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Robust load–frequency regulation: A real-time laboratory experiment

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SUMMARY

This paper addresses a new method for robust decentralized design of proportional-integral-based load–frequency control (LFC) with communication delays. In the proposed methodology, the LFC problem is reduced to a static output feedback control synthesis for a multiple delays power system, and then the control parameters are easily carried out using robust H_∞ control technique. To demonstrate the efficiency of the proposed control strategy, an experimental study has been performed on the Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Co. in Japan. Copyright © 2007 John Wiley & Sons, Ltd.

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1. INTRODUCTION

In a restructured power system, load–frequency control (LFC) acquires a fundamental role to enable power exchanges and to provide better conditions for the electricity trading. An effective power system market highly needs an open communication infrastructure to support the increasing decentralized property of control processes, and a major challenge in a new environment is to integrate computing, communication and control into appropriate levels of real-world power system operation and control.

In the control systems, it is well known 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

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as one of the important uncertainties in the LFC synthesis/analysis due to expanding physical set-ups, functionality and complexity of power system is to become a significant problem. On the other hand, the real-world LFC systems use the proportional-integral (PI) type controllers. Since the PI controller parameters are usually tuned based on classical, experiences and trial-and-error approaches, they are incapable of obtaining good dynamical performance for a wide range of operating conditions and various load scenarios.

Recently, several papers have been published to address the LFC modelling/synthesis in the presence of communication delays [4–6]. Reference [4] is focused on the network delay models and communication network requirement for a third-party LFC service. A compensation method for communication time delay in the LFC systems is addressed in Reference [5] and a control design method based on linear matrix inequalities (LMIs) is proposed for LFC system with communication delays in Reference [6]. These references clearly addressed the effects of signal delays on the load following task.

Most published research works on the PI-based LFC have neglected problems associated with the communication network. Although, under the traditional dedicated communication links, this was a valid assumption, however, the use of an open communication infrastructure to support the ancillary services in deregulated environments raises concerns about problems that may arise in the communication system. It should be noted for a variety of reasons optimal setting of the PI parameters is difficult and as a result the most of robust and optimal approaches suggest complex state-feedback or high-order dynamic controllers.

In this paper, the PI-based multi-delayed LFC problem is transferred to a static output feedback (SOF) control design and to tune the PI parameters, the optimal H_∞ control is used *via* a multi-constraint minimization problem. The problem formulation is based on expressing the constraints as LMI which can be easily solved using available semi-definite programming methods [7, 8]. Simplicity of control structure, keeping the fundamental LFC concepts, using multi-delay-based LFC system and no need to additional controller can be considered as advantages of the proposed LFC design methodology. To demonstrate the efficiency of the proposed control method, some real-time simulations have been performed on the Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Co. (Japan).

2. PRELIMINARIES

2.1. H_∞ control for time-delay systems

Consider a class of time-delay systems of the form [1]

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

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 and $C_2 \in \Re^n$ 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

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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 adapts H_∞ theory in the control synthesis for time-delay systems (using LMI description) 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

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

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

where

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

Proof

According to the Schur complement method [7], LMI (3) is equivalent to the following matrix inequality:

$$PA_c + A_c^{\mathrm{T}}P + Q_1 + Q_2 + PA_dQ_1^{-1}A_d^{\mathrm{T}}P + PB_hKQ_2^{-1}K^{\mathrm{T}}B_h^{\mathrm{T}}P + C_1^{\mathrm{T}}C_1 + \gamma^{-2}PFF^{\mathrm{T}}P < 0 \tag{5}$$

The sufficiency of theorem for the inequality notation (5) is given in [1]. □

2.2. *LFC with time delays*

The time-delayed LFC system is well discussed in [4, 6]. For purposes of this work, the communication delays are considered on the control input and control output of the LFC system: the delays on the measured frequency and power tie-line flow from remote terminal units to control centre which can be considered on the area control error (ACE) signal and the produced rise/lower signal from control centre to individual generation units.

The time-delayed LFC system is shown in Figure 1. The communication delay is expressed by an exponential function $\mathrm{e}^{-s\tau}$, where τ gives the communication delay time. Following a load disturbance within the control area, the frequency of the area experiences a transient change and the feedback mechanism comes into work and generates appropriate control signal to make the generation readjusts to meet the load demand. The balance between connected control areas is achieved by detecting the frequency and tie-line power deviation *via* communication line to

