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AUTOMATIC GENERATION CONTROL: A DECENTRALIZED ROBUST APPROACH

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ABSTRACT—Automatic Generation Control (AGC) problem has been one of the major subjects in electric power system design/operation and is becoming much more significant today in accordance with increasing size, changing structure and complexity of interconnected power systems. In practice, AGC systems use simple proportional-integral (PI) controllers. However, since the PI controller parameters are usually tuned based on classical or trial-and-error approaches, they are incapable of obtaining good dynamical performance for a wide range of operating conditions and various load changes scenarios in a multi-area power system.
In this paper, in order to design a robust PI controller for the AGC in a multi-area power system, first the problem is formulated as an H_∞ static output feedback control problem, and then it is solved using a developed iterative linear matrix inequalities algorithm to get an optimal performance index. A three control area power system example with a wide range of load changes is given to illustrate the proposed approach and the results are compared with H_∞ dynamic output feedback control design.

Key Words: Power system, AGC, static output feedback control, H_∞ control, linear matrix inequalities, robust performance

NOTATIONS

Δf_i	frequency deviation
ΔP_{gi}	governor valve position
ΔP_{ci}	governor load setpoint
ΔP_{ti}	turbine power

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ΔP_{tie-i}	net tie-line power flow
ΔP_{di}	area load disturbance
M_i	equivalent inertia constant
D_i	equivalent damping coefficient
T_{gi}	governor time constant
T_{ti}	turbine time constant
T_{ij}	tie-line synchronizing coefficient between area *i* and *j*
B_i	frequency bias
R_i	drooping characteristic
α	ACE participation factor
$\Delta P_{tie\text{-}i}$	tie-line power changes

1. INTRODUCTION

In a restructured power system, vertically integrated utilities (VIU) no longer exist, however the common objectives for AGC system, i.e. restoring the frequency and the net interchanges to specified values for each control area are remained [1]. Currently, AGC acquires a fundamental role to enable power exchanges and to provide better conditions for the electricity trading. During the recent decade several AGC scenarios are proposed to adapt well-tested conventional AGC scheme to the changing environment of power system operation under deregulation [2-5]. In the new environment, generation companies (Gencos) submit their ramp rates (Megawatts per minute) and bids to the market operator. After a bidding evaluation, those Gencos selected to provide regulation service must perform their functions according to the ramp rates approved by the responsible organization.

In the past two decades, there has been continuing interest in designing AGC with better performance to maintain the frequency and to keep tie-line power flows within pre-specified values, using various decentralised robust and optimal control methods [6-13]. But most of them suggest complex state-feedback or high-order dynamic controllers, which are not practical for industry practices. Furthermore, some references have used untested AGC frameworks, which may have some difficulties to implement in real-world power systems. Usually, the existing AGC systems in the practical power systems use the proportional-integral (PI) type controllers that are tuned online based on classical and trial-and-error approaches.

Recently, some control methods are applied to design of decentralised robust PI or low order controllers in order to solve the AGC problem [14-17]. A method for PI control design which uses a combination of H∞ control and genetic algorithm techniques for tuning the PI parameters is reported in [14]. [15] gives a sequential decentralized technique based on μ-synthesis and analysis to obtain a set of low order robust controllers. [16] Introduces a decentralised AGC method using structured singular values. [17] has used the Kharitonov's theorem and its results to solve the same problem.

In this paper, the decentralised AGC problem is formulated as an H∞ control problem to obtain the PI controller via a static output feedback (SOF) control design. An iterative linear matrix inequalities (ILMI) algorithm is used to compute the PI parameters.

The proposed strategy is applied to a three control area example. The obtained robust PI controllers are compared with the H∞ dynamic output feedback controllers (using standard LMI-based H∞ technique) and those are proposed in [14]. The results show the controllers guarantee the robust performance for a wide range of operating conditions as well as high order H∞ controllers. This paper is organized as follows: The AGC structure in a deregulated environment and a suitable dynamical model are given in section 2. Section 3 presents the proposed control strategy and problem formulation for a given control area. The developed methodology is applied to a three control area power system as a case study, in section 4. Finally to demonstrate the effectiveness of the proposed control strategy, some simulation results for a set of serious load disturbance scenarios are given in section 5.

2. AUTOMATIC GENERATION CONTROL

2.1 AGC in a deregulated power system

In an open energy market, generation companies (Gencos) may or may not participate in the AGC task, therefore the control strategies for new structure with a few number of AGC participators are not such straight than those for vertically integrated utility structure. Technically, this problem will be more important as Independent Power Producers (IPPs) get into the electric power markets [18].

