Robust Load-Frequency Control Design for Time-Delay Power Systems

Hassan BEVRANI and Takashi HIYAMA
Department of Electrical and Computer Eng., Kumamoto University
Kumamoto 860-8555, Japan

ABSTRACT

This paper addresses a control strategy to design a PI-based load-frequency control (LFC) in face of communication delays. First the PI-based LFC design is transferred to a static output feedback (SOF) control design and then to obtain the optimal PI gains, a multi constraint minimization problem is solved using the H_∞ control technique.

A multi-area power system example is given to illustrate the proposed control methodology and the results are compared with the delay less system-based H_∞ control design.

Keywords: H_∞ control, LFC, time-delay systems, static output feedback control, LMI.

1. INTRODUCTION

Currently in many countries, power electric systems are restructured. Operating the power system in a new environment will certainly be more complex than in the past due to the considerable degree of interconnection, and to the presence of technical constraints to be considered together with the traditional requirements of system reliability.

In a deregulated environment, load-frequency control (LFC) acquires a fundamental role to enable power exchanges and to provide better conditions for the electricity trading. Since the LFC system is faced by new uncertainties in the liberalized electricity market, the modeling of these uncertainties and simulation of dynamic behavior of new structure is very important. A major challenge in new environment is to integrate computing, communication and control into appropriate levels of system operation and control. An effective power system market highly needs to an open communication infrastructure to support the increasing decentralized property of control processes.

It is well known in control systems that time delays can degrade a system's performance and even cause system instability [1-3]. In light of this fact, in near future the communication delays as one of important uncertainties in LFC synthesis and analysis due to expanding physical setups, functionality, complexity of power system structure and changing the "Control area" concept is to become a significant problem [4].

Recently, several papers are published to address the LFC modeling/synthesis in presence of communication delays [5-7]. [5] is focused on the communication network requirement for a third party LFC service. A compensation method for communication time delay in the LFC systems is addressed in [6] and a control design method based on linear matrix inequalities is proposed for LFC system with communication delays in [7].

This paper proposes a new control methodology to design a decentralized LFC in face of multi-delayed signals. First the LFC problem is reduced to a static output feedback control synthesis for a multiple delays system, and then the control parameters are easily carried out using robust H_∞ control technique.

The main goal is to keep the fundamental LFC concepts and well-tested simple PI control structure to develop new LFC synthesis. In comparison of [7], simplicity of control structure, using a more complete model for delayed LFC system and no need to additional controller can be considered as advantages of the proposed methodology. This approach is applied to a 3-control area power system example.

2. CONTROL METHODOLOGY

Preliminary

Consider a class of time-delay systems of the form

$$\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t) + A_d x(t-d) + B_h u(t-h) + Fw(t) \\
z(t) &= C_1 x(t) \\
y(t) &= C_2 x(t), \quad x(t) \in \psi(t) \quad \forall\, t \in [-\max(d,h), 0]
\end{aligned} \tag{1}$$

Here $x \in \Re^n$ is the state, $u \in \Re^n$ is the control input, $w \in \Re^n$ is the input disturbance, $z \in \Re^n$ is the controlled output, $y \in \Re^n$ is the measured output, $C_2 \in \Re^n$ is the constant matrix such that the pair (A, C_2) is detectable. d and h represent the delay amounts in the state and the input respectively. $A \in \Re^{n\times n}$ and $B \in \Re^{n\times m}$ represent the nominal system without delay such that the pair (A, B) is stabilizable. $A_d \in \Re^{n\times n}$, $B_h \in \Re^{n\times m}$, $F \in \Re^{n\times q}$ are known matrices and $\psi(t)$ is a continuous vector-valued initial function.

The following theorem adopts H_∞ theory in the control synthesis for time-delay systems and establishes the conditions under which the state feedback control law

$$u(t) = Kx(t) \tag{2}$$

stabilizes (1) and guarantees the H_∞ norm bound γ of the closed-loop transfer function T_{zw}, namely $\|T_{zw}\|_\infty < \gamma$; $\gamma > 0$.