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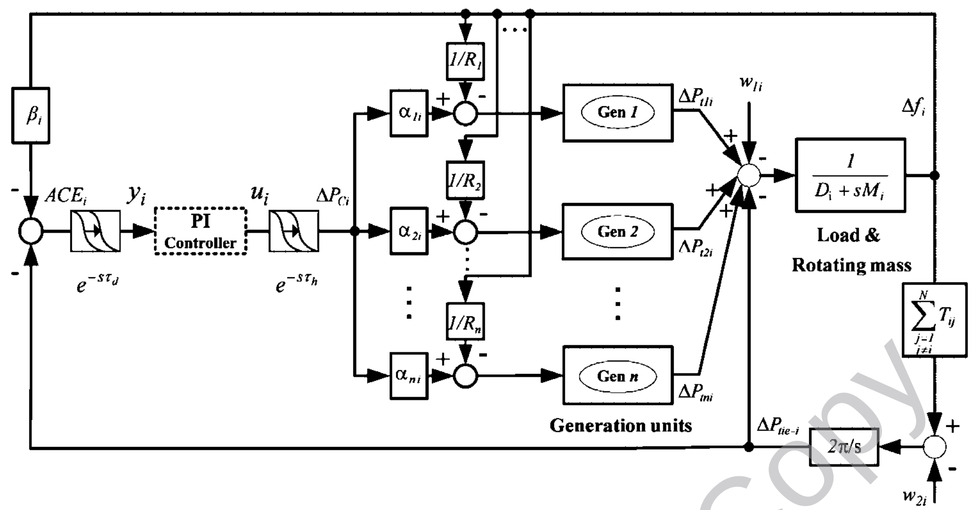

Figure 1. A general control area with time delays.

generate the ACE signal used by the PI controller. The control signal is submitted to the participated generation companies (Gencos) *via* another link, based on their participation factors. w_{1i} and w_{2i} demonstrate the area load disturbance and interconnection effects (area interface), respectively.

$$w_{1i} = \Delta P_{di}, \quad w_{2i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} \Delta f_j \tag{6}$$

where $\Delta P_{\text{tie}-i}$ is the net tie-line power flow, M_i the equivalent inertia constant, D_i the equivalent damping coefficient, T_{ij} the tie-line synchronizing coefficient for area i and j, β_i the frequency bias, R_k the drooping characteristic, ACE_i the area control error (ACE) and α_{ki} the ACE participation factors.

3. PROPOSED CONTROL STRATEGY

3.1. Problem formulation

The PI-based LFC problem can be transferred to a SOF control problem by augmenting the measured output signal to include the ACE and its integral [9]

$$u(t) = ky(t) \tag{7}$$

$$u(t) = k_{\text{P}}\text{ACE} + k_{\text{I}} \int \text{ACE} = [k_{\text{P}} \;\; k_{\text{I}}] \left[\text{ACE} \quad \int \text{ACE}\right]^{\text{T}} \tag{8}$$

where k_{P} and k_{I} are constant real numbers (PI parameters). ACE is the area control error signal for which each control area can be expressed as a linear combination of tie-line power change and

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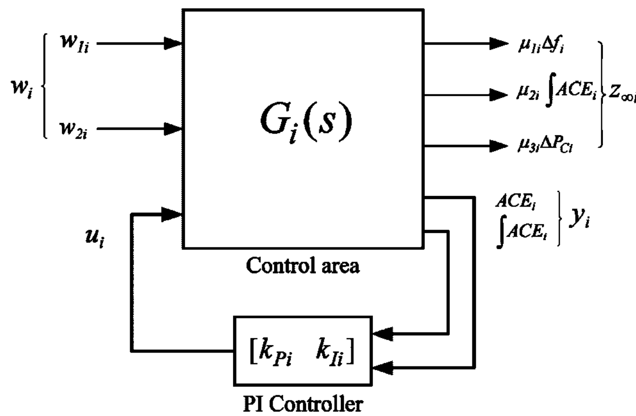

Figure 2. H_∞-SOF control framework.

frequency deviation:

$$\mathrm{ACE} = \beta \Delta f + \Delta P_{\mathrm{tie}} \tag{9}$$

The main merit of this transformation is in the 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.

The overall control framework to formulate the time-delayed LFC problem *via* a H_∞-based SOF (H_∞-SOF) control design is shown in Figure 2. The output channel $z_{\infty i}$ is associated with the H_∞ performance while the y_i is the augmented measured output vector (performed by ACE and its integral). μ_{1i}, μ_{2i} and μ_{3i} are constant weights that must be chosen by designer to get the desired closed-loop performance. Experience suggests that one can fix the weights μ_{1i}, μ_{2i} and μ_{3i} to unity and use the method with regional pole placement technique for performance tuning [10]. The first two terms of $z_{\infty i}$ output are used to minimize the effects of disturbances on area frequency and ACE by introducing appropriate fictitious controlled outputs. Furthermore, fictitious output $\mu_{3i}\Delta P_{Ci}$ sets a limit on the allowed control signal to penalize fast changes and large overshoot in the governor load set point with regards to practical constraint on power generation by generator units [11, 12].