In response to the new challenge of integrating computation, communication and control into appropriate levels of system operation and control, a comprehensive scenario is proposed to perform the AGC task in a deregulated environment. The overall control framework is conceptually shown in Figure 1. The boundary of control area encloses the generation companies (Gencos) and the distribution companies (Discos) associated with the performed contracts.

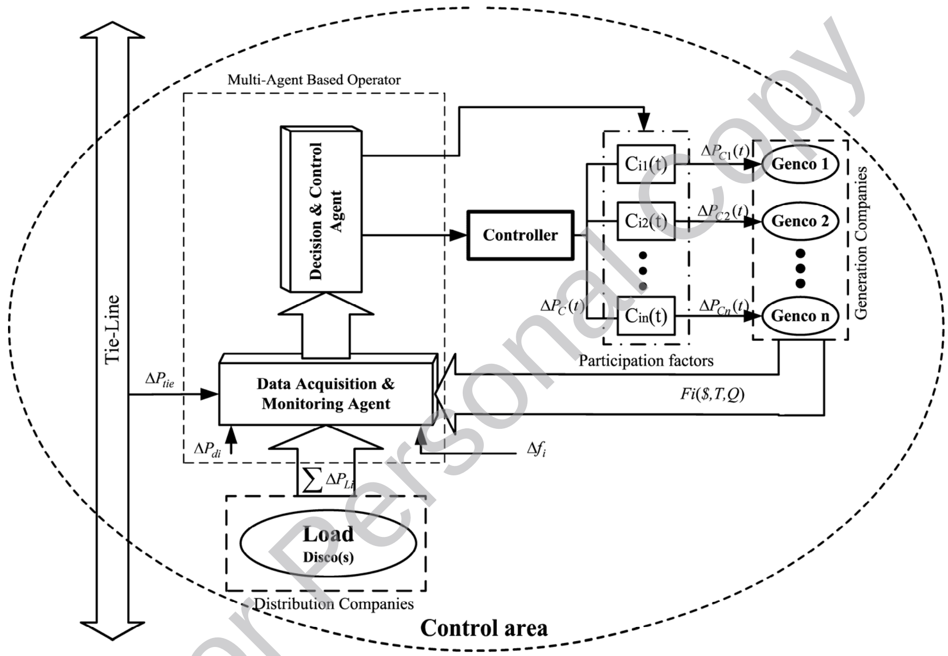


Figure 1. A scenario for AGC in a deregulated environment.

The operating center includes two agents: Data Acquisition and Monitoring (DAM) agent, and, Decision and Control (DC) agent. The Gencos send the bid regulating reserves $Fi(\$,T,Q)$ 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 $C_i(t)$ 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 $\Delta P_{di}(t)$ [19].

It is assumed that in a control area, 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). Each participating unit will receive its share of the demand $\Delta P_{Ci}(t)$, according to its participation factor; through a dynamic controller which it usually includes a simple PI structure in real world power system.

An appropriate computation method for the participation factors and desired optimization algorithms for the mentioned agents have been already proposed by authors [19], [20]. As a part of the mentioned overall scenario, this paper focuses on the design of "Controller" unit (Figure 1) using a developed H∞-based ILMI algorithm. Technically, this unit has a very important role to guarantee a desired AGC performance. An optimal design ensures a smooth coordination between generator set-point signals and the scheduled operating points $C_i(t)\Delta P_C(t)$. This paper shows that the proposed control design provides an effective design methodology for the AGC synthesis in a new environment.

It is notable that this paper is not about how to price either energy or any other economical aspects and services. These subjects have already gotten much attention. It is assumed that the necessary pricing mechanism and congestion management program are established either by free market, by specific government regulation or by voluntary agreements, and, this paper focuses on technical solution to design of optimal tuning of PI parameters.

2.2 Dynamical model

A power system has a highly nonlinear and time-varying nature; but a linearized model is usually used for AGC synthesis. In this paper we use the linearized model, which is widely used by the researchers [2-17], however the practical constraint on generation rate and areas interfaces are properly considered. The AGC structure is well discussed in many published documents during last three decades. The interested reader can find the important related concepts in [1].

