On Market-based Robust Load-frequency Control

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Abstract

In a deregulated environment, Load-frequency control (LFC), as an ancillary service essential for maintaining the system reliability, 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, a reevaluation in traditional modeling and control structures is highly needed. In response to the coming challenge of integrating computation, communication and control into appropriate levels of system operation and control, a comprehensive scenario is proposed to perform the LFC task in a deregulated environment.

As a part of the mentioned scenario, this paper addresses a new method to design of robust LFC with considering the communication delays. First 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 via a mixed H_2/H_∞ control technique, using a developed iterative linear matrix inequalities (ILMI) algorithm. The proposed method is applied to a 3-control area power system and the results are compared with the recently developed H_∞-based LFC designs.

1. Introduction

In a liberalized electricity market, control is highly decentralized. Each load matching contract requires a separate control process, yet this control processes must cooperatively interact to maintain system frequency and minimize time error. Since a separate control process is needed for each load matching contract, there must be a Virtual Control Area (VCA) associated with each contract group. Therefore, the concept of physical control area is replaced by VCA. The boundary of the VCA encloses the generation companies (Gencos) and the distribution companies (Discos) associated with the contract. The Discos receive the regulating power directly or through transmission companies (Transcos). Such an overall configuration is shown conceptually in Fig. 1. Each VCA will be interconnected to each other either through Transco or Gencos.

The control center includes two agents: Data Acquisition and Monitoring (DAM) agent, and, Decision and Control (DC) agent. The Gencos send the bid regulating reserves $Fi(\$,t)$ to the DAM agent through a secure internet service. The DAM agent sorts these bids by pre-specified time period and price. Then, it sends the sorted regulating reserves with the demanded load from Discos and the measured tie-line flow and area frequency to

the DC agent, continuously. DC agent checks and resorts the bids according the congestion condition and screening of available capacity. Then DC agent performs the Area Control Error (ACE) signal and the participation factors $\alpha_i(t)$ in order to load following by the available Gencos to cover the total contracted load demand $\sum \Delta P_{Li}(t)$ and local load disturbance $\Delta P_{di}(t)$ [1].

It is assumed that in a VCA, the necessary hardware and communication facilities to enable reception of data and control signals are available and Gencos can bid up and down regulations by price and MW-volume for each predetermined time period T to the regulating market. Also the control center can distributes load demand signals to available generating units on a real-time basis.

The participation factors which are actually time dependent variables, must be computed dynamically by DC agent based on the received bid prices, availability, congestion problem and other related costs in case of using each applicant (Genco). An appropriate computation method for the participation factors and desired optimization algorithms for the mentioned agents have been already proposed by authors [2]. In continuation, this paper focuses on designing the "Controller" unit (in Fig. 1) considering the communication time-delays.

Technically, this unit has a very important role to guarantee a desired LFC performance. The real-world LFC systems usually 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.

In the control systems, it is well known that time delays can degrade a system's performance and even cause system instability [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 [1].