Theorem 1, [1]: The state feedback controller K asymptotically stabilizes the time-delay system (1) and $\|T_{zw}\|_\infty < \gamma$ for $d, h \geq 0$ if there exist matrices $0 < P^T = P \in \Re^{n\times n}$, $0 < Q_1^T = Q_1 \in \Re^{n\times n}$, $0 < Q_2^T = Q_2 \in \Re^{n\times n}$ satisfying the LMI

$$\begin{bmatrix} PA_c + A_c^T P + Q_1 + Q_2 & A_d^T P & K^T B_h^T P & C_1 & F^T P \\ PA_d & -Q_1 & 0 & 0 & 0 \\ PB_h K & 0 & -Q_2 & 0 & 0 \\ C_1^T & 0 & 0 & I & 0 \\ PF & 0 & 0 & 0 & -\gamma^2 I \end{bmatrix} < 0 \tag{3}$$

where

$$A_c = A + BK \tag{4}$$

Proposed Strategy

In this work, by augmenting the control area description to include the area control error (ACE) as a measured output signal and its integral, the PI-based LFC problem is transferred to a static output feedback (SOF) control problem [8, 9].

$$u(t) = ky(t) \tag{5}$$

$$\begin{aligned} u(t) &= k_P ACE + k_I \int ACE \\ &= [k_P \quad k_I]\left[ACE \quad \int ACE\right]^T \end{aligned} \tag{6}$$

k_P and k_I are constant real numbers (PI parameters). The main merit of this transformation is in possibility of using the well-known SOF control techniques to calculate the fixed gains, and once the SOF gain vector is obtained, the PI gains are ready in hand and no additional computation is needed.

Now, the control problem is that of designing a SOF control for the time-delay system (1) of the form of Eq. (5). k is a static gain to be determined. Following theorem provides an LMI based H_∞ solution:

Theorem 2: The SOF controller k asymptotically stabilizes the system (1) and $\|T_{zw}\|_\infty < \gamma$ for $d, h \geq 0$ if there exist matrixes $0 < Y^T = Y \in \Re^{n\times n}$, $0 < Q_t^T = Q_t \in \Re^{n\times n}$ and $0 < Q_s^T = Q_s \in \Re^{n\times n}$ satisfying the matrix inequality (7).

Proof: The controller (5) can be considered as a replica of the state-feedback controller (2):

$$u(t) = ky(t) = kC_2 x(t) \tag{8}$$

Based on theorem 1, there exists a memory less feedback controller with constant gain

$$K = kC_2 \tag{9}$$

$$W_s = \begin{bmatrix} AY + YA^T + Q_t + Q_s & (BkC_2)^T & Y & YA_d^T & (B_h kC_2 Y)^T & C_1 Y & F^T \\ BkC_2 & -I_n & 0 & 0 & 0 & 0 & 0 \\ Y & 0 & -I_n & 0 & 0 & 0 & 0 \\ A_d Y & 0 & 0 & -Q_t & 0 & 0 & 0 \\ B_h kC_2 Y & 0 & 0 & 0 & -Q_s & 0 & 0 \\ YC_1^T & 0 & 0 & 0 & 0 & -I_p & 0 \\ F & 0 & 0 & 0 & 0 & 0 & -\gamma^2 I_q \end{bmatrix} < 0 \tag{7}$$

such that the closed-loop system is asymptotically stable and $\|T_{zw}\|_\infty < \gamma$ for $d, h \geq 0$. According to Eq. (4), for the closed-loop system we have

$$A_c = A + BkC_2 \tag{10}$$

The stabilizing controller satisfies inequality (3). Therefore, using Eq. (10) we can write

$$\begin{aligned} &P(A + BkC_2) + (A + BkC_2)^T P + Q_1 + Q_2 + PA_d Q_1^{-1} A_d^T P \\ &+ PB_h kC_2 Q_2^{-1} (kC_2)^T B_h^T P + C_1^T C_1 + \gamma^{-2} PFF^T P < 0 \end{aligned} \tag{11}$$

Premultiplying and postmultiplying (11) by P^{-1} and letting $P^{-1} = Y$, assuming $YQ_1Y = Q_t$, $YQ_2Y = Q_s$ and using the following inequality [10]:

$$\begin{aligned} &\forall\ \Omega_1, \Omega_2 \in \Re: \\ &\Omega_1^T \Omega_2 + \Omega_2^T \Omega_1 \leq \alpha \Omega_1^T \Omega_1 + \alpha^{-1} \Omega_2^T \Omega_2, \quad \alpha < 0 \end{aligned} \tag{12}$$

(11) can be reduced to

$$\begin{aligned} &[AY + YA^T + Q_t + Q_s] + [BkC_2(BkC_2)^T + Y^T Y] + [A_d Y Q_t^{-1} (A_d Y)^T] \\ &+ [B_h kC_2 Y Q_s^{-1} (B_h kC_2 Y)^T] + YC_1^T C_1 Y + \gamma^{-2} FF^T < 0 \end{aligned} \tag{13}$$

In the light of the Schur complement method, (13) can be arranged conveniently to yield the block form (7) as desired.