A large scale power system consists of a number of interconnected control areas. Figure 2 shows an appropriate block diagram for the AGC synthesis purpose (of control area-i), which includes n Gencos, from an N-control area power system. Following a load disturbance within a control area the frequency of that area, experiences a transient change and the feedback mechanism comes into play and generates appropriate rise/lower signal to the participated Gencos according to their participation factors to make generation follow the load. In the steady state, the generation is matched with the load, driving the tie-line power and frequency deviations to zero. The balance between connected control areas is achieved by detecting the frequency and tie line power deviations to generate the area control error (ACE) signal which is turn utilized in the (PI) control strategy as shown in Figure 2. The input signals w_{1i} and w_{2i} demonstrate the area load disturbance and interconnection effects (area interface) respectively, where

$$w_{1i} = \Delta P_{di} \tag{1}$$

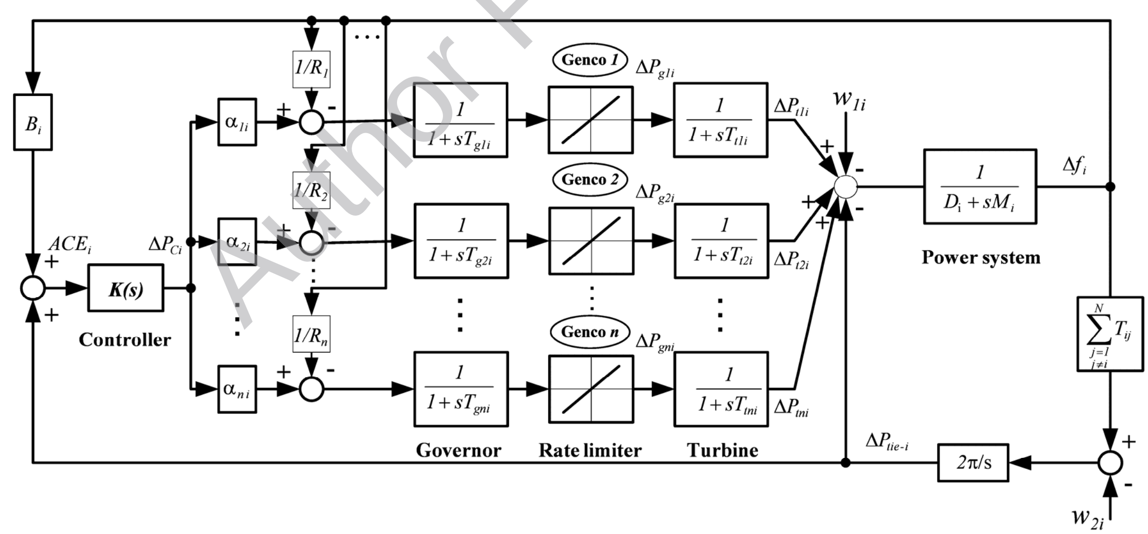


Figure 2. A general control area.

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

Now, consider $G_i(s)$ as a linear time invariant model for the given control area (i) with the following state space model.

$$G_i(s): \begin{array}{l} \dot{x}_i = A_i x_i + B_{1_i} w_i + B_{2i} u_i \\ z_i = C_{1i} x_i + D_{12i} u_i \\ y_i = C_{2i} x_i \end{array} \tag{3}$$

where x_i is the state variable vector, w_i is the disturbance and area interface vector, z_i is the controlled output vector and y_i is the measured output vector which is performed by ACE signal. It is expected the robust controller (K_i) to be able to minimize the fictitious output (z_i) in the presence of disturbance and external input (w_i). Therefore the vector z_i must properly cover all signals which be minimized to meet the AGC goals, e.g. frequency regulation and tracking the load changes, maintaining the tie-line power interchanges to specified values in the presence of generation constraints and minimizing the ACE signal. A useful fictitious output vector can be considered as follows

$$z_i^T = \left[\eta_{1i} \Delta f \quad \eta_{2i} \int ACE_i \quad \eta_{3i} \Delta P_{tie\text{-}i} \quad \eta_{4i} \Delta P_{Ci} \right] \tag{4}$$

η_{1i}, η_{2i}, η_{3i} and η_{4i} are constant weighting coefficients and must be chosen by the designer to obtain the desired performance. The fictitious controlled outputs $\eta_{1i} \Delta f_i$, $\eta_{2i} \int ACE_i$ and $\eta_{3i} \Delta P_{tie\text{-}i}$ are used to minimize the effects of input disturbances on area frequency, ACE and tie-line power flow signals. Furthermore, the fictitious output $\eta_{4i} \Delta P_{Ci}$ sets a limit on the allowed control signal to penalize fast changes and large overshoot in the governor load set-point with regard to corresponded practical constraint on power generation by generator units.