$G_i(s)$ is the nominal dynamic model of the given control area, u_i is the control input and w_i includes the perturbed and disturbance signals in the given control area. According to (1), the open-loop state-space model ($G_i(s)$) for the LFC system of control area 'i' can be obtained as follows:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) + A_{di} x_i(t-d) + B_{hi} u_i(t-h) + F_i w_i(t) \\ z_i(t) &= C_{1i} x_i(t) \\ y_i(t) &= C_{2i} x_i(t) \end{aligned} \tag{10}$$

Using the standard simplified LFC model for the prime mover and governor in Figure 1, the state variables can be considered as follows:

$$x_i^{\mathrm{T}} = \left[\Delta f_i \quad \Delta P_{\mathrm{tie}-i} \quad \int \mathrm{ACE}_i \quad x_{ti} \quad x_{gi} \right] \tag{11}$$

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where

$$x_{ti}=[\Delta P_{t1i}\ \ \Delta P_{t2i}\ \ \ldots\ \ \Delta P_{tni}],\quad x_{gi}=[\Delta P_{g1i}\ \ \Delta P_{g2i}\ \ \ldots\ \ \Delta P_{gni}] \tag{12}$$

and

$$y_i^{\mathrm{T}}=\left[\mathrm{ACE}_i\ \ \int \mathrm{ACE}_i\right],\quad u_i=\Delta P_{Ci} \tag{13}$$

$$z_i^{\mathrm{T}}=\left[\mu_{1i}\Delta f_i\ \ \mu_{2i}\int \mathrm{ACE}_i\ \ \mu_{3i}\Delta P_{Ci}\right] \tag{14}$$

$$w_i^{\mathrm{T}}=[w_{1i}\ \ w_{2i}] \tag{15}$$

where Δf_i is the frequency deviation, ΔP_{gi} the governor valve position, ΔP_{ci} the governor load set point and ΔP_{ti} the turbine power.

3.2. H_∞-SOF-based LFC design

Using the described transformation from PI to SOF control design, the time-delayed LFC problem is reduced to synthesis of SOF control for the time-delay system (1) of the form of (7). k is a static gain vector to be determined.

The SOF control problem is one of the most important research areas in control engineering [13–15]. One reason why SOF has received so much attention is that it represents the simplest control structure that can be realized in the real-world systems. Another reason is that many existing dynamic control synthesis problems can be transferred to a SOF control problem by a well-known system augmentation techniques [15, 16]. A comprehensive survey on SOF control is given in [15]. A variety of SOF problems were studied by many researchers with many analytical and numerical methods to approach a local/global solution, however, only few references have addressed the time-delayed systems. Here, in order to obtain an optimal LMI-based H_∞ solution for the mentioned SOF problem from the delay-based LFC synthesis, the following theorem is used:

Theorem 2

The SOF controller k asymptotically stabilizes system (1) and $\|T_{zw}\|_\infty<\gamma$ for $d, h\geqslant 0$ if there exists matrices $0<Y^{\mathrm{T}}=Y\in\Re^{n\times n}$, $0<Q_t^{\mathrm{T}}=Q_t\in\Re^{n\times n}$ and $0<Q_s^{\mathrm{T}}=Q_s\in\Re^{n\times n}$ satisfying the following matrix inequality

$$W_s=\begin{bmatrix} AY+YA^{\mathrm{T}}+Q_t+Q_s & (BkC_2)^{\mathrm{T}} & Y & YA_d^{\mathrm{T}} & (B_hkC_2Y)^{\mathrm{T}} & C_1Y & F^{\mathrm{T}} \\ BkC_2 & -I_n & 0 & 0 & 0 & 0 & 0 \\ Y & 0 & -I_n & 0 & 0 & 0 & 0 \\ A_dY & 0 & 0 & -Q_t & 0 & 0 & 0 \\ B_hkC_2Y & 0 & 0 & 0 & -Q_s & 0 & 0 \\ YC_1^{\mathrm{T}} & 0 & 0 & 0 & 0 & -I_p & 0 \\ F & 0 & 0 & 0 & 0 & 0 & -\gamma^2 I_q \end{bmatrix}<0 \tag{16}$$

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An equivalent theorem with a different configuration using some relaxation parameters is given in [1]. Since the mentioned theorem and its result are not straightly applicable to the PI-based LFC design, above-modified theorem is proposed.

Proof
The controller (7) can be considered as a replica of the state-feedback controller (2):

$$u(t) = ky(t) = kC_2x(t) \tag{17}$$

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

$$K = kC_2 \tag{18}$$

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

$$A_c = A + BkC_2 \tag{19}$$

The stabilizing controller satisfies inequality (5). Therefore, using (19) we can write

$$\begin{aligned} &P(A + BkC_2) + (A + BkC_2)^{\mathrm{T}}P + Q_1 + Q_2 + PA_dQ_1^{-1}A_d^{\mathrm{T}}P \\ &+PB_hkC_2Q_2^{-1}(kC_2)^{\mathrm{T}}B_h^{\mathrm{T}}P + C_1^{\mathrm{T}}C_1 + \gamma^{-2}PFF^{\mathrm{T}}P < 0 \end{aligned} \tag{20}$$

Premultiplying and postmultiplying (20) by P^{-1} and letting $P^{-1} = Y$, we get

$$\begin{aligned} &AY + YA^{\mathrm{T}} + YQ_1Y + YQ_2Y + BkC_2Y + Y(kC_2)^{\mathrm{T}}B^{\mathrm{T}} + A_dQ_1^{-1}A_d^{\mathrm{T}} \\ &+B_hkC_2Q_2^{-1}(kC_2)^{\mathrm{T}}B_h^{\mathrm{T}} + YC_1^{\mathrm{T}}C_1Y + \gamma^{-2}FF^{\mathrm{T}} < 0 \end{aligned} \tag{21}$$

