} and η_{4i} are constant weighting coefficients that must be chosen by designer to getting the desired performance.,

3.2 Proposed ILMI Algorithm

H∞ static output control problem can be easily reduced to a generalized static output stabilization feedback control problem. Using this key point an iterative LMI algorithm, which is mainly based on given approach in [4], is developed. The proposed algorithm gives an LMI-based solution for the following optimization problem.

Optimization problem: Given an optimal performance index γ , determine an admissible static output feedback law

$$u_i = K_i y_i \quad , \quad K_i \in K_{sof} \tag{4}$$

such that

$$\| T_{zi\,wi}(s) \|_{\infty} < \gamma^{*} \tag{5}$$

where K_{sof} is a family of internally stabilizing static output feedback gains and γ^{*} indicates a lower bound such that the closed-loop system is H∞ stabilizable via static output feedback. In this case we could see that $|\gamma - \gamma^{*}| < \varepsilon$, where ε is a small positive number.

The following algorithm gives an iterative LMI solution for above optimization problem:

Step 1. Using (3) to compute a generalized system $(\overline{A}, \overline{B}, \overline{C})$ as follows,

$$\overline{A} = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix}, \quad \overline{B} = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix}, \quad \overline{C} = [C_{2i} \quad 0 \quad 0]$$

Set $i = 1$, $\Delta\gamma = \Delta\gamma_0$ and let $\gamma_i = \gamma_0 > \gamma$. $\Delta\gamma_0$ and γ_0 are positive real numbers.

Step 2. Select $Q > 0$, and solve $\overline{X}$ from the following algebraic Riccati equation

$$\overline{A}^T \overline{X} + \overline{X}\overline{A} - \overline{X}\overline{B}\overline{B}^T \overline{X} + Q = 0 \tag{6}$$

Set $P_1 = \overline{X}$.

Step 3. Solve the following optimization problem for $\overline{X}_i$, K_i and a_i .

Minimize a_i subject to the bellow LMI constraints:

$$\begin{bmatrix} \overline{A}^T \overline{X}_i + \overline{X}_i \overline{A} - P_i \overline{B}\overline{B}^T \overline{X}_i - \overline{X}_i \overline{B}\overline{B}^T P_i + P_i \overline{B}\overline{B}^T P_i - a_i \overline{X}_i & (\overline{B}^T \overline{X}_i + K_i \overline{C})^T \\ \overline{B}^T \overline{X}_i + K_i \overline{C} & -I \end{bmatrix} < 0 \tag{7}$$

$$\overline{X}_i = \overline{X}_i^T > 0 . \tag{8}$$

Denote a_i^{*} as the minimized value of a_i .

Step 4. If $a_i^{*} \leq 0$, go to step 8.

Step 5. For $i > 1$ if $a_{i-1}^{*} \leq 0$, $K_{i-1} \in K_{sof}$ and it is desired H∞ controller and $\gamma^{*} = \gamma_i + \Delta\gamma$ indicates a lower bound such that the above system is H∞ stabilizable via static output feedback.

Step 6. Solve the following optimization problem for $\overline{X}_i$ and K_i:

Minimize trace($\overline{X}_i$) subject to the above LMI constraints (7-8) with $a_i = a_i^*$. Denote $\overline{X}_i^*$ as the $\overline{X}_i$ that minimized trace($\overline{X}_i$).

Step 7. Set $i = i+1$ and $P_i = \overline{X}_{i-1}^*$, then go to step 3.

Step 8. Set $\gamma_i = \gamma_i - \Delta\gamma$, $i = i+1$. Then do steps 2 to 4.

The matrix inequalities (7) and (8) give a sufficient condition for the existence of static output feedback controller.

4 APPLICATION TO A 3-AREA POWER SYSTEM

To illustrate the effectiveness of proposed control strategy, a three control area power system, shown in Fig. 3, is considered as a test system. It is assumed that each control area includes three Gencos. The power system parameters are considered the same as [1].