Using Figure 2, the other variables and coefficients of state-space model (3) can be obtained as follows:

$$x_i^T = [\Delta f_i \quad \Delta P_{tie-i} \quad \int ACE_i \quad x_{ti} \quad x_{gi}] \tag{5}$$

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

$$y_i^T = ACE_i, \; u_i = \Delta P_{\mathrm{C}i} \tag{6}$$

$$w_i^{\mathrm{T}} = \left[w_{1i} \quad w_{2i} \right] \tag{7}$$

where,

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

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

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

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

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

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

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

3. PROPOSED CONTROL STRATEGY

3.1 Static output feedback control

The static output feedback (SOF) control problem is one of the most important research areas in control engineering [21-23]. 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 [23-24]. A comprehensive survey on SOF control is given in [23].

It is well-known that because of using simple constant gains, pertaining to the SOF synthesis for dynamical systems in the presence of strong constraints and tight objectives are few and restrictive. Usually, design of a full-order output feedback controller reduces to the solution of two convex problems, a state feedback and a Kalman filter; however the design of a SOF gain is more difficult. The reason is that the separation principle does not hold in such cases [25]. The existence of SOF controller is shown to be equivalent to the existence of a positive definite matrix satisfying simultaneously two lyapunov inequalities [26], where the determination of such a matrix leads to solving a non convex optimization problem [24, 26, 27, 28]. Approaching to a solution can be a difficult task demanding to the great computational effort.

Necessary and sufficient conditions for SOF design, as has mentioned above, can be obtained in terms of two LMI's couples through a bilinear matrix equation [24, 27, 29]. Particularly, the problem of finding a SOF controller can be restated as a linear algebra problem, which involves two LMIs. In example, an LMI on a positive definite matrix variable P, an LMI on a positive definite matrix variable Q and a coupling bilinear matrix equation of the form $PQ=I$. But finding such positive definite matrices is a difficult task, since the bilinear matrix equation implies $Q = P^{-1}$. Thus, the two LMIs are not convex in P [24].

A variety of SOF problems were studied by many researchers with many analytical and numerical methods to approach a local/global solution [21-23, 27, 30, 31]. In this paper, to solve the resulted SOF problem from the AGC synthesis, an iterative LMI is used based on the given necessary and sufficient condition for SOF stabilization in [31], via the H∞ control technique.

3.2 Transformation from PI-based AGC to a SOF control problem

In this section, the PI-based AGC problem is transferred to a SOF control problem. The main merit of this transformation is to use 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.

In a given control area (Figure 2) which is simplified in Figure 3a, ACE performs the input signal of the PI controller to be used by the AGC system and we can write

$$u_i = \Delta Pci = k_{Pi} ACE_i + k_{Ii} \int ACE_i \tag{8}$$

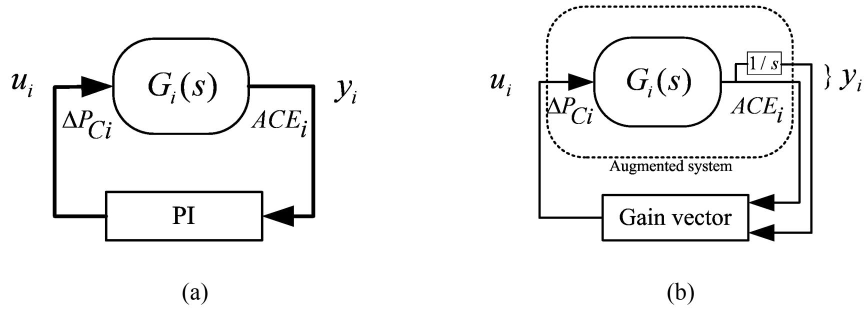


Figure 3. Transformation from PI to SOF control; a) PI control, b) SOF control.

where k_{Pi} and k_{Ii} are constant real numbers. Therefore, by augmenting the system description to include the ACE and its integral as a new measured output vector, the PI-based AGC problem becomes one of finding a SOF that satisfied prescribed performance requirements. In order to change (8) to a simple SOF control as

$$u_i = K_i y_i \tag{9}$$

We can rewrite (8) as follows

$$u_i = [k_{Pi} \quad k_{Ii}] \begin{bmatrix} ACE_i \\ \int ACE_i \end{bmatrix} \tag{10}$$

Therefore, y_i and C_{2i} in (3) can be augmented as given in (11). Figure 3b shows this transformation and the overall control framework is given in Figure 4.

$$y_i^T = [ACE_i \quad \int ACE_i], \; C_{2i} = [c_{2i} \quad 0_{2\times n} \quad 0_{2\times n}], \; c_{2i} = \begin{bmatrix} B_i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{11}$$