Now, assuming $YQ_1Y = Q_t$, $YQ_1Y = Q_s$ and using the following inequality [7]:

$$\forall \Omega_1, \Omega_2 \in \Re: \quad \Omega_1^{\mathrm{T}}\Omega_2 + \Omega_2^{\mathrm{T}}\Omega_1 \leqslant \alpha\Omega_1^{\mathrm{T}}\Omega_1 + \alpha^{-1}\Omega_2^{\mathrm{T}}\Omega_2, \quad \alpha > 0 \tag{22}$$

Equation (21) can be reduced to

$$\begin{aligned} &[AY + YA^{\mathrm{T}} + Q_t + Q_s] + [BkC_2(BkC_2)^{\mathrm{T}} + Y^{\mathrm{T}}Y] + [A_dYQ_t^{-1}(A_dY)^{\mathrm{T}}] \\ &+[B_hkC_2YQ_s^{-1}(B_hkC_2Y)^{\mathrm{T}}] + YC_1^{\mathrm{T}}C_1Y + \gamma^{-2}FF^{\mathrm{T}} < 0 \end{aligned} \tag{23}$$

Using the Schur complement method, (23) can be arranged conveniently to yield the block form (16) as desired. □

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

$$\min_{Q_t, Q_s, Y, k} \gamma \quad \text{subject to} \quad -Y < 0, \ \ -Q_t < 0, \ \ -Q_s < 0, \ \ -W_s < 0 \tag{24}$$

The matrix inequality (16) 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

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convex and can be solved efficiently using the LMI Control Toolbox [8], if a feasible solution exists. One may use a simple optimization algorithm similar to that is given in [9].

Remark 1

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

$$T(s) = kC_2[sI - A]^{-1}B \tag{25}$$

is strictly positive real (SPR) [17]. 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 the presence of strong constraints and tight objectives are few and restrictive. Under such conditions, the minimization problem (24) may not approach to a strictly feasible solution.

4. REAL-TIME LABORATORY EXPERIMENT

4.1. Configuration of study system

To illustrate the effectiveness of the proposed control strategy, some real-time simulations have been performed on the Analog Power System Simulator at the Research Laboratory of the Kyushu

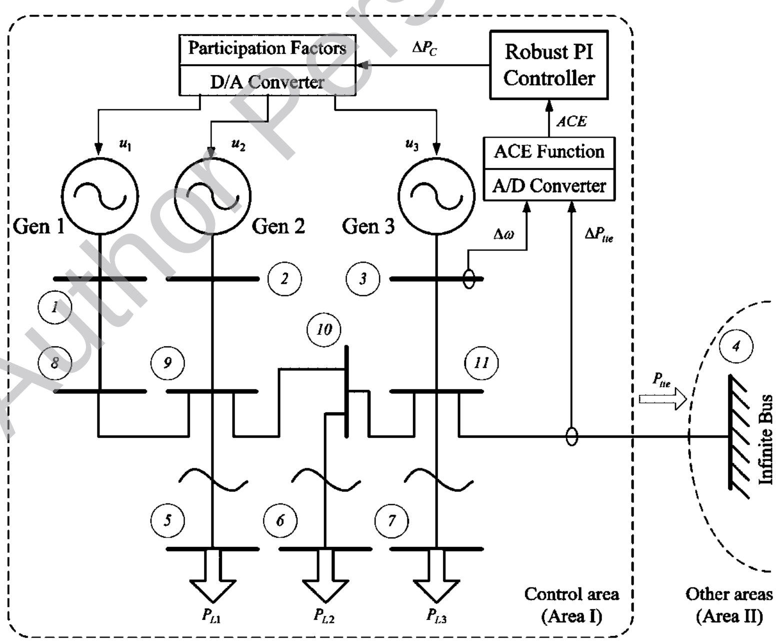

Figure 3. Study power system.

Electric Power Company. For the purpose of this study, a longitudinal three-machine infinite bus system is considered as a test system. The study system is shown in Figure 3. All generator units are thermal type, with separately conventional excitation control systems. Set of three generators represent a control area (Area I), and, the infinite bus is considered as other connected systems (Area II).

The whole power system has been implemented in the mentioned laboratory. The proposed controller, ACE computing unit and participation factors which build in SIMULINK environment (shown in Figure 4) have been connected to the power system using a digital signal processing (DSP) board equipped with analog to digital (A/D) and digital to analog (D/A) converters as the physical interface between the personal computer and the Analog Power System Simulator. Figure 5 shows the overview of the applied laboratory experiment devices. The block diagram