Recently, several papers are published to address the LFC modeling/synthesis in the presence of communication delays [4, 5]. Ref. [4] is focused on the communication network requirement for a third party LFC service. A control design method based on linear matrix inequalities is proposed for the LFC system with communication delays in Ref. [5].
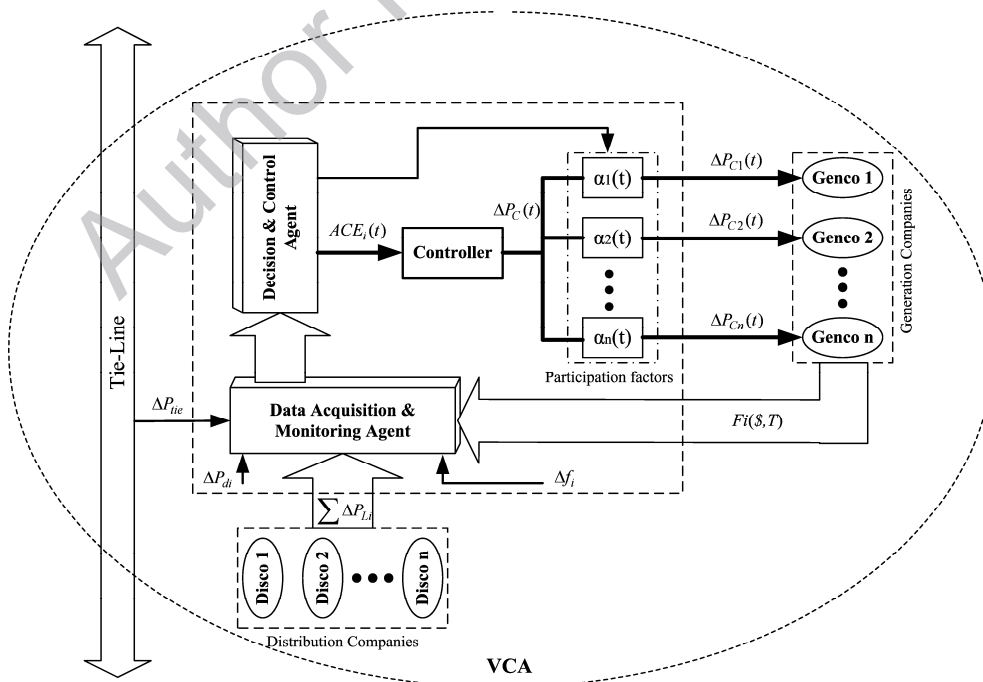

Fig. 1. Overall control framework for a market based LFC.

The most of existing methodologies suggest high-order dynamic controllers which are not common for industry practices. Ref. [6] presented an H_∞-SOF control technique to design a PI-based LFC with communication delays. But 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 addressed optimization problem may dose not give a strictly feasible solution. Furthermore, in the most of mentioned reports, only one single norm is used to capture design specifications, while meeting all LFC design objectives by single control approach with regard to increasing the complexity of power system structure and the role of time delays is difficult.

This paper proposes a new control methodology to design a decentralized LFC in face of multi-delayed signals. First the PI-based LFC design is transferred to a static output feedback (SOF) control design and then to obtain the constant PI gains, the mixed H_2/H_∞ control is used via an iterative linear matrix inequalities (ILMI) algorithm. The time-delays are considered as model uncertainties in each control area and the uncertainties are covered by an unstructured multiplicative uncertainty block.

Simplicity of control structure, using a more complete model for delayed LFC system, no need to additional controller and reach to a suboptimal solution for the assumed design objectives can be considered as advantages of the proposed methodology. This approach is applied to a 3-control area power system example.

2. Background

A general control scheme using mixed H_2/H_∞ control technique is shown in Fig. 2 [7]. $G_i(s)$ is a linear time invariant system with the following state-space realization,

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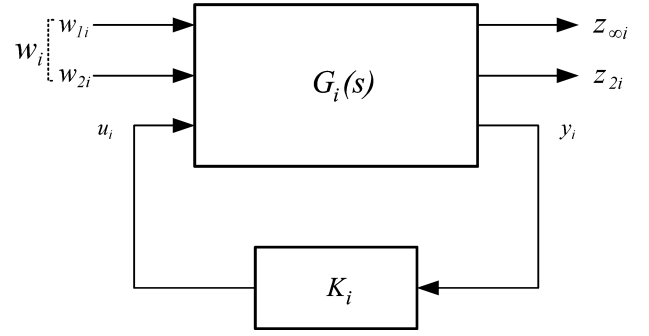y_i &= C_{yi} x_i + D_{y1_i} w_i
\end{aligned}
\tag{1}
$$

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

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. 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 $T_{z_{2i} w_{2i}}$ as the transfer functions from $w_i = [w_{1i} \ w_{2i}]^T$ to $z_{\infty i}$ and z_{2i} respectively, and consider the following state-space realization for closed-loop system.

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

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

$$
u_i = k_i y_i \ , \ k_i \in K_{sof}
\tag{3}
$$

such that

$$
\inf_{K_i \in K_{sof}} \left\| T_{z_{2i} w_{2i}} \right\|_2 \ subject \ to \ \left\| T_{z_{\infty i} w_{1i}} \right\|_\infty < 1
\tag{4}
$$

The PI-based LFC problem can be transferred to a static output feedback (SOF) control problem by augmenting the measured output signal to include the area control error (ACE) and its integral.