□

Theorem 2 shows that to determine the SOF controller *k*, one has to solve the following minimization problem:

$$\min_{Q_t, Q_s, Y, k} \gamma \quad \text{subject to} \quad -Y < 0,\ -Q_t < 0,\ -Q_s < 0,\ -W_s < 0 \tag{14}$$

The matrix inequality (7) points to an iterative approach to solve k, Q_t and Q_s namely, if Y is fixed, then it reduces to an LMI problem in the unknown k, Q_t and Q_s. The LMI problem is convex and can be solved efficiently using the LMI Control Toolbox [11], if a feasible solution exists. One may use a simple optimization algorithm similar to that is given in [8].

Remark 1: It is shown that the necessary condition for the existence of solution is that the nominal transfer function

$$T(s) = kC_2[sI - A]^{-1} B \tag{15}$$

Is strictly positive real (SPR) [12]. To approach the solution for some positive real cases, it is possible to use a reasonable approximation to close those systems to SPR ones.

Remark 2: It is significant to note that because of using simple constant gains, pertaining to SOF synthesis for dynamical systems in presence of strong constraints and tight objectives are few and restrictive. Under such conditions, the minimization problem (14) may be not approach to a strictly feasible solution.

3. TIME DELAY POWER SYSTEM

The traditional LFC model [4, 13] is modified to include communication delays. These delays are considered on three communication links. The delays on the measured frequency and power tie-line flow from RTUs to control center and the produced rise/lower signal from control center to individual generation units.

The modified LFC model is given in Fig. 1. The given labels and notations are:

Δf_i :	frequency deviation,
ΔP_{ci} :	governor load setpoint,
ΔP_{ti} :	turbine power,
ΔP_{tie-i} :	net tie-line power flow,
M_i :	equivalent inertia constant,
D_i :	equivalent damping coefficient,
T_{ij} :	tie-line synchronizing coefficient for area *i* & *j*,
β_i :	frequency bias,
R_k :	drooping characteristic,
ACE_i :	area control error (ACE),
α_{ki} :	ACE participation factors.

Following a load disturbance within the control area, the frequency of the area experiences a transient change and the feedback mechanism comes into play and generates appropriate control signal to make generation follow the load. The balance between connected control areas is achieved by detecting the frequency and tie line power deviation via communication line to generate the ACE signal used by PI controller. The control signal is submitted to the participated Gencos via other link, based on their participation factors.

According to (1), the open-loop state space model for the LFC system of control area "*i*" can be obtained as follows:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) + A_{di} x_i(t-d) + B_{hi} u_i(t-h) + F_i w_i(t) \\ z_i(t) &= C_{1i} x_i(t) \\ y_i(t) &= C_{2i} x_i(t) \end{aligned} \tag{16}$$

