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Robust decentralised PI based LFC design for time delay power systems

Hassan Bevrani [a,*], Takashi Hiyama [b]

[a] Department of Electrical Engineering, University of Kurdistan, P.O. Box 416, Kurdistan, Sanandaj, Iran
[b] Department of Electrical Engineering, Kumamoto University, Kumamoto, Japan

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Abstract

In this paper, two robust decentralised proportional integral (PI) control designs are proposed for load frequency control (LFC) with communication delays. In both methodologies, the PI based LFC problem is reduced to a static output feedback (SOF) control synthesis for a multiple delay system. The first one is based on the optimal H_∞ control design using a linear matrix inequalities (LMI) technique. The second control design gives a suboptimal solution using a developed iterative linear matrix inequalities (ILMI) algorithm via the mixed H_2/H_∞ control technique. The control strategies are suitable for LFC applications that usually employ PI control. The proposed control strategies are applied to a three control area power system with time delays and load disturbance to demonstrate their robustness.

Keywords: Load frequency control; H_∞ control; Mixed H_2/H_∞ control; Static output feedback control; Robust performance; PI; Linear matrix inequalities

1. Introduction

Since load frequency control (LFC) systems are faced by new uncertainties in the liberalized electricity markets, modeling of these uncertainties and dynamic behavior is very important to design suitable controllers and to provide better conditions for electricity trading. An effective power system market highly needs an open communication infrastructure to support the increasingly decentralized property of control processes, and a major challenge in the new environment is to integrate computing, communication and control into appropriate levels of real world power system operation and control.

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

Recently, several papers have been published to address LFC modeling/synthesis in the presence of communication delays [4–6]. Ref. [4] is focused on 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 Ref. [5], and a control design method based on linear matrix inequalities (LMI) is proposed for a LFC system with communication delays in Ref. [6]. These references have clearly addressed the effects of signal delays on the load following task.

Most published research works on 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

* Corresponding author. Tel.: +98 871 6660073; fax: +98 871 6624004.
E-mail address: bevrani@uok.ac.ir (H. Bevrani).

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raises concerns about problems that may arise in the communication system. It should be noted that for a variety of reasons, optimal setting of the PI parameters is difficult, and as a result, most of the 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 obtain constant gains, two robust decentralized design methodologies are proposed. In the first control design, 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 that can be easily solved using available semi-definite programming methods [7,8].

In the presence of strong constraints and tight objectives conditions, the addressed optimization algorithm may not approach a strictly feasible solution. The second control design addresses a more flexible methodology to invoke the strict positive realness condition. The time delay is considered as a model uncertainty, and the H_2/H_∞ control is used via an iterative linear matrix inequalities (ILMI) algorithm to approach a suboptimal solution for the assumed design objectives. Simplicity of control structure, keeping the fundamental LFC concepts, using multi-delay based LFC system and no need of an additional controller can be considered as advantages of the proposed LFC design methodologies. The proposed controllers are applied to a three control area power system example.

2. LFC with time delays

2.1. Time delayed LFC structure

A time-delayed LFC system is shown in Fig. 1a. The given lables and notations on the LFC block diagram are defined as follows:

Δf_i	frequency deviation,
ΔP_{ci}	governor load setpoint,
ΔP_{ti}	turbine power,
$\Delta P_{\text{tie}-i}$	net tie line power flow,
M_i	equivalent inertia constant,
D_i	equivalent damping coefficient,
T_{ij}	tie line synchronizing coefficient for area i and j,
β_i	frequency bias,
R_k	drooping characteristic,
α_{ki}	ACE participation factors.

For the purposes of this work, communication delays are considered on the control input, measured frequency and measured power tie line flow. The delays on the measured frequency and power tie line flow from remote termi-

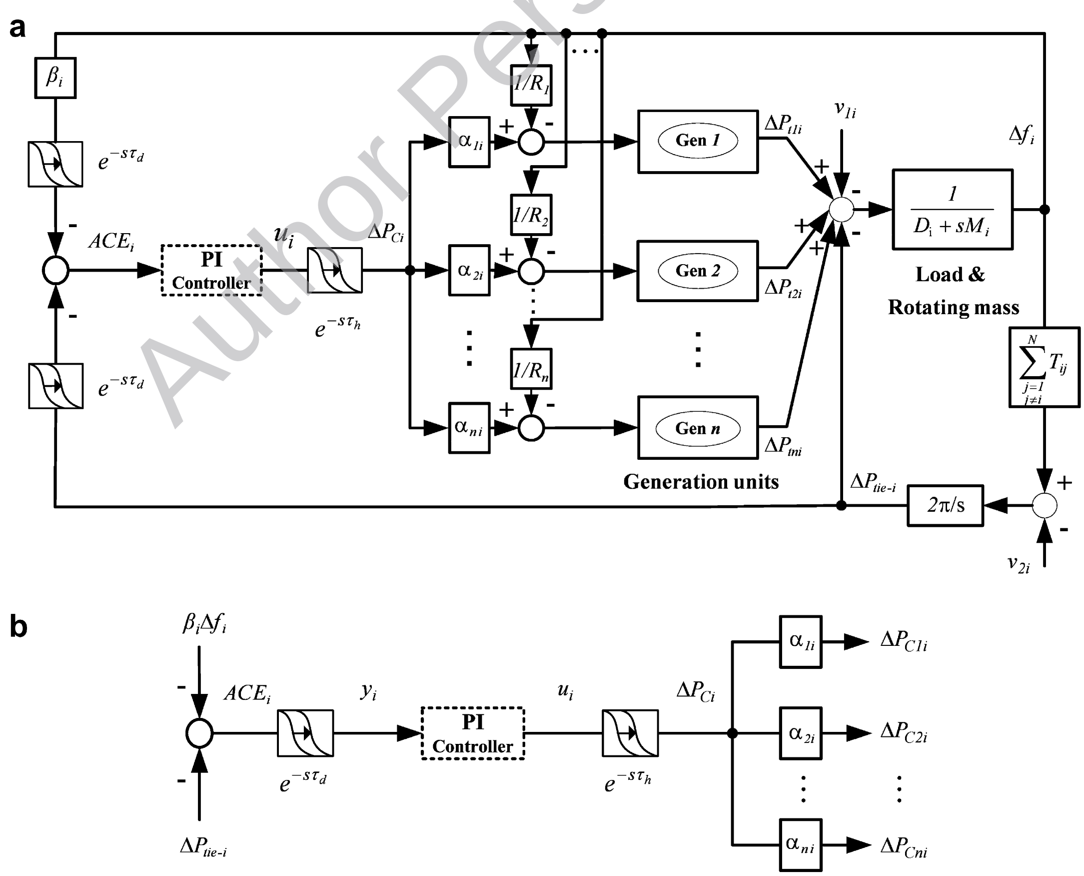

Fig. 1. (a) A general control area with time delays and (b) delays representation.

nal units (RTUs) to the control center can be easily transferred to the ACE (area control error) signal side, as shown in Fig. 1b. The delay in the control action signal is considered on the produced raise/lower signal from the control center to individual generation units.