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

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

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.

3. Proposed control strategy

3.1 LFC with time delays

The time-delayed LFC system is well discussed in [4]. 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 (RTUs) to control center which can be considered on the ACE signal and the produced rise/lower signal from control center to individual generation units (Fig. 3).
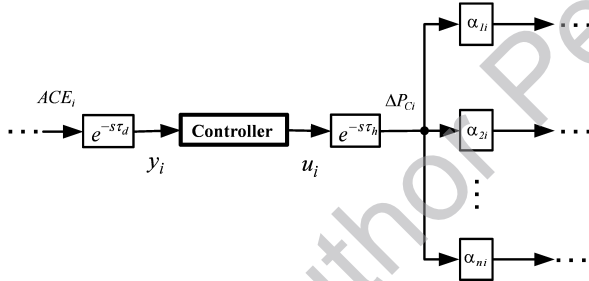

Fig. 3. Time delays.

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 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 (α_{ji}).

3.2 H_2/H_∞ -based LFC design

Using conventional linear models for governor and turbine in each generation unit, it will be easy to find the state-space realization in form of (1) for the LFC system of control area "i". Here, similar to [8], the states, inputs and output vectors are considered as follows:

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

$$x_{ti} = [\Delta P_{t1i} \quad \Delta P_{t2i} \quad \cdots \quad \Delta P_{tni}] \quad (8)$$

$$x_{gi} = [\Delta P_{g1i} \quad \Delta P_{g2i} \quad \cdots \quad \Delta P_{gni}] \quad (9)$$

$$w_i^T = [w_{1i} \quad w_{2i}], \ w_{2i}^T = [v_{1i} \quad v_{2i}] \quad (10)$$

$$u_i = \Delta P_{Ci}, \quad y_i = [ACE_i \quad \int ACE_i]^T \quad (11)$$

and

$$v_{1i} = \Delta P_{di} \quad (12)$$

$$v_{2i} = \sum_{\substack{j=1 \\ j \neq i}}^{N} T_{ij} \Delta f_j \quad (13)$$

Where, v_{1i} and v_{2i} demonstrate the area load disturbance and interconnection effects (area interface), respectively.

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_{tie-i} tie-line power changes.

Naturally, LFC is a multi-objective control problem. LFC goals, i.e. frequency regulation and tracking the load changes, maintaining the 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 could 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 H_∞ approach is more useful to holding closed-loop stability in the

presence of model uncertainties. While the H_∞ norm is natural for norm-bounded perturbations, in many applications the natural norm for the input-output performance is the H_2 norm [7].

Here, the LFC synthesis problem with time-delay is formulated as a mixed H_2/H_∞ static output feedback (SOF) control problem to obtain the appropriate PI controller. Specifically, the H_∞ performance is used to meet the robustness of 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.

Similar to the power system dynamic model uncertainties [9], the uncertainties due to time-delays can be modeled as an unstructured multiplicative uncertainty block that contains all possible variation in the assumed delays range. Let $\hat{G}_i(s)$ denotes the transfer function from the control input u_i to the control output y_i at operating points other than nominal point. Following a practice common in robust control, we can represent this transfer function as

$$\left| \Delta_i(s)W_i(s) \right| = \left| [\hat{G}_i(s) - G_i(s)]G_i(s)^{-1} \right| \quad (14)$$

where,

$$\left\| \Delta_i(s) \right\|_\infty = sup_\omega \left| \Delta_i(s) \right| \le 1; \quad G_i(s) \ne 0 \quad (15)$$

$\Delta_i(s)$ shows the uncertainty block corresponding to delayed terms and $G_i(s)$ is the nominal transfer function model. $W_i(s)$ is the associated weighting function such that its respective magnitude bode plot covers the bode plots of all possible time-delayed structures. Fig. 4 shows the simplified open-loop system after modeling the time delays as a multiplicative uncertainty.
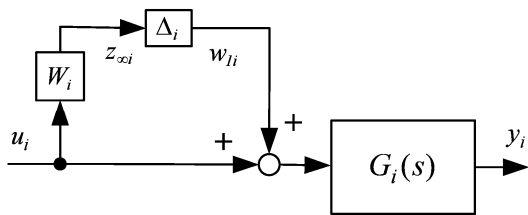

Fig. 4. Modeling the time delays as multiplicative uncertainty.