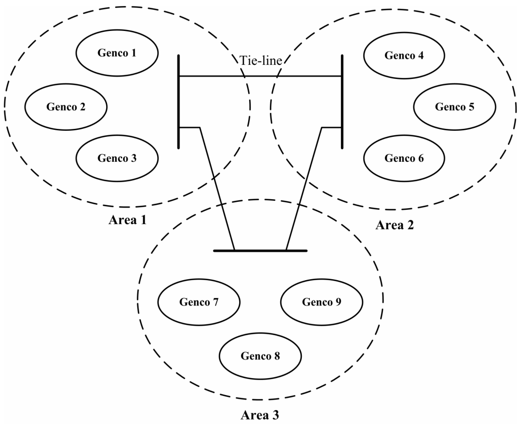


Figure 3. Three control area power system

An important issue with regard to selection of weights η_{1i}, η_{2i}, η_{3i} and η_{4i} is the degree to which they can guarantee the satisfaction of design performance objectives. The coefficients η_{1i}, η_{2i} and η_{3i} at controlled outputs set the performance goals e.t. tracking the load variation and disturbance attenuation. η_{4i} sets a limit on the allowed control signal to penalize fast change and large overshoot in the governor load set-point signal. Here, a set of suitable values for constant weights are considered as:

$$\eta_{1i}=0.4,\ \eta_{2i}=1.075,\ \eta_{3i}=0.39,\ \eta_{4i}=333$$

For each control area, in addition to the proposed control strategy to obtain the robust PI controller, we designed a H∞ dynamic output feedback controller using LMI control toolbox using the function *hinflmi*, provided by the MATLAB's LMI control toolbox [5]. This function gives an optimal H∞ controller through the minimizing the guaranteed robust performance index (γ) and returns the controller *K(s)* with optimal robust performance index. The resulted controllers using the *hinflmi* function are dynamic type and have the following state-space form, whose orders are the same as size of plant model (here 9).

$$\begin{aligned} \dot{x}_{ki} &= A_{ki}x_{ki} + B_{ki}y_i \\ u_i &= C_{ki}x_{ki} + D_{ki}y_i \end{aligned} \tag{9}$$

At the next step, according to synthesis methodology described in section 3, a set of three decentralized robust PI controllers are designed. Using ILMI approach, the controllers are obtained following several iterations. The control parameters for three areas are shown in Table 1.

Table 1. Control parameters (ILMI design)

Parameter	*Area 1*	*Area 2*	*Area 3*
a^*	-0.0246	-0.3909	-0.2615
k_{Pi}	-9.8e-03	-2.6e-03	-3.8e-03
k_{Ii}	-0.5945	-0.3432	-0.2700

The resulted robust performance indices of both synthesis methods are too close to each other and are shown in Table 2. It shows that although the proposed ILMI approach gives a set of much simpler controllers (PI) than the dynamic H∞ design, however they hold robust performance as well as dynamic H∞ controllers.

Table 2. Robust performance index

Control design	*Control structure*	*index*	*Area 1*	*Area 2*	*Area 3*
H∞	9th order	γ	333.0084	333.0083	333.0080
ILMI	PI	γ^*	333.0261	333.0147	333.0238

5 SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed control design, some simulations were carried out. In these simulations, the proposed controllers were applied to the three control area power system described in Fig. 3. In this section, the performance of the closed-loop system using the robust PI controllers in comparison of dynamic H∞ controllers is tested for some serious load disturbances.

Scenario 1:

As the first test scenario, the following large load disturbances (step increase in demand) are applied to three areas:

$$\Delta P_{d1} = 105\ MW,\ \Delta P_{d2} = 105\ MW,\ \Delta P_{d3} = 105\ MW$$

Frequency deviation (Δf), area control error (ACE) and control action (ΔPc) signals of closed-loop system are shown in Fig. 4 and Fig. 5. Using the proposed method (ILMI), the area control error and frequency deviation of all control areas are quickly driven back to zero as well as full dynamic H∞ control.