Here, the communication delay is expressed by an exponential function $e^{-s\tau}$ 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 play and generates an appropriate control signal to make the generation follow the load. The balance between connected control areas is achieved by detecting the frequency and tie line power deviation via the communication line to generate the ACE signal used by the PI controller. The control signal is submitted to the participating generation companies (Gencos) via another link, based on their participation factors (α_{ki}).

The ACE for each control area can be expressed as a linear combination of tie line power change and frequency deviation.

$$\mathrm{ACE}_i = \beta_i \Delta f_i + \Delta P_{\text{tie}-i} \tag{1}$$

where β_i is the frequency bias coefficient. In Fig. 1, v_{1i} and v_{2i} demonstrate the area load disturbance and interconnection effects (area interface), respectively.

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

Now, according to Fig. 1a and for the purpose of applying robust control techniques, the time delayed LFC system can be obtained in the following standard state space model, which is commonly used for time delay systems.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + A_d x(t-d) + B_h u(t-h) + Fw(t) \\ z(t) &= C_1 x(t) \\ y(t) &= C_2 x(t), \quad x(t) \in \psi(t) \quad \forall t \in [-\max(d,h), 0] \end{aligned} \tag{3}$$

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 LFC 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.

2.2. Transformation from PI to SOF control

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.

$$u(t) = ky(t) \tag{4}$$

$$u(t) = k_{\mathrm{P}}\mathrm{ACE} + k_{\mathrm{I}}\int \mathrm{ACE} = [k_{\mathrm{P}} \quad k_{\mathrm{I}}][\mathrm{ACE} \quad \textstyle\int \mathrm{ACE}]^{\mathrm{T}} \tag{5}$$

where k_{P} and k_{I} are constant real numbers (PI parameters). The main merit of this transformation lies 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.

3. PI based LFC design using H_∞

Using the above transformation from PI to SOF control design, the time delayed LFC problem is reduced to synthesis of the SOF control for the time delay system Eq. (3) of the form of Eq. (4). k is a static gain to be determined. According to Eq. (3), the open loop state space model for the LFC system of control area "i" in a multi-area power system can be obtained as follows:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) + A_{di} x_i(t-d) + B_{hi} u_i(t-h) + F_i w_i(t) \\ z_i(t) &= C_{1i} x_i(t) \\ y_i(t) &= C_{2i} x_i(t) \end{aligned} \tag{6}$$

Using the standard simplified LFC model [9] for the prime mover and governor in Fig. 1, the state variables can be considered as follows:

$$x_i^{\mathrm{T}} = [\Delta f_i \quad \Delta P_{tie-i} \quad \textstyle\int ACE_i \quad x_{ti} \quad x_{gi}] \tag{7}$$

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

$$y_i^{\mathrm{T}} = [ACE_i \quad \textstyle\int ACE_i], \quad u_i = \Delta P_{Ci} \tag{8}$$

$$z_i^{\mathrm{T}} = [\xi_{1i}\Delta f_i \quad \xi_{2i}\textstyle\int ACE_i] \tag{9}$$

$$w_i^{\mathrm{T}} = [v_{1i} \quad v_{2i}] \tag{10}$$

The ξ_{1i} and ξ_{2i} are constant weights that must be chosen by the designer to get a desired closed loop performance. In Eq. (6), the following matrices and parameters are defined:

$$A_i = \begin{bmatrix} A_{i11} & A_{i12} & A_{i13} \\ A_{i21} & A_{i22} & A_{i23} \\ A_{i31} & A_{i32} & A_{i33} \end{bmatrix}, \quad A_{di} = \begin{bmatrix} A_{i11} & 0_{3\times n} & 0_{3\times n} \\ 0_{n\times 3} & 0_{n\times n} & 0_{n\times n} \\ A_{i31} & 0_{n\times n} & 0_{n\times n} \end{bmatrix},$$

$$B_i = \begin{bmatrix} B_{i1} \\ B_{i2} \\ B_{i3} \end{bmatrix}, \quad B_{hi} = B_i, \quad F_i = \begin{bmatrix} F_{i1} \\ F_{i2} \\ F_{i3} \end{bmatrix}$$

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

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

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

$A_{i22} = -A_{i23} = diag[-1/T_{t1i} \;\; -1/T_{t2i} \;\; \cdots \;\; -1/T_{tni}]$
$A_{i33} = diag[-1/T_{g1i} \;\; -1/T_{g2i} \;\; \cdots \;\; -1/T_{gni}]$,

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

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

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

where ΔP_{gi} is the governor valve position, T_{gi} is the governor time constant and T_{ti} is the turbine time constant.

To adapt Eq. (6) with the time delayed LFC system in Fig. 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 both the states and control input. The following theorem adapts H_∞ theory in the control synthesis for a time delayed LFC system (using LMI description) and establishes the conditions under which the SOF control law exists.