The optimization problem given in (4) 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 proposed 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

$$\left| \gamma_2^* - \gamma_2 \right| < \varepsilon, \quad \gamma_\infty = \left\| T_{z_{\infty i} w_{li}} \right\|_\infty < 1 \quad (16)$$

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

In the proposed strategy, based on the generalized static output stabilization feedback lemma [10], first the stability domain of (PI parameters) space, which guarantees the stability of closed-loop system, is specified.

In the second step, the subset of the stability domain in the PI parameter space in step one is specified so that minimizes the H_2 tracking performance. Finally and in the third step, the design problem becomes, in the previous subset domain, what is the point with closest H_2 performance index to optimal one which meets the H_∞ constraint.

The main effort, is to formulate the H_2/H_∞ problem via the generalized static output stabilization feedback lemma such that all eigenvalues of (A-BKC) shift towards the left half-plane through the reduction of a_i, a real number, to close to feasibility of (4). The proposed algorithm includes the following steps:

Step 1. Compute the state-space model (1) for the given control system.

Step 2. Compute the optimal guaranteed H_2 performance index γ_2 using function *hinfmix* in MATLAB based LMI control toolbox [11] to design standard H_2/H_∞ dynamic output controller for the performed system in step 1.

Step 3. Set $i = 1$, $\Delta\gamma_2 = \Delta\gamma_0$ and let $\gamma_{2i} = \gamma_0 > \gamma_2$. $\Delta\gamma_0$ and γ_0 are positive real numbers. Select $Q = Q_0 > 0$, and solve X from the following algebraic Riccati equation

$$A_i X + X A_i^T - X C_{yi}^T C_{yi} X + Q = 0, \quad X > 0 \quad (17)$$

Set $P_l = X$.

Step 4. Solve the following optimization problem for X_i, K_i and a_i: Minimize a_i subject to the LMI constraints:

$$\begin{bmatrix} A_i X_i + X_i A_i^T + B_{1i} B_{1i}^T + \Sigma_i & B_{2i} K_i + X_i C_{yi}^T \\ (B_{2i} K_i + X_i C_{yi}^T)^T & -I \end{bmatrix} < 0$$

$$(18)$$

$$trace(C_{2ic} X_i C_{2ic}^T) < \gamma_{2i} \quad (19)$$

$$X_i = X_i^T > 0 \quad (20)$$

where

$$\Sigma_i = \\ -P_i C_{yi}^T C_{yi} X_i - X_i C_{yi}^T C_{yi} P_i + P_i C_{yi}^T C_{yi} P_i - a_i X_i$$

Denote a_i^* as the minimized value of a_i.

Step 5. If $a_i^* \leq 0$, go to step 9.

Step 6. For $i > 1$ if $a_{i-1}^* \leq 0$, $K_{i-1} \in K_{sof}$ and go to step 10. Otherwise go to step 7.

Step 7. Solve the following optimization problem for X_i and K_i: Minimize $trace(X_i)$ subject to LMI constraints (18-20) with $a_i = a_i^*$. Denote X_i^* as the X_i that minimized $trace(X_i)$.

Step 8. Set $i = i+1$ and $P_i = X_{i-1}^*$, then go to step 4.

Step 9. Set $\gamma_{2i} = \gamma_{2i} - \Delta \gamma_2$, $i = i+1$. Then do steps 3 to 5.

Step 10. If $\gamma_{\infty, i-1} = \|T_{z_{\infty i} w_{1i}}\|_\infty \leq 1$, K_{i-1} is a suboptimal H_2/H_∞ SOF controller and $\gamma_2^* = \gamma_{2i} - \Delta \gamma_2$ indicates a lower H_2 bound such that the obtained controller satisfies (16). Otherwise go to 7.

4. Application to a 3-control area

To illustrate the effectiveness of the proposed control strategy, a three control area power system, shown in Fig. 5, 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 in [8] and [12].