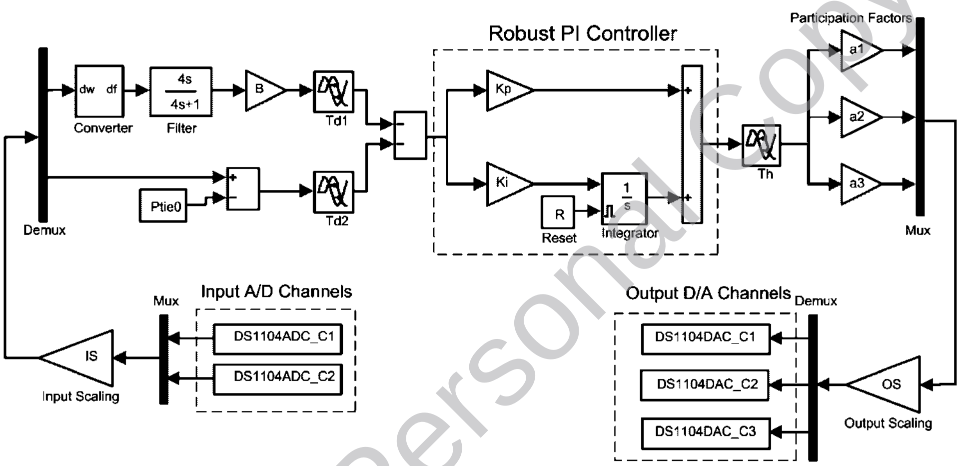

Figure 4. SIMULINK-based control loop.

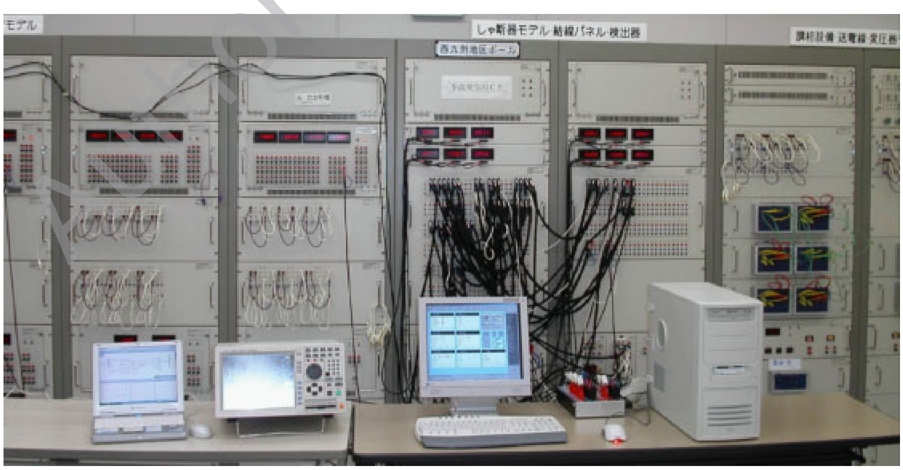

Figure 5. Overview of the performed laboratory experiment.

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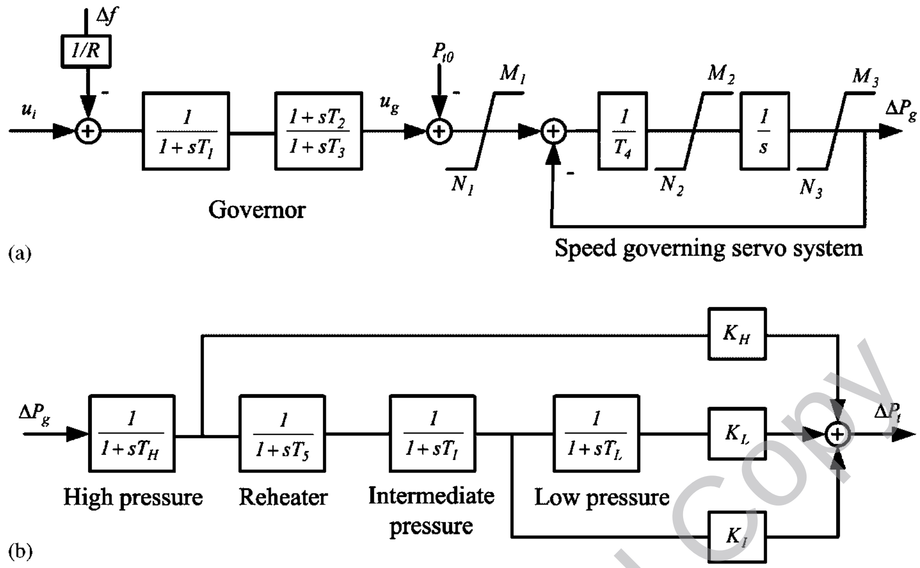

Figure 6. Generator unit: (a) speed governing system and (b) detailed turbine system.

given in Figure 4 has been implemented in a personal computer. The digital oscilloscope and notebook computer (shown in the right side of Figure 5) are used for monitoring purposes.

The detailed block diagram of each generator unit and its associated turbine system (including the high-pressure, intermediate-pressure and low-pressure parts) is illustrated in Figure 6. The power system parameters are given in Table AI (Appendix).