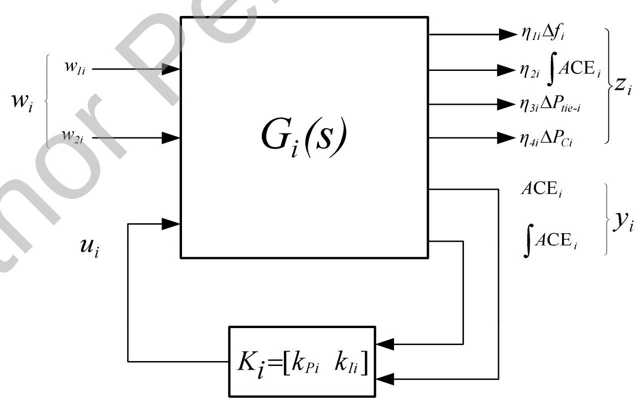


Figure 4. Proposed control framework.

3.3 ILMI algorithm

The H∞ static output feedback (H∞-SOF) control problem for the linear time invariant system $G_i(s)$ with the state-space realization of (3) is to find a gain matrix K_i ($u_i = K_i y_i$), such that the resulted closed-loop system is internally stable, and the H∞ norm from w_i to z_i is smaller than γ, a specified positive number, i.e.

$$\left\| T_{z_i w_i}(s) \right\|_\infty < \gamma \tag{12}$$

It is notable that the H∞-SOF control problem can be transferred to a generalized SOF stabilization problem which is expressed via the following theorem.

Theorem. The system (*A, B, C*) that may also be identified by the state-space model,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{13}$$

is stabilizable via SOF if and only if there exist $P>0$, $X>0$ and K_i satisfying the following quadratic matrix inequality

$$\begin{bmatrix} A^T X + XA - PBB^T X - XBB^T P + PBB^T P & (B^T X + K_i C)^T \\ B^T X + K_i C & -I \end{bmatrix} < 0 \tag{14}$$

Proof is given in [31]. Since a solution for the consequent non convex optimization problem (14) can not be directly achieved by using general LMI technique, to synthesis the H∞-SOF based AGC we will introduce an iterative LMI algorithm that is mainly based on the given approach in [31]. The key point is to formulate the H∞ problem via a generalized static output stabilization feedback such that all eigenvalues of $(A\text{-}B\,K_i\,C)$ shift towards the left half plane through the reduction of a, a real number, to close to feasibility of (14). Above theorem gives a family of internally stabilizing SOF gains is defined as K_{sof}. But we are looking for the solution of following optimization problem.

Optimization problem: Given an optimal performance index γ, (12), resulted from the application of H∞ dynamic output feedback control to the control area i, determine an admissible SOF law

$$u_i = K_i y_i \ , \ K_i \in K_{sof} \tag{15}$$

such that

$$\left\| T_{zi\,wi}(s) \right\|_\infty < \gamma^* \tag{16}$$

where γ^* indicates a lower bound such that the closed-loop system is H∞ stabilizable via SOF. In this case we could see that $\left|\gamma - \gamma^*\right| < \varepsilon$, where ε is a small positive number. The following algorithm gives an iterative LMI solution for above optimization problem.

Step 1. Compute a new system $(\overline{A}_i, \overline{B}_i, \overline{C}_i)$ for the given control area, where [4]:

$$\overline{A}_i = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix}, \ \overline{B}_i = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix}, \ \overline{C}_i = \begin{bmatrix} C_{2i} & 0 & 0 \end{bmatrix} \tag{17}$$

Step 2. Set $i=1$, $\Delta\gamma = \Delta\gamma_0$ and let $\gamma_i = \gamma_0 > \gamma$. $\Delta\gamma_0$ and γ_0 are positive real numbers.

Step 3. Select $Q > 0$, and solve $\overline{X}$ from the following algebraic Riccati equation

$$\overline{A}_i^T \overline{X} + \overline{X}\overline{A}_i - \overline{X}\overline{B}_i \overline{B}_i^T \overline{X} + Q = 0 \tag{18}$$

Set $P_1 = \overline{X}$.

Step 4. Solve the following optimization problem for $\overline{X}_i$, K_i and a_i.

Minimize a_i subject to the LMI constraints:

$$\begin{bmatrix} \overline{A}_i^T \overline{X}_i + \overline{X}_i \overline{A}_i - P_i \overline{B}_i \overline{B}_i^T \overline{X}_i - \overline{X}_i \overline{B}_i \overline{B}_i^T P_i + P_i \overline{B}_i \overline{B}_i^T P_i - a_i \overline{X}_i & (\overline{B}_i^T \overline{X}_i + K_i \overline{C}_i)^T \\ \overline{B}_i^T \overline{X}_i + K_i \overline{C} & -I \end{bmatrix} < 0 \tag{19}$$

$$\overline{X}_i = \overline{X}_i^T > 0 . \tag{20}$$

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 $a_{i-1}^* \leq 0$, $K_{i-1} \in K_{sof}$ is desired H∞ controller and $\gamma^* = \gamma_i + \Delta\gamma$ indicates a lower bound such that the above system is H∞ stabilizable via SOF control.