Based on a simple stability condition [13], the open loop system (1) with real matrices is stable if
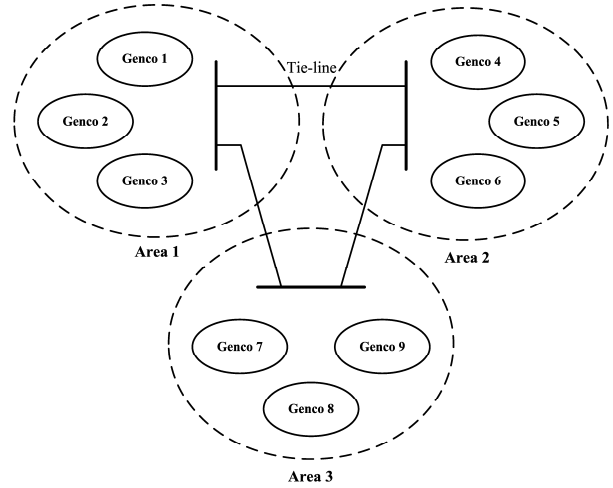
$$\mu(A_i) + \|A_{di}\| < 0 \quad (21)$$

Fig. 5. Three control area power system.

where

$$\mu(A_i) = \frac{1}{2} \max_j \lambda_j (A_i^T + A_i) \quad (22)$$

Here, A_{di} is the associated matrix with the delayed states and λ_j denotes the jth eigenvalue of $(A_i^T + A_i)$. Using above stability rule, we note that for the example at hand, the control areas are unstable:

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

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

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

The overall control framework to formulate the time-delayed LFC problem via a mixed H_2/H_∞ control design is shown in Fig. 6. It is easy to find the state-space realization of each control area in form of (1). The output channel $z_{\infty i}$ is associated with the H_∞ performance while the fictitious output vector z_{2i} is associated with LQG aspects or H_2 performance. η_{1i}, η_{2i} and η_{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 η_{1i}, η_{2i} and η_{3i} to unity and use the method with regional pole placement technique for performance tuning [14]. $G_i(s)$ 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

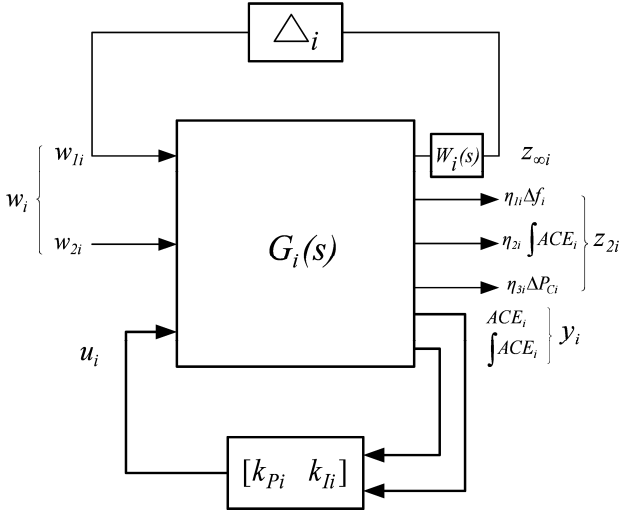w_i includes the perturbed and disturbance signals in the given control area.

Fig. 6. H_2/H_∞ SOF control framework.

The H_2 performance is used to minimize the effects of disturbances on area frequency and area control error by introducing appropriate fictitious controlled outputs. Furthermore, 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 practical constraint on power generation by generator units [15]. The H_∞ performance is used to meat the robustness against specified uncertainties due to communication delays and reduction of its impact on the closed-loop system performance.

Using (14), some sample uncertainties due to delays variation for area 1, within the following delays range, are shown in Fig. 7.

$$\tau_{di} \in [0 \quad 2.5]\,s\ ,\ \ \tau_{hi} \in [0 \quad 3.0]\,s \qquad (23)$$

To keep the complexity of design procedure low, we can model 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.