4.2. H_∞-SOF-based PI controller

To adapt (10) with the shown time-delayed LFC system in Figure 1, the A_{di} can be easily computed by transferring the ACE delay (τ_d) through its components (Δf_i and $\Delta P_{\text{tie}-i}$ as states). Therefore, the delay is considered in the both states and control input. Based on a simple stability condition [18], the open-loop system (10) with real matrices is stable if

$$\mu(A_i) + \|A_{di}\| < 0 \tag{26}$$

where

$$\mu(A_i) = \frac{1}{2} \max_j \lambda_j (A_i^{\mathrm{T}} + A_i) \tag{27}$$

Here, λ_j denotes the jth eigenvalue of $(A_i^{\mathrm{T}} + A_i)$. Using the above stability rule, we note that for the example at hand, the control area is unstable:

$$\mu(A_i) + \|A_{di}\| = 12.9714 > 0 \tag{28}$$

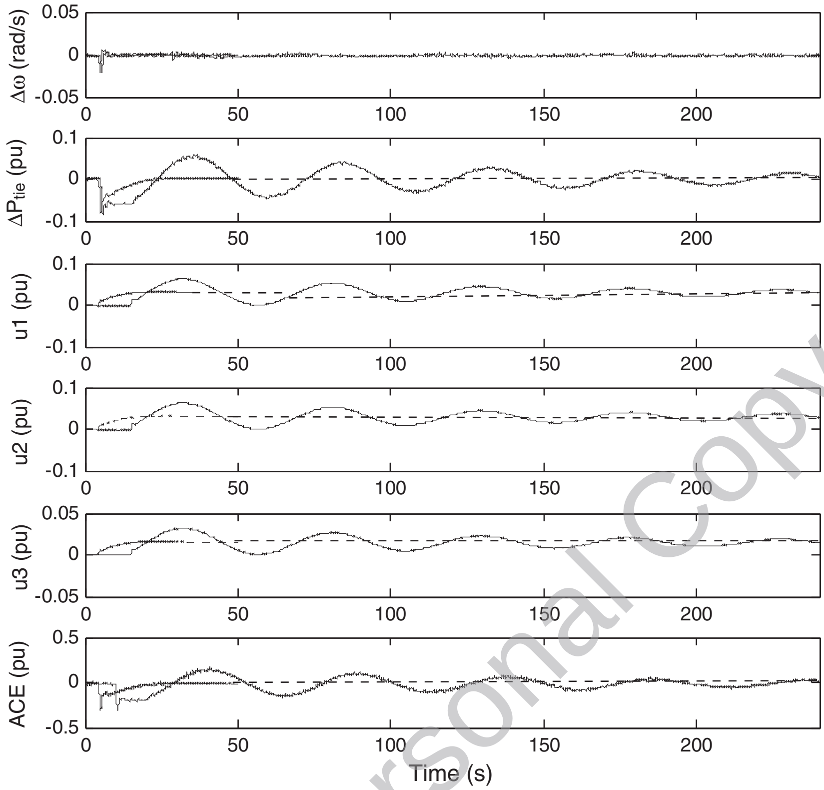

Figure 7. System response with 10 s delay (solid) and without delay (dotted), following a 5% step load increase.

Table I. Participation factors.

Generators	Unit 1	Unit 2	Unit 3
α	0.4	0.4	0.2

According to the described synthesis methodology in Section 3, the PI parameters are obtained as (29). For the study system at hand, the total time delay of communication channels is considered near to the LFC cycle rate of the power system and a suitable value for constant weights μ_{1i}, μ_{2i} and μ_{3i} are considered as 0.5, 1 and 25, respectively,

$$k_P = 0.0611, \quad k_I = 0.1369 \tag{29}$$

Based on Theorem 2, since a solution for the time-delayed LFC problem will be obtained through minimizing the guaranteed the H_∞ performance index γ (as a valid performance measure) subject

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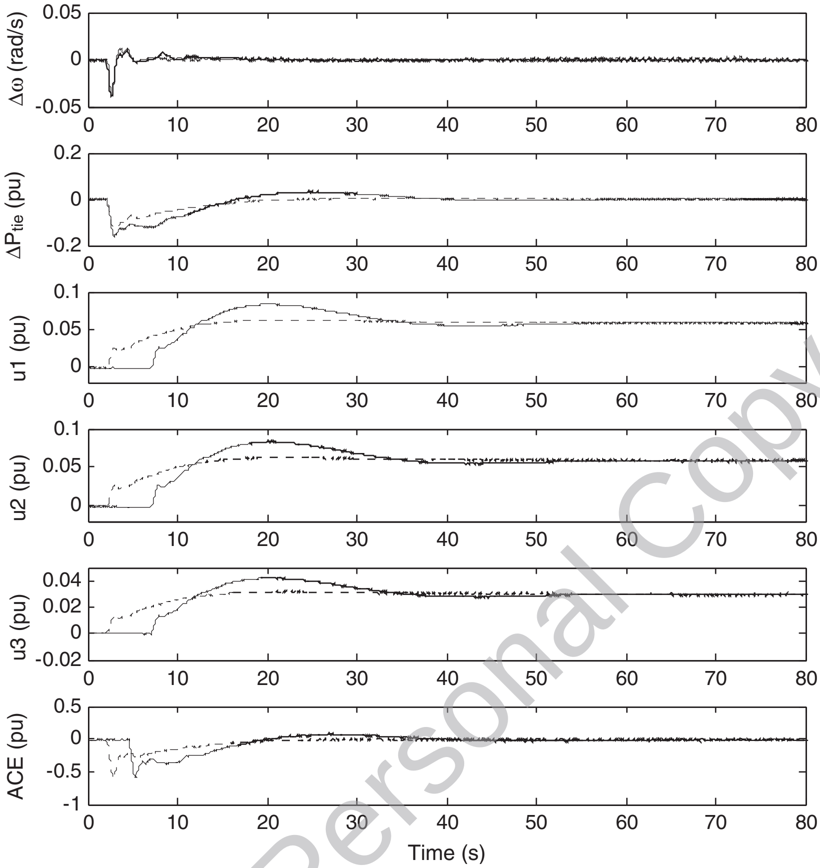