The state variables are considered as those given in [9, 13] and

$$y_i^T = [ACE_i \quad \int ACE_i],\ \ u_i = \Delta P_{Ci} \tag{17}$$

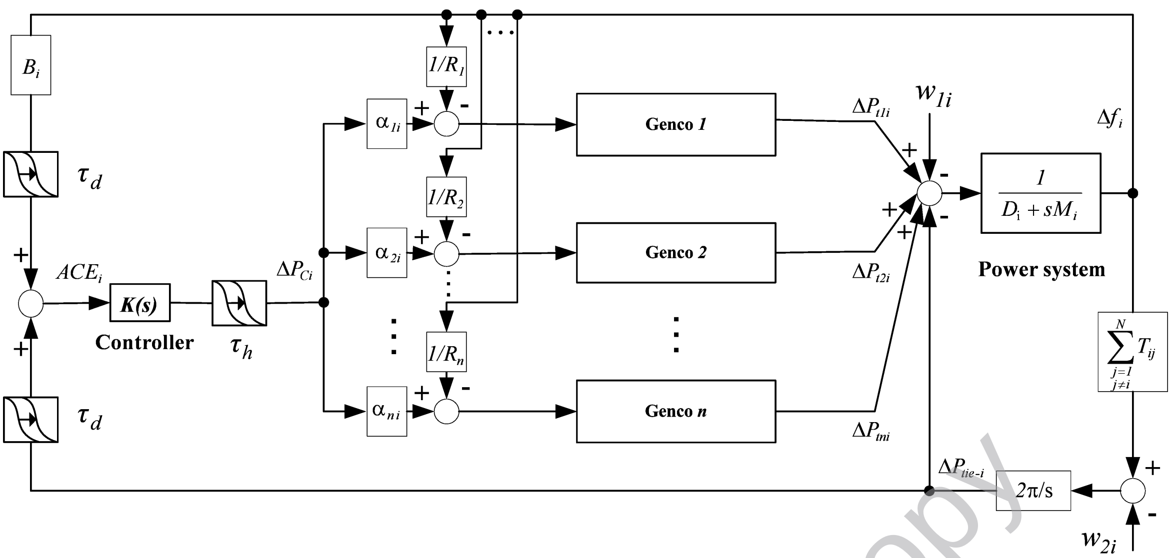


Fig. 1. LFC system with communication delays

$$z_i^T = \left[\eta_{1i}\Delta f_i \quad \eta_{2i}\int ACE_i\right] \tag{18}$$

$$w_i^T = \left[w_{1i} \quad w_{2i}\right] \tag{19}$$

$$A_{di} = \begin{bmatrix} A_{i11} & 0_{3\times n} & 0_{3\times n} \\ 0_{n\times 3} & 0_{n\times n} & 0_{n\times n} \\ A_{i31} & 0_{n\times n} & 0_{n\times n} \end{bmatrix},\ B_{hi} = \begin{bmatrix} 0_{3\times 1} \\ 0_{n\times 1} \\ B_{i3} \end{bmatrix} \tag{20}$$

$$C_{1i} = \left[c_{1i} \quad 0_{2\times n} \quad 0_{2\times n}\right],\ c_{1i} = \begin{bmatrix} \eta_{1i} & 0 \\ 0 & \eta_{2i} \end{bmatrix} \tag{21}$$

where,

$$A_{i11} = \begin{bmatrix} -D_i/M_i & -1/M_i & 0 \\ 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 & 0 \\ \beta_i & 1 & 0 \end{bmatrix},\ A_{i31} = \begin{bmatrix} -1/(T_{g1i}R_{1i}) & 0 & 0 \\ \vdots & \vdots & \vdots \\ -1/(T_{gni}R_{ni}) & 0 & 0 \end{bmatrix}$$

$$B_{i3}^{\ T} = \left[\alpha_{1i}/T_{g1i} \quad \alpha_{2i}/T_{g2i} \quad \cdots \quad \alpha_{ni}/T_{gni}\right]$$

$$\eta_1 = 0.5,\ \eta_2 = 1$$

Other parameters and matrix factors are the same as given in [9].

4. APPLICATION TO A 3-CONTROL AREA

To illustrate the effectiveness of the proposed control strategy, the PI-based LFC design in a 3-control area power system, shown in Fig. 2, is considered as an example. Each control area includes three generation companies (Gencos) with 9th order.

The power system data and parameters are considered the same as in [13]. It is assumed that the maximum frequency, tie-line and control signal delays for each control area are as follows:

$$d_i = 1\,s\ ,\ h_i = 1.5\,s \quad ; \quad i = 1, 2, 3$$

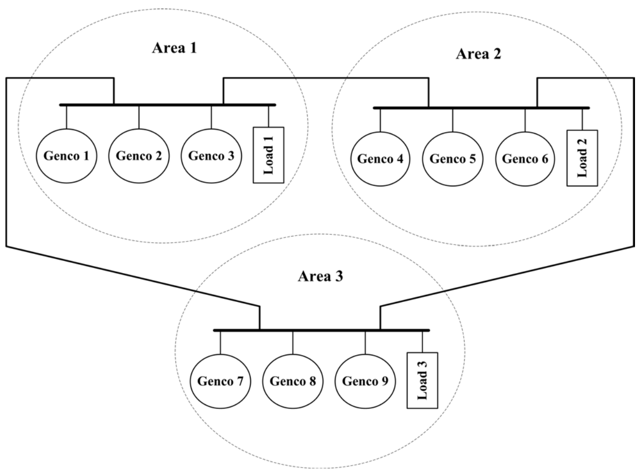


Fig. 2. Three control area power system

Based on the given simple stability condition in [14], the open loop system (16) with real matrices is stable if

$$\mu(A_i) + \|A_{di}\| < 0 \tag{22}$$

where

$$\mu(A_i) = \frac{1}{2} \max_{j} \ \lambda_j (A_i^T + A_i) \tag{23}$$

Here, λ_j denotes the jth eigenvalue of $(A_i^T + A_i)$. In light of above stability rule, we note that for the example at hand, the control areas are unstable:

$$\mu(A_1) + \|A_{d1}\| = 10.4736 > 0$$

$$\mu(A_2) + \|A_{d2}\| = 12.2615 > 0$$

$$\mu(A_3) + \|A_{d3}\| = 10.2285 > 0$$

According to synthesis methodology described in section 3, a set of three decentralized robust PI controllers are obtained. For comparisons, a robust PI controller is designed for nominal system (without delays) of each control area using the H_∞-SOF control technique [8].

5. SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed strategy, some simulations were carried out. Fig. 3 shows the closed-loop response (frequency deviation, area control error and control action signals) in presence of delays

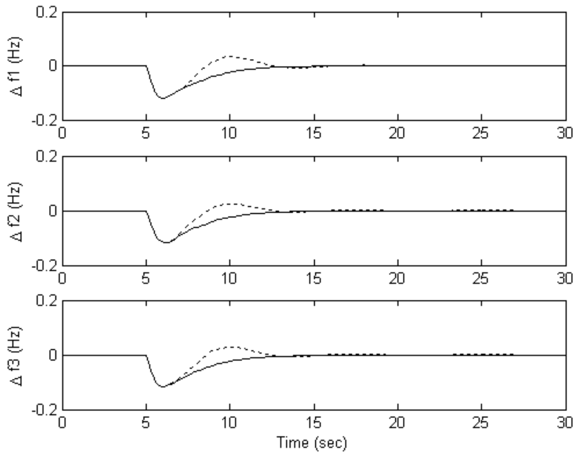
$$d_i = 0.5\,s \ , \ h_i = 0.5\,s \qquad ; \qquad i = 1, 2, 3$$

Following a *0.1 pu* step load disturbance at *5s* in each control area. Both types of designed controllers act to return the frequency and ACE signals to scheduled values, however the applied delays degrade the system performance for nominal (delay less) system based H_∞ control design.

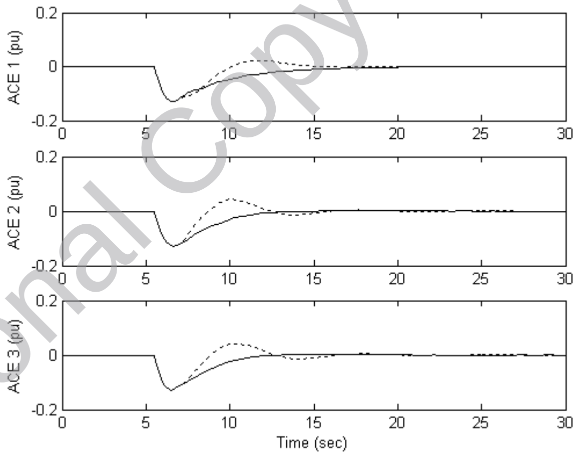
Increasing the delays will degrade the conventional LFC system performance seriously. F.g 4 shows the frequency deviation for control areas in face of following delays in communication channels:

$$d_i = 1.5\,s \ , \ h_i = 2\,s \qquad ; \qquad i = 1, 2, 3$$

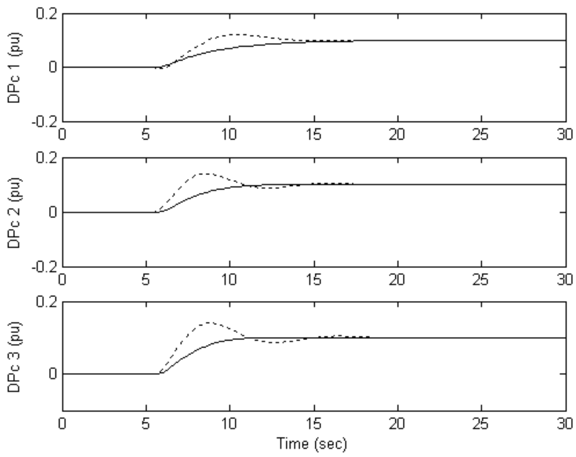
It shows that the conventional H_∞ controllers are not capable to hold the stability of closed-loop system.