Theorem 1. *The SOF controller k asymptotically stabilizes the system Eq. (6) and* $\|T_{z\,w}\|_\infty < \gamma$ *for* $d,h \geqslant 0$ *if there exist 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 matrix inequality Eq. (11).*

$$\begin{aligned} W_s = {} & \left[A_iY + YA_i^{\mathrm{T}} + Q_t + Q_s\right] + \left[B_ikC_{2i}(B_ikC_{2i})^{\mathrm{T}} + Y^{\mathrm{T}}Y\right] \\ & + \left[A_{di}YQ_t^{-1}(A_{di}Y)^{\mathrm{T}}\right] + \left[B_{hi}kC_{2i}YQ_s^{-1}(B_{hi}kC_{2i}Y)^{\mathrm{T}}\right] \\ & + YC_{1i}^{\mathrm{T}}C_{1i}Y + \gamma^{-2}F_iF_i^{\mathrm{T}} < 0 \end{aligned} \tag{11}$$

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

Above theorem shows that to determine the SOF controller k (PI parameters), one has to solve the following minimization problem:

$$\begin{aligned} & \min_{Q_t,Q_s,Y,k} \quad \gamma \\ & \text{subject to} \quad -Y < 0, \quad -Q_t < 0, \quad -Q_s < 0, \quad W_s < 0 \end{aligned} \tag{12}$$

The matrix inequality Eq. (11) points to an iterative approach to solve k, Q_t and Q_s, namely, if Y is fixed, then it reduces to a LMI problem in the unknowns k, Q_t and Q_s. The LMI problem is 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 given in Ref. [10].

In the next section, a more relaxed control strategy is introduced to invoke the strict positive realness condition, which will be explained in Section 5. The time delay is considered as an uncertainty, and the stability and performance objectives are formulated via H_∞ and H_2 norms. Finally, a suboptimal solution is obtained using a developed ILMI algorithm.

4. PI based LFC design using H_2/H_∞

Naturally, LFC is a multi-objective control problem. LFC goals, i.e. frequency regulation and tracking load changes and maintaining tie line power interchanges to specified values in the presence of generation constraints and time delays, determines the LFC synthesis as a multi-objective control problem. Therefore, it is expected that an appropriate multi-objective control strategy would be able to give a good solution for this problem.

It is well known that each robust method is mainly useful to capture a set of special specifications. For instance, the H_2 tracking design is more adapted to deal with transient performance by minimizing the linear quadratic cost of tracking error and control input, but the H_∞ approach is more useful to maintain closed loop stability in the presence of model uncertainties [11].

A general control scheme using a mixed H_2/H_∞ control technique is shown in Fig. 2. $G_i(s)$ is a linear time invariant system with the following state space realization,

$$\begin{aligned} \dot{x}_i &= A_ix_i + B_{1_i}w_i + B_{2_i}u_i \\ z_{\infty i} &= C_{\infty i}x_i + D_{\infty 1_i}w_i + D_{\infty 2_i}u_i \\ z_{2i} &= C_{2i}x_i + D_{21_i}w_i + D_{22_i}u_i \\ y_i &= C_{yi}x_i + D_{y1_i}w_i \end{aligned} \tag{13}$$

where x_i is the state variable vector, w_i is the disturbance and other external input vector, y_i is the measured output vector and K_i is the controller gain. The output channel z_{2i} is associated with the LQG aspects (H_2 performance) while the output channel $z_{\infty i}$ is associated with the H_∞ performance. Let $T_{z_{\infty i}w_{1i}}$ and $T_{z_{2i}w_{2i}}$ be the transfer functions from w_{1i} and w_{2i} to $z_{\infty i}$ and z_{2i}, respectively, and consider the following state space realization for the closed loop system.

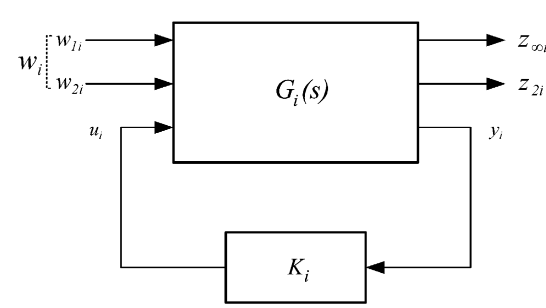

Fig. 2. Closed loop system via mixed H_2/H_∞ control.

$$\begin{aligned}\dot{x}_i &= A_{ic}x_i + B_{1_{ic}}w_i \\ z_{\infty i} &= C_{\infty ic}x_i + D_{\infty_{ic}}w_i \\ z_{2i} &= C_{2ic}x_i + D_{2_{ic}}w_i \\ y_i &= C_{y_{ic}}x_i + D_{y_{ic}}w_i\end{aligned} \tag{14}$$

A mixed H_2/H_∞ SOF control design can be expressed as the following optimization problem: Determine an admissible SOF law k_i, belonging to a family of internally stabilizing SOF gains K_{sof},

$$u_i = k_i y_i, \quad k_i \in K_{\text{sof}} \tag{15}$$

such that

$$\inf_{K_i \in K_{\text{sof}}} \|T_{z_{2i}w_{2i}}\|_2 \text{subject to } \|T_{z_{\infty i}\ w_{1i}}\|_\infty < 1 \tag{16}$$

4.1. Proposed control framework

Here, the LFC synthesis problem with time delay is formulated as a mixed H_2/H_∞ SOF control problem to obtain the appropriate PI controller. Specifically, the H_∞ performance is used to meet the robustness requirement of the closed loop system against communication delays (as uncertainties). The H_2 performance is used to satisfy the other LFC performance objectives, e.g. minimizing the effects of load disturbances on area frequency and ACE and penalizing fast changes and large overshoot in the governor load set point.

The overall control framework to formulate the time delayed LFC problem via a mixed H_2/H_∞ control design is shown in Fig. 3. It is easy to find the state space realization of each control area in the form of Eq. (13). The states can be considered as given in Eq. (7), and

$$w_i^{\mathrm{T}} = [\,w_{1i} \quad w_{2i}\,], \quad w_{2i}^{\mathrm{T}} = [\,v_{1i} \quad v_{2i}\,] \tag{17}$$

The output channel $z_{\infty i}$ is associated with the H_∞ performance while the fictitious output vector z_{2i} is associated with LQG aspects of H_2 performance. η_{1i}, η_{2i} and η_{3i} are constant weights that must be chosen by the designer. $G_i(s)$ is the nominal dynamic model of the given control area, y_i is the augmented measured output vector (performed by ACE and its integral), u_i is the control input and w_i includes the perturbed and disturbance signals in the given control area.

The fictitious output $\eta_{3i}\Delta P_{Ci}$ sets a limit on the allowed control signal to penalize fast changes and large overshoot in the governor load set point with regards to the practical constraint on power generation by generator units [12]. The H_∞ performance is used to meat the robustness requirement against specified uncertainties due to communication delays and reduction of its impact on the closed loop system performance.