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

The selection of performance constant weights η_{1i}, η_{2i} and η_{3i} is dependent on specified performance objectives. In fact an important issue with regard to selection of these weights is the degree to which they can guarantee the satisfaction of design performance objectives. The selection of weights entails a trade off among several performance requirements [12]. The coefficients η_{1i} and η_{2i} at controlled outputs set the performance goals (tracking the load variation and disturbance attenuation).
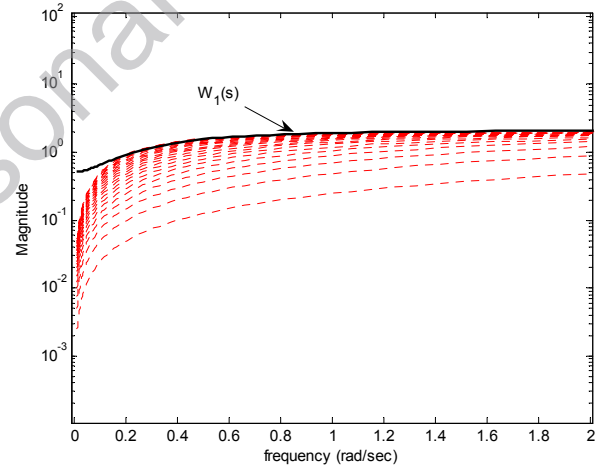

Fig. 7. Uncertainty plots (dotted) due to communication delays and the upper bound (solid) in area 1.

The proposed control strategy includes enough flexibility to set a desired level of performance to cover the practical constraint on control action signal. It is easily carried out by tuning of η_{3i} in the fictitious controlled output (Fig. 6). η_{3i} sets a limit on the allowed control action to penalize fast change and large overshoot in the governor load set-point signal. Here, the constant weights are considered to be the same as in [12].

According to the synthesis methodology described in sections 3, a set of three decentralized robust PI controllers are designed as shown in table 1.

Table 1. 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

5. Simulation results

In order to demonstrate the effectiveness of the proposed strategies, some simulations were carried out. In these simulations, the proposed PI controllers were applied to the three control area power system described in Fig. 5. The performance of the closed-loop system in comparison of designed robust H_∞-PI based controllers for the time-delayed [6] and delay-less (nominal) [12] systems, is tested in the presence of load disturbances and uncertainties.

Two types of communication delays, fixed and random, are simulated. To simply the presentation and because of space limitation here, case studies of fixed delays are used. Fig. 8 shows the closed-loop response (frequency deviation, ACE and control action signal) in face of delays,

$$\tau_{di} = 0.5\,\text{s} \; , \; \tau_{hi} = 1\,\text{s} \qquad ; \qquad i = 1,2,3$$

following a *0.1 pu* step load disturbance at *5s* in each control area. Both designed PI controllers act to return the frequency and ACE signals to scheduled values properly, however the applied delays degrade the system performance for delay-less conventional robust H_∞-PI ([12]) control design.

Increasing the delays will degrade the conventional LFC system performance seriously. F.g 9 shows the closed-loop system response in the presence of following delays in communication channels:

$$\tau_{di} = 1.5\,\text{s} \; , \; \tau_{hi} = 2\,\text{s} \qquad ; \qquad i = 1,2,3$$