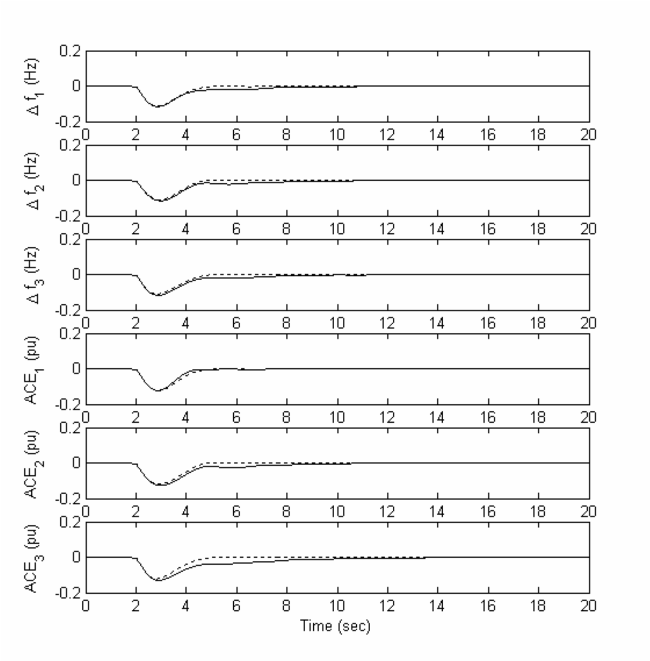


Figure 4. Frequency deviation and ACE signals following a large step load demand (105 MW) in each area; solid (PI), dotted (H∞).

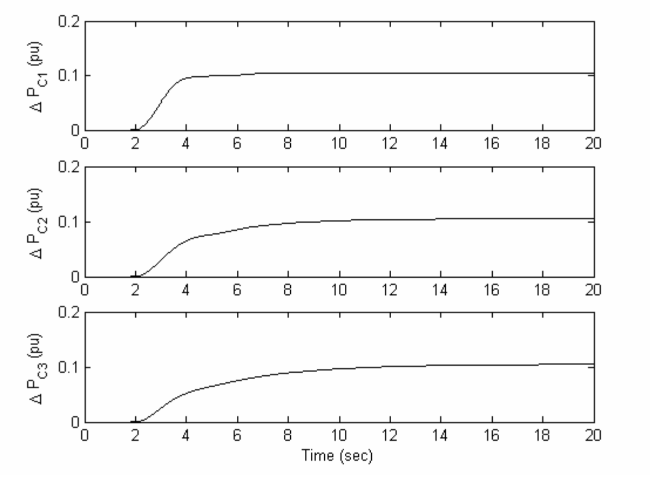


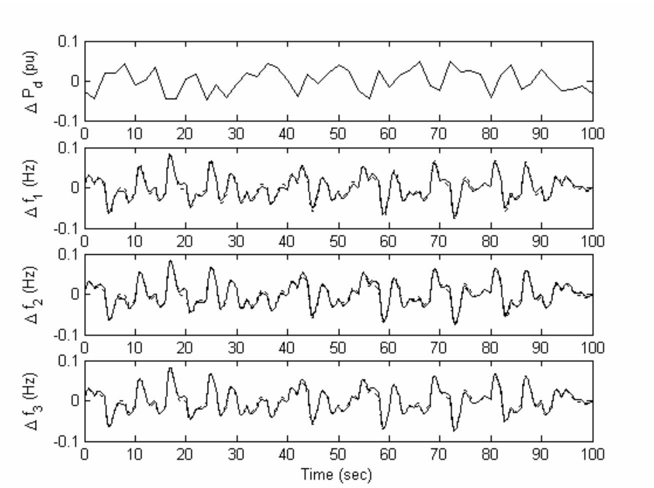
Figure 5. Control signals following a large step load demand (105 MW) in each area.

Scenario 2:

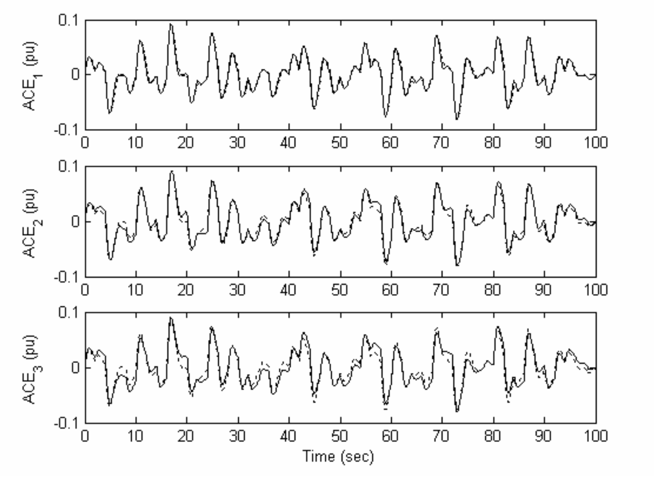
As another sever condition, assume a bounded random load change (shown in Fig. 6a) is applied to each control area, where