Similar to the power system dynamic model uncertainties [13,14], the uncertainties due to time delays can be modeled as an unstructured multiplicative uncertainty block that contains all possible variations in the assumed delays range. Fig. 4 shows the simplified open loop system

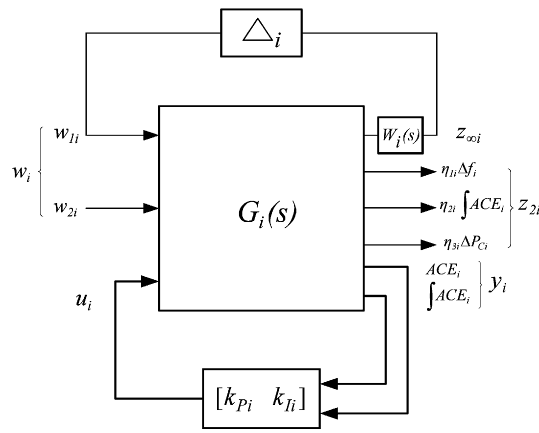

Fig. 3. H_2/H_∞ SOF control framework.

after modeling the time delays as a multiplicative uncertainty. Δ_i shows the uncertainty block corresponding to delayed terms and W_i is the associated weighting function. $G_i(s)$ is the nominal transfer function model.

The optimization problem given in Eq. (16) defines a robust performance synthesis problem where the H_2 norm is chosen as the performance measure. Here, an ILMI algorithm is introduced to get a suboptimal solution for the above optimization problem. Specifically, the developed algorithm formulates the H_2/H_∞ SOF control through a general SOF stabilization problem. The proposed algorithm searches the desired suboptimal H_2/H_∞ SOF controller k_i within a family of H_2 stabilizing controllers K_{sof}, such that

$$|\gamma_2^* - \gamma_2| < \varepsilon, \quad \gamma_\infty = \|T_{z_{\infty i}\ w_{1i}}\|_\infty < 1 \tag{18}$$

where ε is a small real positive number, γ_2^* is the H_2 performance corresponding to the H_2/H_∞ SOF controller k_i and γ_2 is the optimal H_2 performance index, which can result from application of standard H_2/H_∞ dynamic output feedback control.

In the proposed strategy, based on the generalized static output stabilization feedback lemma [15], first, the stability domain of (PI parameters) space, which guarantees the stability of the closed loop system, is specified. In the second step, the subset of the stability domain in the PI parameter space in step one is determined so that the H_2 tracking performance is minimized. Finally, and in the third step, the design problem becomes, in the previous subset domain, what is the point with the closest H_2 performance index to the optimal one that meets the H_∞ constraint.

The proposed algorithm, which is described in Fig. 5, gives an iterative LMI suboptimal solution for the above optimization problem. The main effort is to formulate the

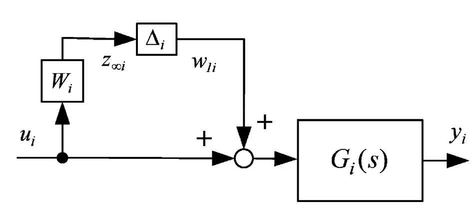

Fig. 4. Modeling the time delays as multiplicative uncertainty.

H_2/H_∞ problem via the generalized static output stabilization feedback lemma such that all eigenvalues of $(A\text{-}BKC)$ shift towards the left half plane (LHP) through the reduction of a_i, a real number, to close to the feasibility of Eq. (16).

4.2. Weights selection (η_i, W_i)

As has been mentioned, $\eta_i = [\eta_{1i} \quad \eta_{2i} \quad \eta_{3i}]$ is a constant weight vector that must be chosen by the designer to get a desired closed loop performance. The selection of these performance weights is dependent on the specified LFC