It shows that the conventional H_∞-PI controllers are not capable to hold the stability of the closed-loop system. In the simplified models used, above delays lead to instabilities in the system (of course, in the actual system, the existing protection and control logics may prevent such response).
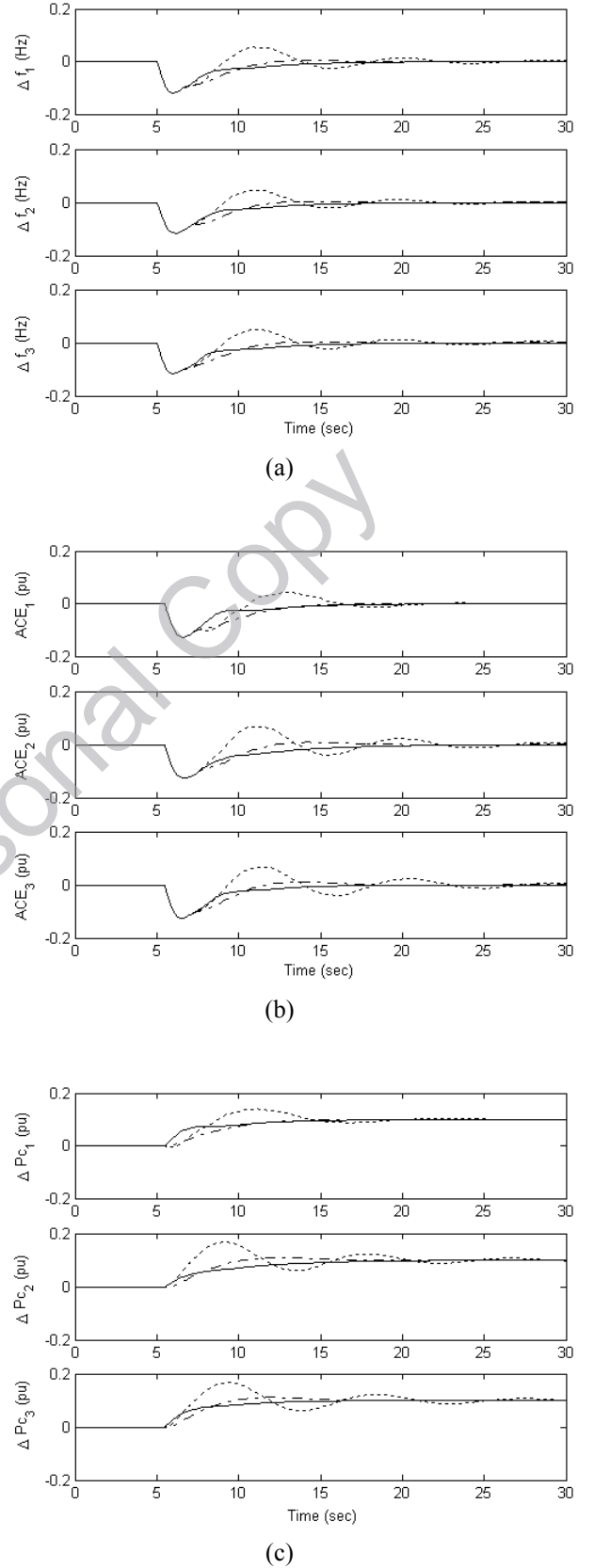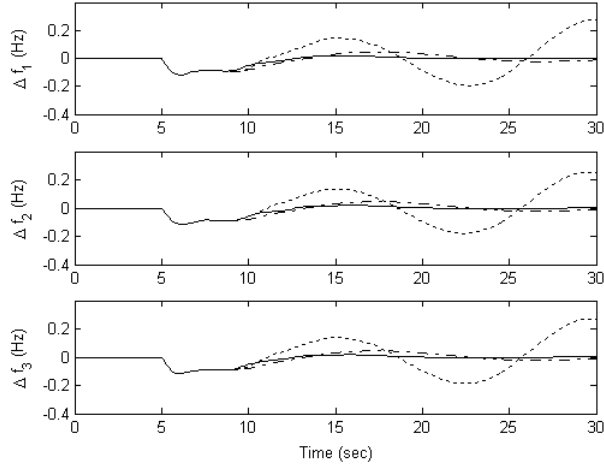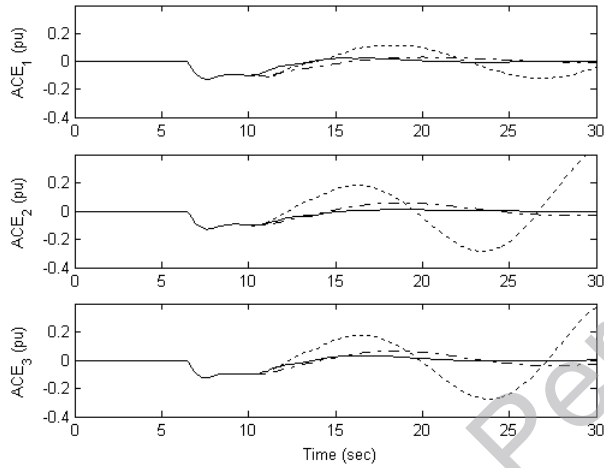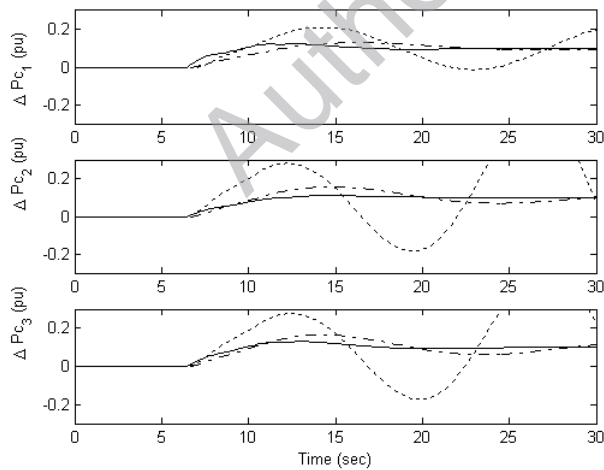