$$-50\ MW \le \Delta P_d \le +50\ MW$$

The purpose of this scenario is to test the robustness of the proposed controllers against random large load disturbances. The control areas response is shown in Fig. 6 and Fig. 7. These figures demonstrate that the designed controllers track the load fluctuations, effectively. The simulation results show the proposed PI controllers perform robustness as well as robust dynamic H∞ controllers (with complex structures) for a wide range of load disturbances.



(a)



(b)

Figure 6. a) Random load pattern and frequency deviation, b) ACE signals in each area; solid (PI), dotted (H∞).

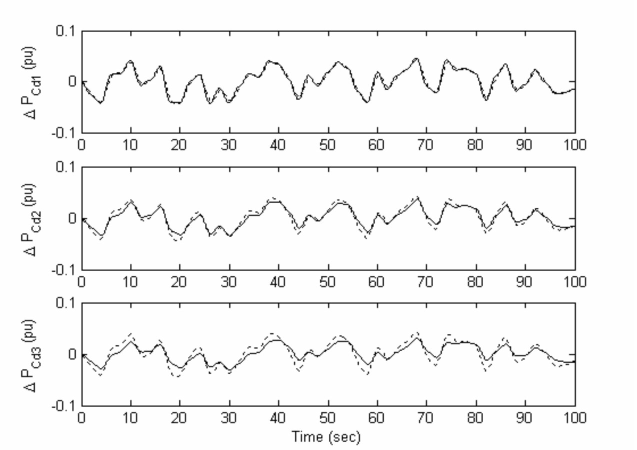


Figure 7. Control action signals in each area, following the random load demand; solid (PI), dotted (H∞).

6 CONCLUSION

In this paper a new decentralized method for robust LFC design using a developed iterative LMI algorithm has been proposed for a large scale power system. Design strategy includes enough flexibility to setting the desired level of performance, and, gives a set of simple PI controllers which commonly useful in real-world power systems, using the H∞ static output control design,.

The proposed method was applied to a three control area power system and is tested under serious load change scenarios. The results are compared with the results of applied full dynamic H∞ controllers. It was shown that the designed controllers are capable to guarantee the robust performance for a wide range of area-load disturbances, as well as dynamic H∞ controllers.

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BIOGRAPHIES

Hassan Bevrani received his M.Sc. degree (first class honors) in Electrical Engineering from K. N. Toosi University of Technology, Tehran, Iran in 1997. He is currently a Ph.D student at Osaka University, Japan. His special fields of interest included robust control and modern control applications in Power system and Power electronic industry. He is an academic member at Kurdistan University (Iran) and a member of the Institute of Electrical Engineers of Japan, IEE, and IEEE.

Yasunori Mitani received his B.Sc., M.Sc., and Dr. of Engineering degrees in electrical engineering from Osaka University, Japan in 1981, 1983, and 1986 respectively. He joined the Department of Electrical Engineering of the same university in 1990. He is currently a professor in Kyushu Institute of Technology. His research interests are in the areas of analysis and control of power systems. He is a member of the Institute of Electrical Engineers of Japan, the Institute of Systems, Control and Information Engineers of Japan, and the IEEE.

Kiichiro Tsuji received his B.Sc and M.Sc. degrees in electrical engineering from Osaka University, Japan, in 1966 and 1968, respectively, and his Ph.D in systems engineering from Case Western Reserve University, Cleveland, Ohio in 1973. In 1973 he jointed the Department of Electrical Engineering, Osaka University, and is currently a professor at Osaka University. His research interests are in the areas of analysis, planning, and evaluation of energy systems, including electrical power systems. He is a member of the Institute of Electrical Engineers of Japan, the Japan Society of Energy and Resources, the Society of Instrument and Control Engineers, the Institute of Systems, Control and Information Engineers, and the IEEE.