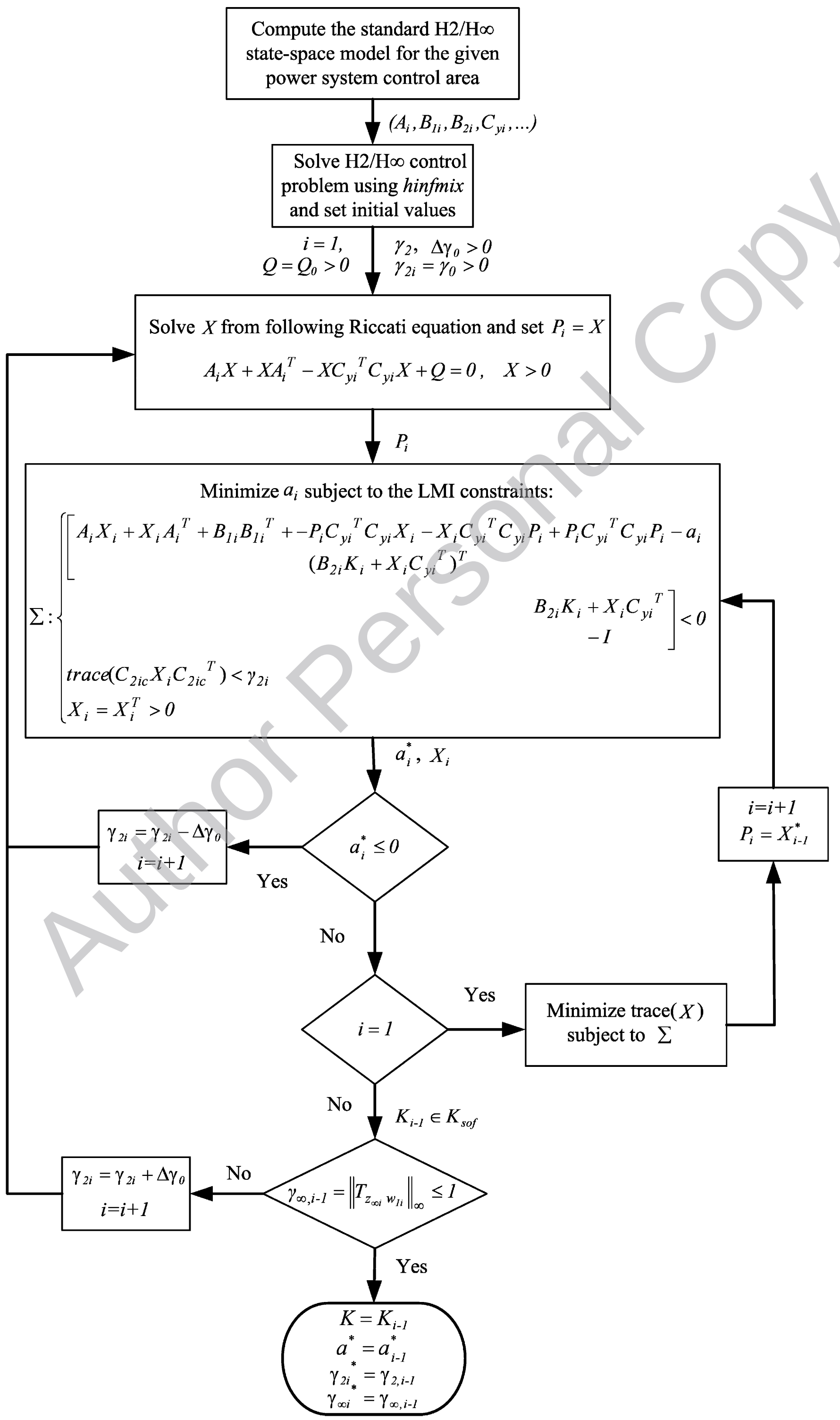

Fig. 5. Iterative LMI algorithm.

performance objectives. In fact, an important issue with regard to selection of these weights is the degree to which they can guarantee satisfaction of the design performance objectives. The selection of weights entails a trade off among several performance requirements. Coefficients η_{1i} and η_{2i} as controlled outputs set the performance goals (tracking the load variation and disturbance attenuation), while η_{3i} sets a limit on the allowed control action to penalize fast change and large overshoot in the governor load set point signal. As another alternative to select the mentioned weights, the designer can fix the weights η_{1i}, η_{2i} and η_{3i} to unity and use the method with regional pole placement technique for performance tuning [16].

For computing weight function W_i in each control area, let us consider $\widehat{G}_i(s)$ as the transfer function from the control input u_i to the control output y_i at operating points other than the nominal point. According to Fig. 4, following a practice common in robust control, we can represent this transfer function as

$$|\Delta_i(s)W_i(s)| = \left|[\widehat{G}_i(s) - G_i(s)]G_i(s)^{-1}\right| \tag{19}$$

where

$$\|\Delta_i(s)\|_\infty = sup_\omega|\Delta_i(s)| \leqslant 1; \quad G_i(s) \neq 0 \tag{20}$$

$G_i(s)$ is the nominal transfer function model. $\Delta_i(s)$ and $W_i(s)$ are the uncertainty block corresponding to the delayed terms and associated weighting function, respectively. The $W_i(s)$ must be considered such that its respective magnitude Bode plot covers the Bode plots of all possible time delayed structures.

5. Discussion

As has been mentioned, the complex and high order dynamic controllers are not applicable for real world load frequency control (LFC) systems. Usually, the load frequency controllers used in the industry are PI type. Since the PI controller parameters are commonly tuned online based on experiences and trial and error approaches, they are incapable of obtaining good dynamical performance for a variety of load scenarios and operating conditions.

As we know, there are hardly any results in PI based LFC design literature with time delay consideration. The design of PI based load frequency controllers is, in most cases, performed using classical tuning rules without consideration of delay impacts. On the other hand, the modern and post modern control theory including H_2 and H_∞ optimal control can not be directly applied to the PI based LFC problem. Indeed, until recently, it was not known how to even determine whether stabilization of a nominal system was possible using PI controllers [17]. Therefore, in comparison of previous works, the appropriate formulation of "time delay" in the PI based LFC design through an optimal minimization problem can be considered as a significant contribution.

The stability margin and performance specifications could be evaluated using classical analysis tools such as gain and phase margin as well as modern ones such as H_2 and H_∞ norms of closed loop transfer functions. In the proposed LFC solutions, robust performance indices, resulting from solution of the optimal H_∞ and H_2/H_∞ control synthesis, that provide strong criteria and powerful tools have been used as robust performance measures for the sake of closed loop stability and performance analysis. Since the main theme in both SOF control designs is to stabilize the overall system and guarantee the H_∞ and H_2 norms of the closed loop transfer functions, the designed load frequency controllers meet the robust specifications.

For example, in the resulting PI solution from the H_∞ based LFC design (described in Section 3), since the solution for the time delayed LFC problem is obtained through minimizing the H_∞ performance index γ subject to the given constraints in Eq. (12), the designed PI controllers satisfy robustness of the closed loop system. In other words, the basis of designing the SOF controllers Eq. (4) is to stabilize simultaneously Eq. (6) and guarantee the H_∞ norm bound γ of the closed loop transfer function $T_{z\ w}$, namely $\|T_{z\ w}\|_\infty < \gamma$; $\gamma > 0$.

Although the H_∞ based LFC design (Section 3) gives a simple design procedure, because of the following reasons, the second proposed PI based LFC design strategy (H_2/H_∞), which provides a more flexible control strategy, could be applicable for a wider range of control area power systems: (i) it is shown that the necessary condition for the existence of a solution is that the nominal transfer function

$$T(s) = kC_2[sI - A]^{-1}B \tag{21}$$

is strictly positive real (SPR) [18]; (ii) it is significant to note that because of using simple constant gains pertaining to optimal SOF synthesis for dynamical systems in the presence of strong constraints and tight objectives are few and restrictive. Under such conditions, the minimization problem Eq. (12) may not approach a strictly feasible solution.

The stability area for any controlled system is limited by a border, such that for the outside operating points, the system may go to an unstable condition. In the proposed LFC designs, the stability area is dependent on the considered range of time delay in the related LFC loop during the synthesis procedures. Therefore, in the assumed delay range, robust stability and robust performance are guaranteed for the power system control areas. However, to get a larger margin of stability, for example in the mixed H_2/H_∞ PI based LFC design, one can consider a wider range of delays by choosing a larger τ_d and τ_h (Fig. 1). As a result, it provides a new upper bound for the modeled uncertainty without any change in the design procedure.

In the view point of stability and performance analysis, it is shown that the impact of delay on the dynamic behavior of a control system is the same as the effect of a perturbation and system uncertainty [19]. Similar to unmodeled dynamic uncertainties, time delays can degrade a system's performance and stability [1–3]. That is why it could be reasonable to consider the time delay as a model uncertainty.

In the present paper, with regards to the communication issue, the general theme is based on the premise that the necessary communication software/hardware facilities are available in the power system network to receive/transmit the measurements and control signals via appropriate secure links.