Step 7. Solve the following optimization problem for $\overline{X}_i$ and K_i:

Minimize trace($\overline{X}_i$) subject to the above LMI constraints (19-20) with $a_i = a_i^*$. Denote $\overline{X}_i^*$ as the $\overline{X}_i$ that minimized trace($\overline{X}_i$).

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

Step 9. Set $\gamma_i = \gamma_i - \Delta\gamma$, $i = i+1$. Then do steps 3 to 5.

The matrix inequalities (19) and (20) give a sufficient condition for the existence of SOF controller. In the next section, two types of robust controllers are developed for a power system example including three control areas. The first one is dynamic H∞ controller based on general robust LMI design and the second controller is based on the introduced ILMI algorithm with the same assumed objectives to achieve desired robust performance.

4. CASE STUDY

A three control area power system, shown in Figure 5, is considered as a test system. It is assumed that each control area includes three Gencos. For the sake of comparison, the power system parameters are considered to be the same as in [14].

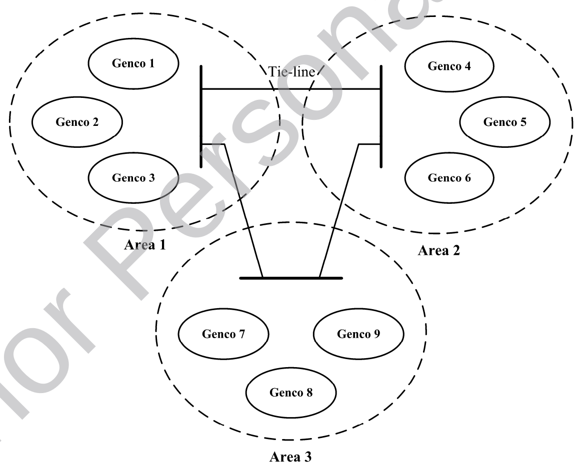


Figure 5. Three control area power system.

The selection of constant weights η_{1i}, η_{2i}, η_{3i} and η_{4i} is dependent on specified performance objectives and must be chosen by designer. 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 these weights entails a trade off among several performance requirements. Here, a set of suitable values for constant weights are considered as:

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

For each control area, in addition to the proposed control strategy to obtain the robust PI controller, a H∞ dynamic output feedback controller is designed using the function *hinflmi*, provided by the MATLAB's LMI control toolbox [32]. The resulted controllers are dynamic; whose orders are the same as size of plant model (9^{th} order in the present example).

At the next step, according to the synthesis methodology described in section 3, a set of three decentralised robust PI controllers are designed. Using ILMI approach, the controllers are obtained following several iterations. For example, the final result for control area 3 is obtained after 29 iterations. Some iterations are listed in Table I. The control parameters for three areas are shown in Table II.

Table I. ILMI algorithm result for controller K_3.

Iteration	γ	k_{P3}	k_{I3}
1	449.3934	-0.0043	-0.0036
5	419.1064	-0.0009	-0.0042
11	352.6694	0.1022	-0.2812
14	340.2224	-0.0006	-0.0154
19	333.0816	-0.0071	-0.1459
22	333.0332	0.0847	-0.2285
24	333.0306	0.0879	-0.2382
26	333.0270	0.0956	-0.2537
28	333.0265	0.0958	-0.2560
29	333.0238	-0.0038	-0.2700

Table II. Control parameters (ILMI design).

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

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

Table III. Robust performance index.

Control design	*Control structure*	*Performance index*	*Area1*	*Area 2*	*Area 3*
H∞	9^{th} order	γ	333.0084	333.0083	333.0080
ILMI	PI	γ^*	333.0261	333.0147	333.0238

5. SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed control design, some simulations were carried out. In these simulations, the proposed controllers were applied to the three control area power system described in Figure 5. In this section, the performance of the closed-loop system using the robust PI controllers in comparison of dynamic H∞ controllers and proposed PI controllers in [14] is tested for some serious load disturbances.

Scenario 1: Large load disturbance

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

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

Frequency deviation (Δf), area control error (ACE) and control action (ΔPc) signals of the closed-loop system are shown in Figure 6 and Figure 7. Using the proposed method (ILMI), the area control error and frequency deviation of all control areas are properly driven back to zero as well as full dynamic H∞ control.