Figure 8. System response with 6 s delay (solid) and without delay (dotted), following a 10% step load increase.

to the given constraints in (24), the designed PI controllers satisfy the robustness of the closed-loop system. In other words, the basis of designing the SOF controllers (7) is to simultaneously stabilize (10) and guarantee the H_∞-norm bound $\gamma$of the closed-loop transfer function T_{zw}, namely,

$$\|T_{zw}\|_\infty < \gamma, \quad \gamma > 0 \tag{30}$$

5. REAL-TIME SIMULATION RESULTS

In the performed non-linear real-time laboratory's simulations, the proposed PI controller was applied to the control area power system described in Figure 3. The performance of the closed-loop system is tested in the presence of load disturbances and time delays. Two types of communication delays, fixed and random, are simulated. To simplify the presentation and because of space limitation

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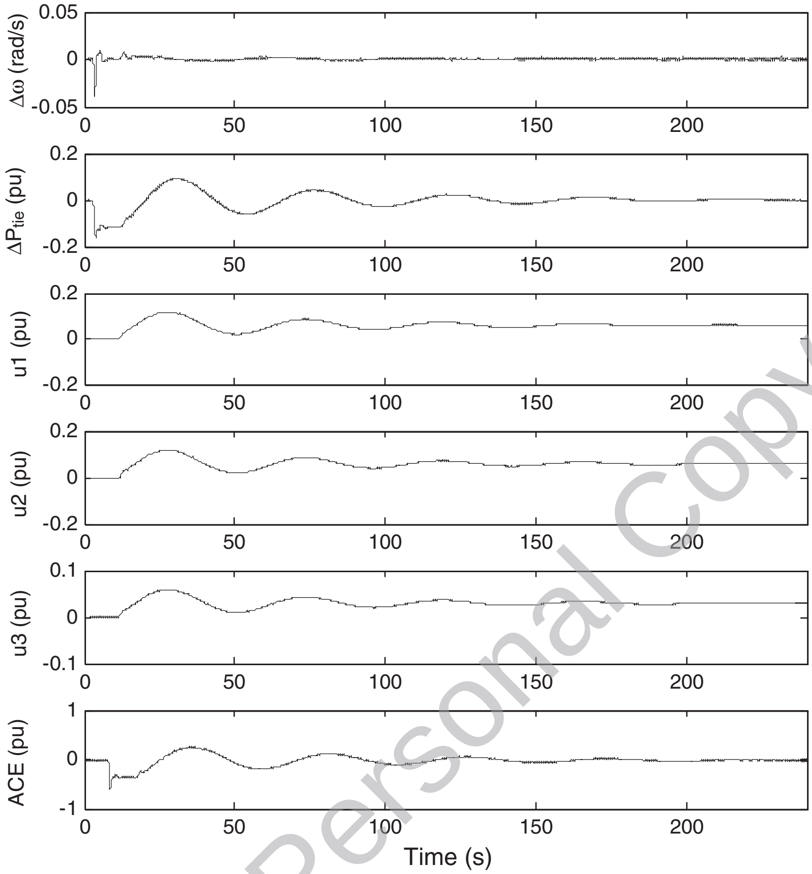

Figure 9. System response in the presence of 10 s delay, following a 10% step load increase.

here, case studies of fixed delays are used. The nominal area load demands P_{L1}, P_{L2} and P_{L3} (in Figure 3) during simulation tests are considered as 0.3, 0.6 and 0.6 pu, respectively.

For the first test scenario, the power system is examined with and without delays, following a 5% step load increase at 5 s in control area. The total communication delay is assumed as 10 s. The closed-loop system response including frequency deviation ($\Delta\omega$), tie-line power change (ΔP_{tie}), control action signals (u_i) and ACE, are shown in Figure 7. The designed PI controller acts to return the frequency, tie-line power and ACE signals to the scheduled values properly. Figure 7 shows the changes in control signals applied to the generator units are provided according to their participation factors (α) listed in Table I.

Figure 8 shows the closed-loop response in the presence of a 6 s total communication delay, following a 10% step load increase in the control area. System response for 10 s delay with the same step load change is shown in Figure 9. Figures show the frequency deviation and ACE of control area are properly maintained within a narrow band using smooth control efforts.