A power system is an inherently nonlinear and complex system. However, since considering all dynamics in LFC synthesis and analysis may not be useful and is difficult, a simplified linear model is usually used by researchers [4,6,10,20], but it should be noted that to get an accurate perception of the LFC subject, it is necessary to consider the important inherent requirement and the basic constraints imposed by the physical system dynamics and model them for the sake of performance evaluation. For example, in a real LFC system, rapidly varying components of system signals are almost unobservable due to the various filters involved in the process. That is why the performance of a designed LFC system is dependent on how generation units respond to control signals. A very fast response for an LFC system is neither possible nor desired [12]. A useful control strategy must be able to maintain sufficient levels of reserved control range and control rate.

The effect of generation rate constraint is properly considered in the synthesis procedure to produce a smooth set point behavior. The proposed H_2/H_∞ control strategy includes enough flexibility to set a desired level of performance to cover the practical constraint on the control action signal. It is easily performed by tuning η_{3i} in the fictitious controlled output (Fig. 3). Hence, it is expected the designed controllers could be useful to perform the LFC task in a real world power system.

As has been mentioned, the power system restructuring, expanding physical setups and functionality lead to communication delays that become an important problem in future LFC synthesis and analysis. In the new environment, the classical, and even modern, delay free LFC design methods (such as conventional H_∞ based) are difficult to obtain good dynamical performance for a wide range of operating conditions. In the proposed LFC methods, an important goal was to keep the simplicity of control algorithms (as well as control structure) for computing the PI parameters among the well known LFC scheme. For reasons of simplicity, flexibility and straight forwardness of the control algorithms, we hope that this work acts as a catalyst to bridge the robust control theory-real world LFC gap as well as the classical–modern LFC design gap.

6. Application to a three control area power system

To illustrate the effectiveness of the proposed control strategy, a three control area power system, shown in Fig. 6, is considered as a test system. It is assumed that each control area includes three Gencos. The power system parameters are considered to be the same as in Refs. [10,20].

6.1. H_∞ based LFC controllers

Based on a simple stability condition [21], the open loop system Eq. (6) with real matrices is stable if

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

where

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

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 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 the synthesis methodology described in Section 3, a set of three decentralized robust PI controllers are obtained as shown in Table 1. For all control area constant weights ξ_1 and ξ_2 are fixed at 0.5 and 1, respectively.

6.2. H_2/H_∞ based LFC controllers

Using Eqs. (19) and (20), some sample uncertainties due to delays variation for area 1 within the following delays range are shown in Fig. 7.

$$\tau_{di} \in [0 \quad 3]\mathrm{s}, \quad \tau_{hi} \in [0 \quad 3.5]s \tag{24}$$

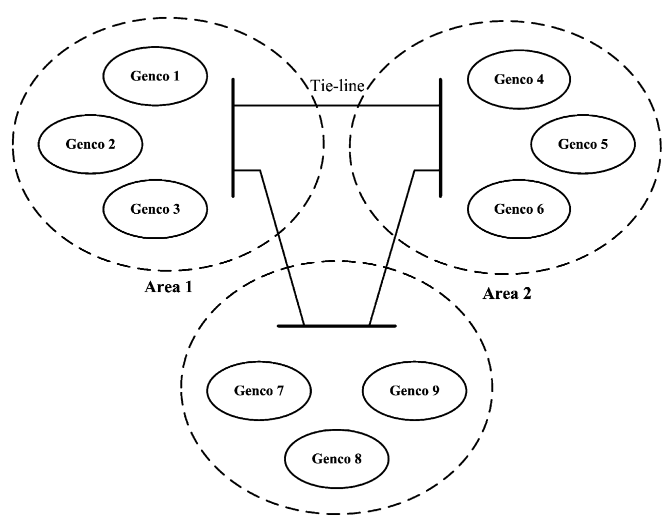

Fig. 6. Three control area power system.

Table 1
PI control parameters using the H_∞ control design

Parameters	Area 1	Area 2	Area 3
k_{Pi}	0.0250	0.0396	0.0308
k_{Ii}	−0.1888	−0.2520	−0.2753

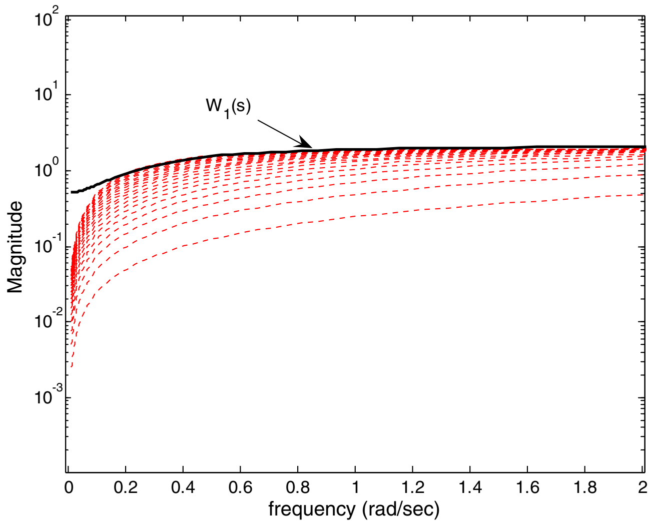

Fig. 7. Uncertainty plots (dotted) due to communication delays and the upper bound (solid) in area 1.

Table 2
PI control parameters from ILMI design

Parameters	Area 1	Area 2	Area 3
k_{Pi}	−0.2728	−0.1475	−0.2142
k_{Ii}	−0.2296	−0.1773	−0.2397

Specifically, to obtain the uncertainty curves, Eq. (19) is to be solved for some different points in the assumed delay range Eq. (24). To keep the complexity of the design procedure low, we can model the uncertainties from both delayed channels by using a norm bonded multiplicative uncertainty to cover all possible plants as follows:

$$W_1(s) = \frac{2.1339s + 0.2557}{s + 0.4962}$$

Fig. 7 shows that the chosen weight W_1 provides a little conservative design at low frequencies; however, it provides a good trade off between robustness and design complexity.