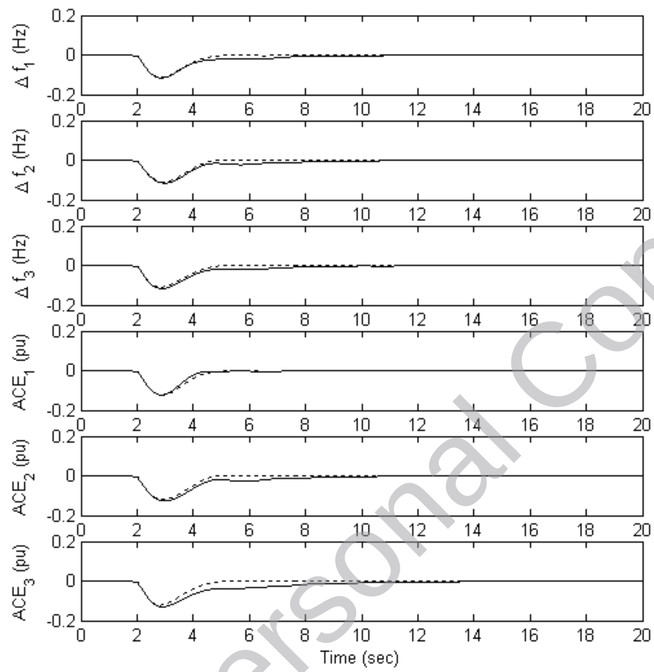


Figure 6. Frequency deviation and ACE signals following a large step load demand (105 MW) in each area. Solid (ILMI-based PI controllers), Dotted (dynamic H∞ controllers).

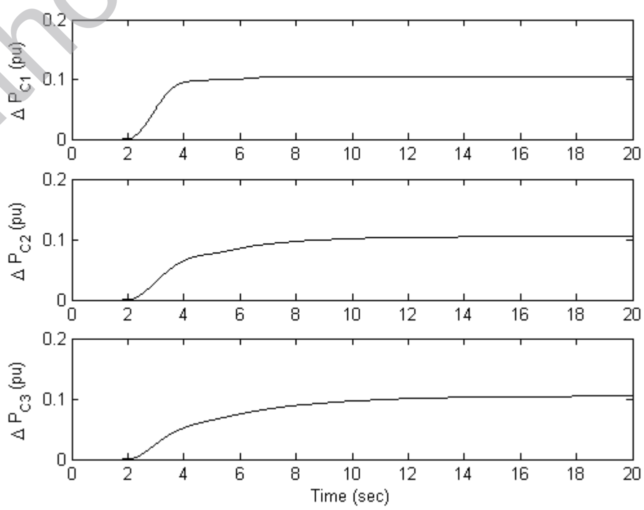
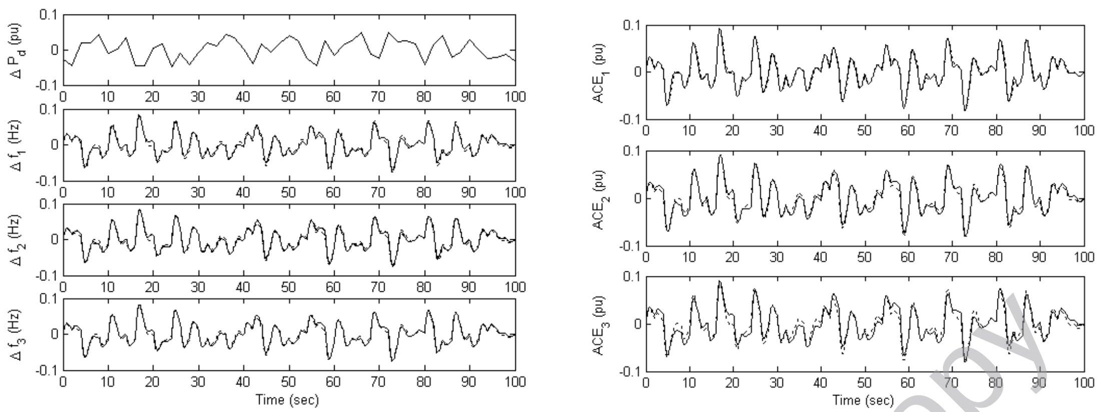


Figure 7. Control signals following a large step load demand (105 MW) in each area.