(a)



(b)



(c)

Fig. 3. System response for $d_i = 0.5\,s$, $h_i = 0.5\,s$. Solid (proposed design), dotted (conventional design): a) frequency deviation, b) ACE and c) control effort

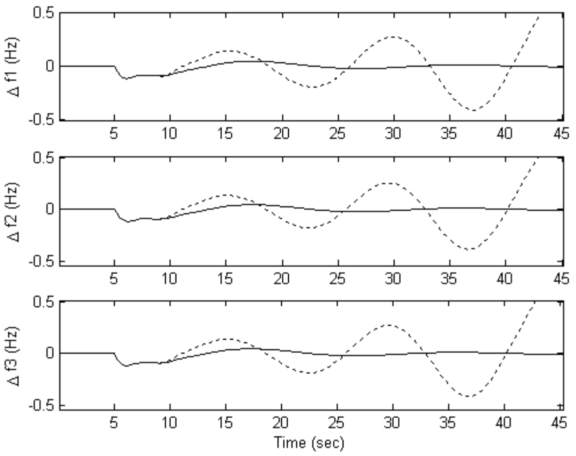


Fig. 4. System response for $d_i = 1.5\,s$, $h_i = 2\,s$. Solid (proposed design), dotted (conventional design)

6. CONCLUSION

An H_∞ - SOF control design is proposed to synthesis of PI based LFC system with multiple communication delays. The proposed method was applied to a 3-control area power system and the results are compared with delay less system based H_∞ control design. The simulations demonstrate the viability of the proposed method.

Acknowledgments
This work is supported by Japan Society for the Promotion of Science (JSPS) under grant P04346. Special thanks go to Prof. Magdi S. Mahmoud from UAE University for his helpful suggestions.

7. REFERENCES

[1] M. S. Mahmoud, **Robust control and filtering for time-delay systems**, Marcel Dekker Inc., New York, 2000.

[2] J. Aweya, D. Y. Montuno and M. Ouellette, "Effects of control loop delay on the stability of a rate control algorithm", **Int. Journal of Communication Sys.**, Vol. 17, 2004, pp. 833-850.

[3] J. K. Yook, D. M. Tilbury and N. R. Soparkar, "A design methodology for distributed control systems to optimize performance in the presence of time delays", **Int. J. Control**, Vol. 74, No. 1, 2001, pp. 58-76.

[4] H. Bevrani, "**Decentralized robust load-frequency control synthesis in restructured power systems**", PhD dissertation, Osaka University, 2004.

[5] S. Bhowmik, K. Tomosovic and A. Bose, "Communication models for third party load frequency control", **IEEE Trans. On Power Systems**, Vol. 19, No. 1, 2004, pp. 543-548.

[6] T. Hiyama, T. Nagata and T. Funabashi, "Multi-agent based automatic generation control of isolated stand alone power system", **In Proc. Of Int. Conf. on Power System Technology**, Vol. 1, 2004, pp. 139-143.

[7] X. Yu and K. Tomosovic, "Application of linear matrix inequalities for load frequency control with communication delays", **IEEE Trans. On Power Systems**, Vol. 19, No. 3, 2004, pp. 1508-1515 .

[8] H. Bevrani and T. Hiyama, "Robust tuning of PI/PID controllers using H_∞ control technique", **In Proc. Of 4th Int. Conf. on System Identification and Control Problems (SICPRO)**, Moscow, 2005, pp. 834-842.

[9] H. Bevrani, Y. Mitani and K. Tsuji, "Robust decentralized load-frequency control using an iterative linear matrix inequalities algorithm", **IEE Proc. Gener. Transm. Distrib**., Vol. 151, No. 3, 2004, pp. 347-354.

[10] M. S. Mahmoud and M. Zribi, "Guaranteed cost observer-based control of uncertain time-lag systems", *Computers and Electrical Engineering*, Vol. 29, 2003, pp. 193-212.

[11] P. Gahinet, A. Nemirovski, A. J. Laub and M. Chilali, **LMI Control Toolbox**, The MathWorks, Inc. , 1995.

[12] K. S. Narendra and A. M. Annaswamy, **Stable adaptive systems**, Prentice-Hall, Englewood Cliffs, New Jersey, 1989.

[13] D. Rerkpreedapong, A. Hasanovic and A. Feliachi, "Robust load frequency control using genetic algorithms and linear matrix inequalities", **IEEE Trans. On Power Systems**, Vol. 18, No. 2, 2003, pp. 855-861.

[14] T. Mori and H. Kokame, "Stability of $\dot{x}(t) = Ax(t) + Bx(t-\tau)$ ", **IEEE Trans. On Automatic Control**, Vol. 34, 1989, pp. 460-462.