Using the same method, the uncertainty weighting functions for areas 2 and 3 are computed.

$$W_2(s) = \frac{2.0558s + 0.2052}{s + 0.3869}, \quad W_3(s) = \frac{2.0910s + 0.2129}{s + 0.5198}$$

For the example at hand, the time delay of communication channels is considered near the LFC cycle rate. However, as has been mentioned, one can consider a wider range of delays by choosing a larger τ_d and τ_h. As a result, it provides a new upper bound for the modeled uncertainty without any change in the design procedure. According to the synthesis methodology described in Section 4, a set of three decentralized robust PI controllers are designed as shown in Table 2.

7. Simulation results

In order to demonstrate the effectiveness of the proposed strategies, some nonlinear simulations were performed. In these simulations, the proposed PI controllers were applied to the three control area power system described in Fig. 6. The performance of the closed loop system in comparison with the designed robust H_∞ PI based controllers for the delayless nominal system given in Ref. [10], 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 here, case studies of fixed delays are used.

In order to project the physical constraint during simulation, a nonlinear model, shown in Fig. 8, is used for each generator unit considering the generation rate constraint. The upper and lower limits (U_i, L_i) of the nonlinear saturation operator [22,23] are chosen as 0.05 pu/min and −0.20 pu/min, respectively. For scenario 1, the power system is tested in the presence of assumed maximum total communication delays Eq. (24), that is 6.5 s following a 0.01 pu step load disturbance at 5 s in each control area. The closed loop system response including frequency deviation (Δf), area control error (ACE), control action signal (ΔP_c) and generated power (ΔP_m) are shown in Fig. 9. Both designed PI controllers act to return the frequency and ACE signals to the scheduled values properly, however, the conventional H_∞ PI controllers are not capable to hold the stability of the closed loop system. In the used simulation environment, the mentioned delays lead to instabilities in the system (of course, in the actual system, the existing protection and other control logics may prevent such response).

Fig. 9c shows the changes in power coming to areas 1 and 2 from their Gencos according to their participation factors (α) listed in Table 3. It is seen that although Genco 5 does not contribute to the LFC task, since its dynamics is considered in the interconnection, the frequency deviation due to a step change of load in all areas is sensed by its speed governor. The simulation result illustrates the ability of the proposed PI based mixed H_2/H_∞ control design in comparison with the H_∞ control design to satisfy the robustness of the time delayed LFC system. Although, because of considering the time delays as unstructured uncertainties, the mentioned method provides a conservative design, it gives a good trade off among the specified objectives using the H_2 and H_∞ performances.

For scenario 2, a set of random load patterns shown in Fig. 10a (representing expected load fluctuations in real power systems) with the assumed total delay in scenario 1

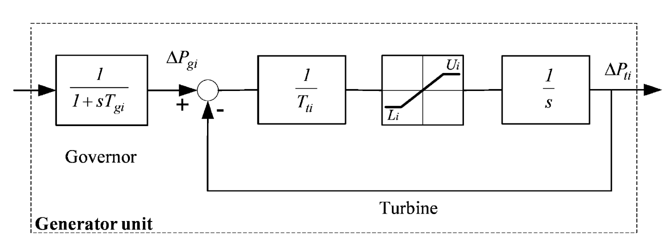

Fig. 8. Model of a generator unit in the proposed nonlinear simulation.

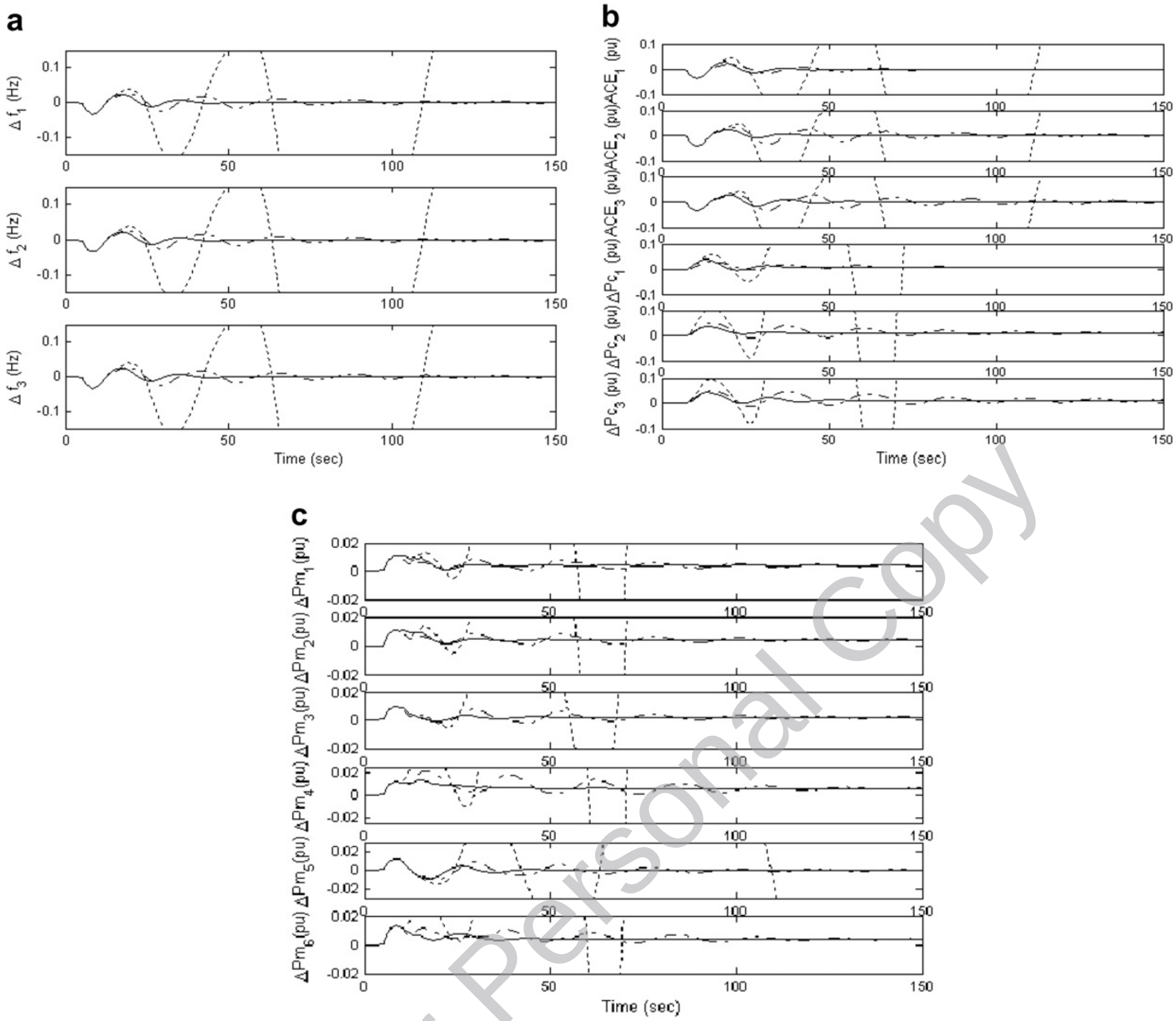

Fig. 9. System response for scenario 1. Solid (H_2/H_∞), dash–dotted (H_∞), dotted (delayless H_∞ [10]): (a) frequency deviation, (b) ACE and control effort and (c) mechanical power change (in areas 1 and 2).