Scenario 2: Random load change

As another sever condition, assume a bounded random load change (Figure 8) is applied to each control area, where



(a) (b)

Figure 8. a) Random load pattern and frequency deviation, b) ACE signals in each area. Solid (ILMI-based PI controllers), Dotted (dynamic H∞ controllers).

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

The purpose of this scenario is to test the robustness of the proposed controllers against random large load disturbances. The control area responses are shown in Figure 8 and Figure 9. These figures demonstrate that the designed controllers track the load fluctuations, effectively. The simulation results show the proposed PI controllers perform robustness as well as robust dynamic H∞ controllers (with complex structures) for a wide range of load disturbances.

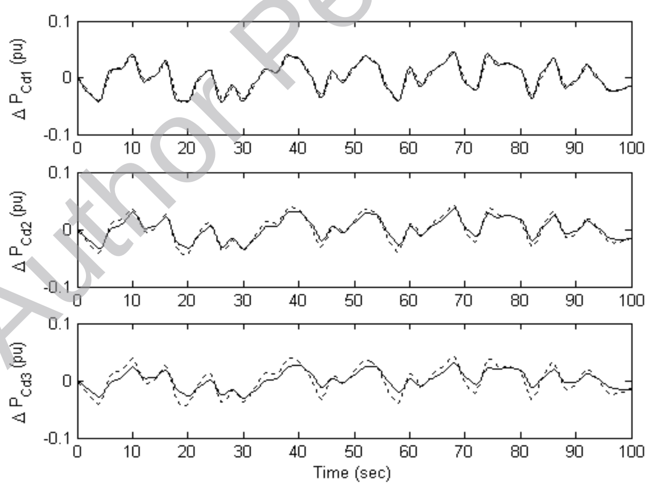
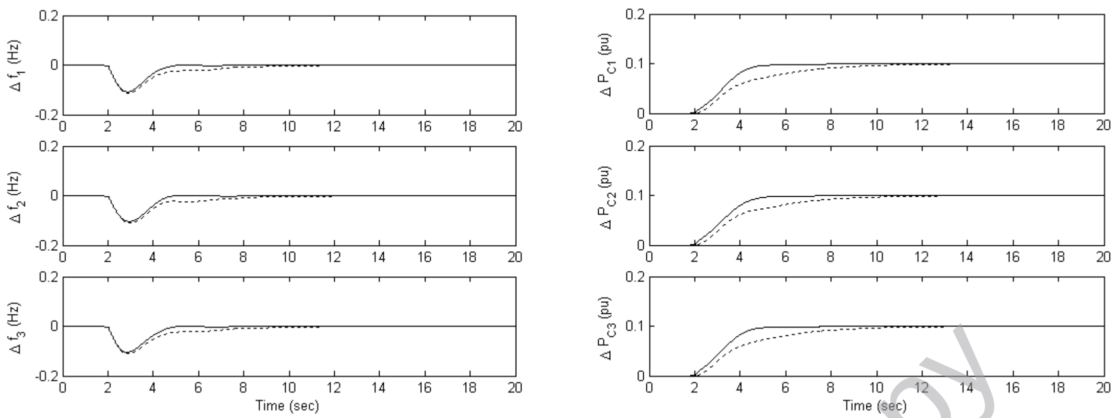


Figure 9. Control action signals in each area, following the random load demand. Solid (ILMI-based PI controllers), Dotted (dynamic H∞ controllers).

Scenario 3: Comparison with [14]

Figure 10 compares the frequency deviation (Δf) and governor load set-point (ΔPc) signals for the proposed method and recent published design technique [14], following 100 MW step load increase in each control area. [14] has used an interesting approach, a combination of genetic algorithm (GA) and

LMI-based H∞ control (GALMI). As it is seen from Figure 10, the proposed controllers track the load changes and meet the robust performance as well as reported results for the same simulation case in [14].



(a) (b)

Figure 10. a) Frequency deviation and b) Control action signals following a +100 MW step load in each area. Solid (ILMI), Dotted ([14]).

The proposed control design uses a simple algorithm that takes a short time (few seconds) for tuning the controller parameters. As it is seen in Figure 4, considering the tie-line power change ($\Delta P_{tie\text{-}i}$) in the controlled output vector (4) through the H∞ control framework increases the flexibility of design to set a desired level of performance with a lower control effort (in comparison with [14] and also [4] as the preliminary step of the present work).

6. CONCLUSION

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

The proposed method is applied to a three control area power system and is tested under serious load change scenarios. The results are compared with the results of dynamic H∞ controllers and recent related published research. It was shown that the designed controllers are capable to guarantee the robust performance such as precise reference frequency tracking and disturbance attenuation under a wide range of area-load disturbances.

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