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Further simulation results show that using the time delay-less H_∞ approach given in [9], the resulted closed-loop system will be unstable for the above-mentioned scenarios; while the designed controller can ensure good performance despite load disturbance and delays in the communication network. The proposed real-time non-linear simulation demonstrates that the robust PI controller acts to maintain area frequency and total exchange power closed to the scheduled values by sending corrective smooth signals to the generator units in proportion to their participation in the LFC task.

6. CONCLUSION

The PI-based LFC problem with communication delays in a multi-area power system is formulated as a robust SOF optimization control problem. To obtain the constant gains, an LMI-based H_∞ methodology has been proposed. Simplicity of control structure, keeping the fundamental LFC concepts, using multi-delay-based LFC system and no need to additional controller can be considered as advantages of the proposed methodology. The proposed method was applied to a control area power system using a laboratory real-time non-linear simulator.

APPENDIX A

Generating unit parameters are given in Table AI.

Table AI. Generating unit parameters.

Parameters	Gen 1	Gen 2	Gen 3
MVA	1000	600	1000
R (Hz/pu)	3.00	3.00	3.30
T_1 (s)	0.08	0.06	0.07
T_2 (s)	0.10	0.10	0.10
T_3 (s)	0.10	0.10	0.10
T_4 (s)	0.40	0.36	0.42
T_5 (s)	10.0	10.0	10.0
β (pu/Hz)	0.3483	0.3473	0.3180
D (pu/Hz)	0.0150	0.0150	0.0150
M (s)	8.05	7.00	8.05
T_H (s)	0.05	0.05	0.05
T_I (s)	0.08	0.08	0.08
T_L (s)	0.58	0.58	0.58
K_H (pu)	0.31	0.31	0.31
K_I (pu)	0.24	0.24	0.24
K_L (pu)	0.45	0.45	0.45
M_1 (pu/min)	0.50	0.50	0.50
M_2 (pu/min)	0.050	0.050	0.050
M_3 (pu/min)	2.00	2.00	2.00
N_1 (pu/min)	−0.50	−0.50	−0.50
N_2 (pu/min)	−0.20	−0.20	−0.20
N_3 (pu/min)	−0.50	−0.50	−0.50

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REFERENCES

1. Mahmoud MS. *Robust Control and Filtering for Time-delay Systems*. Marcel Dekker: New York, U.S.A., 2000.
2. Aweya J, Montuno DY, Ouellette M. Effects of control loop delay on the stability of a rate control algorithm. *International Journal of Communication Systems* 2004; **17**:833–850.
3. Niculescu SI. *Delay Effects on Stability: A Robust Control Approach*. Springer: Berlin, 2001.
4. Bhowmik S, Tomosovic K, Bose A. Communication models for third party load frequency control. *IEEE Transactions on Power Systems* 2004; **19**:543–548.
5. Hiyama T, Nagata T, Funabashi T. Multi-agent based automatic generation control of isolated stand alone power system. *Proceedings of the International Conference on Power System Technology,* Singapore, vol. 1, 2004; 139–143.
6. Yu X, Tomosovic K. Application of linear matrix inequalities for load frequency control with communication delays. *IEEE Transactions on Power Systems* 2004; **19**:1508–1515.
7. Boyd S, Ghaoui L El, Feron E, Balakrishnan V. *Linear Matrix Inequalities in Systems and Control Theory*. SIAM Books: Philadelphia, 1994.
8. Gahinet P, Nemirovski A, Laub AJ, Chilali M. *LMI Control Toolbox*. The MathWorks Inc.: Natick, MA, U.S.A., 1995.
9. Bevrani H, Mitani Y, Tsuji K. Robust decentralised load–frequency control using an iterative linear matrix inequalities algorithm. *IEE Proceedings—Generation Transmission and Distribution* 2004; **150**:347–354.
10. Gahinet P, Chilali M. H_∞-design with pole placement constraints. *IEEE Transactions on Automatic Control* 1996; **41**:358–367.
11. Jaleeli N, Ewart DN, Fink LH. Understanding automatic generation control. *IEEE Transactions on Power Systems* 1992; **7**:1106–1112.
12. Hiyama T. Optimization of discrete-type load–frequency regulators considering generation-rate constraints. *IEE Proceedings—C Generation Transmission and Distribution* 1982; **129**:285–289.
13. Bernstein D. Some open problems in matrix theory arising in linear systems and control. *Linear Algebra and its Applications* 1992; **162–164**:409–432.
14. Blondel V, Gevers M, Lindquist A. Survey on the state of systems and control. *European Journal of Control* 1995; **1**:5–23.
15. Syrmos VL, Abdallah CT, Dorato P, Grigoriadis K. Static output feedback: a survey. *Automatica* 1997; **33**:125–137.
16. Leibfritz F. Static output feedback design problems. *PhD Dissertation*, Trier University, Trier, 1998.
17. Narendra KS, Annaswamy AM. *Stable Adaptive Systems*. Prentice-Hall: Englewood Cliffs, NJ, 1989.
18. Mori T, Kokame H. Stability of $\dot{x}(t) = Ax(t) + Bx(t-\tau)$. *IEEE Transactions on Automatic Control* 1989; **34**:460–462.

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