(a)

(b)

(c)

Fig. 8. System response for $\tau_{di} = 0.5\,\text{s}, \tau_{hi} = 1\,\text{s}$. Solid ($H_2/H_\infty$), dash-dotted ([6]), dotted ([12]): a) frequency deviation, b) ACE and c) control effort.

(a)

(b)

(c)

Fig. 9. System response for $\tau_{di} = 1.5$ s $, \tau_{hi} = 2$ s . Solid (H_2/H_∞), dash-dotted ([6]), dotted ([12]): a) frequency deviation, b) ACE and c) control effort.

As an other sever condition, the performance of the power system is tested in face of the assumed maximum delays in the communication channels (23) following a *0.1 pu* step load disturbance in each control area. Frequency deviations for the control areas are shown in Fig. 10. This figure shows that (like as Fig. 9) the closed-loop system to be unstable using the conventional H_∞-PI control design. Moreover, it clearly illustrates the ability of the proposed PI-based mixed H_2/H_∞ control design in comparison with the H_∞ control design [6] to satisfy the robustness of time-delayed LFC system.

Although, because of considering the time delays as structured uncertainties, the mentioned method provides a conservative design, but it gives a good trade-off among the specified objectives using the H_2 and H_∞ performances.

The proposed controllers require only local ACE signal. Simulation results show that the designed controllers can ensure good performance despite load disturbance and indeterminate delays in the communication network. Simulation also show that these controllers perform well for a wide range of operating condition considering the load fluctuation and a variety of delays including fixed delay, as shown here, and random delays.
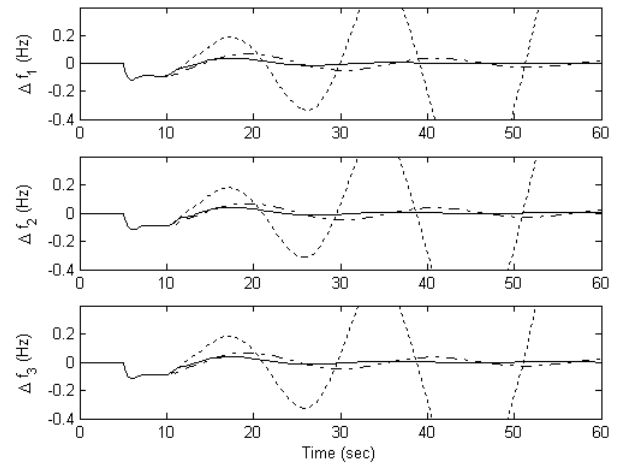

Fig. 10. System response for $\tau_{di} = 2.5$ s $, \tau_{hi} = 3.0$ s . Solid (H_2/H_∞), dash-dotted ([6]), dotted ([12]).

6. Conclusion

The LFC problem with communication delays in a multi-area power system is formulated as a

decentralized multi-objective optimization control problem. An H_2/H_∞ SOF-based iterative LMI algorithm is developed to design a set of simple PI controllers, which are useful in the real-world power systems. The proposed method was applied to a three control area power system and the results are compared with the results of applied with delay less power system with robust H_∞ based PI controllers.

Acknowledgments

References

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