(6.5 s) are applied to the three control areas. Using the delaylees H_∞ design, the system is unstable. For the designed controllers, the closed loop system response (frequency deviations, governor load set points, area control error and mechanical power changes are shown in Fig. 10). This figure shows the frequency deviation and area control error of all control areas are properly maintained within a narrow band using smooth control efforts.

Simulation results show that the designed controllers can ensure good performance despite load disturbance and indeterminate delays in the communication network. The proposed nonlinear simulation shows the robust PI controllers act properly to maintain area frequency and total exchange power close to the scheduled values by sending corrective smooth signals to the Gencos in proportion to their participation in the LFC task. Simulation (some results are given in this paper) also shows that these controllers perform well for a wide range of operating conditions considering the load fluctuation and communication delays.

Table 3
Participation factors

Genco	1	2	3	4	5	6	7	8	9
α	0.4	0.4	0.2	0.6	0.0	0.4	0.0	0.5	0.5

8. 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, two robust decentralized design methodologies are proposed. In the first control design, the optimal H_∞ control is used via a multi-constraint minimization problem. In the second control design, a flexible methodology is developed to invoke the existing strictness. The time delay is

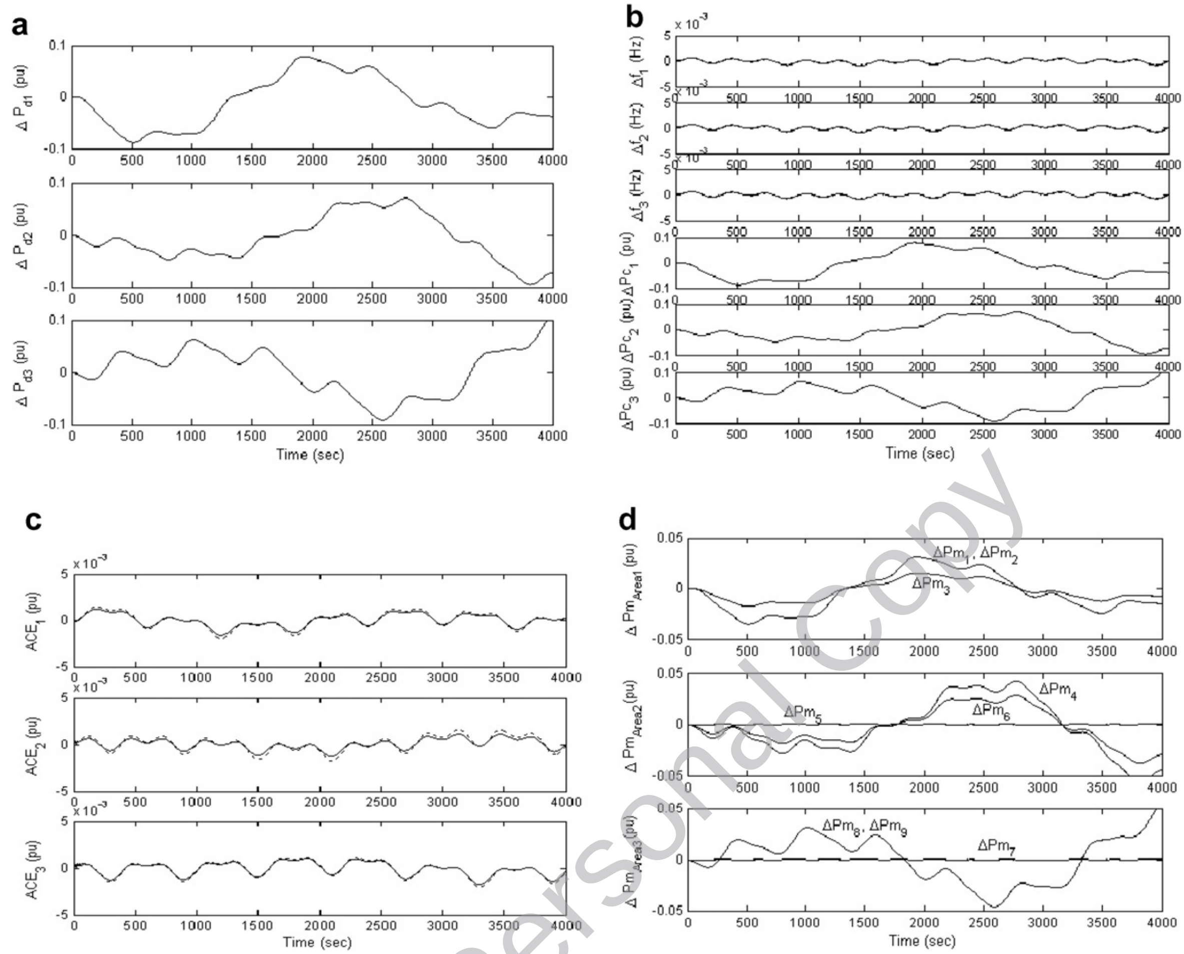

Fig. 10. System response for scenario 2. Solid (H_2/H_∞), dash–dotted (H_∞): (a) random load patterns, (b) frequency deviation and control effort, (c) ACE signals and (d) mechanical power changes.

considered as a model uncertainty, and the H_2/H_∞ control is used via an ILMI algorithm to approach a suboptimal solution for the assumed design objectives. Simplicity of control structure, keeping the fundamental LFC concepts, using multi-delay based LFC system and no need of additional controller can be considered as advantages of the proposed methodologies. The proposed methods were applied to a three control area power system, and using nonlinear simulation, the results are compared with the results of conventional (delayless) H_∞ control design.

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