DECENTRALIZED ROBUST LOAD FREQUENCY CONTROL USING LINEAR MATRIX INEQUALITIES IN A DEREGULATED MULTI-AREA POWER SYSTEM

SHAYEGHI H.
Electrical Eng. Dept., IUST
Tehran, Iran

SHAYANFAR H.A.
Electrical Eng. Dept., IUST
Tehran, Iran

Narmak, Tehran 16844, Iran
Fax: 0098-21-7454055, Tel.: 0098-21-7808022
Email: h_shayeghi@yahoo.com, hashayanfar@yahoo.com,

Abstract: *This paper presents a new decentralized robust controller for load frequency Control (LFC) of the multi area power systems in a deregulated environment based on the possible load following contracts. In each control area, the effects of contracted signals and the interfaces between control areas are treated as a set of new disturbance signals to achieve decentralization. In practice LFC systems use conventional Proportional-Integral (PI) controllers. It is well known that the conventional PI controllers does not yield adequate robust performance with consideration of modeling uncertainties, system nonlinearities and various contracted scenarios. In order to overcome this drawback, a decentralized load frequ-ency controller is designed based on the robust* H_∞ *control technique formulated as a Linear Matrix Inequalities (LMI) optimization problem. The robust performance of the proposed controller is tested on a four-area power system and compared with the PI controller for two scenarios of possible contracts under various area load disturbances and uncertainties. The simulation results show that the proposed control strategy is effective and achieves good robust performance even in the presence of plant parameter changes, contract variations and Generation Rate Constraints (GRC).*

Keywords: **LFC, Linear Matrix Inequalities, Deregulated Power System, Robust Control, Decentralized Control.**

1. Introduction

Nowadays, the electric power industry is in transition to a deregulated market. Under this circumstance, any power system controls such as Load Frequency Control (LFC) will serve as ancillary service and acquires a principal role to enable power exchanges and to provide better condition for electricity trading [1]. LFC is an essential mechanism in the restructured power system, which balance generated power and demand in each control area in order to maintain the frequency of each control area at nominal value and to keep tie-line powers near to the scheduled values. That is why during the past decade several proposed LFC scenarios attempted to adapt well tested traditional LFC schemes to the change of environment in power system under deregulation [2-4]. In the new structure, there are three different entities, viz., Generation Companies (GENCOs), Transmission Comp-anies (TRANSCOs) and Distribution Companies (DISCOs). As there are several GENCOs and DISCOs, a GENCO may or may not participate in the LFC task. On the other hand, a DISCO has the freedom to have a contract with any GENCO for power transaction in its area or other areas. Currently, all transactions have to be cleared through Independent System Operator (ISO) or other organizations.

One of the important issues in the LFC design problem is robustness. In the deregulated power systems, each control area subjects to various disturbances and uncertainties due to increasing the complexity, system modeling errors and chang-ing power system structure. There have been continuing efforts in design of load frequency controller with better perfo-rmance to cope with parameter changes, using various decen-tralized robust, optimal control and neural network methods during the last two decades [5-9]. All the proposed methods are based on state-space approach and require information about the system states, which are not usually known or avail-able. Recently, several optimal and robust control strategies have been developed for LFC synthesis according to the change of environment in power system operation under dere-gulation [10-13]. The proposed methods gave good dyna-mical response, but robustness in the presence of modeling uncertainties and system nonlinearities were not considered. Also, some authors suggest complex state feedback which is not practical for industry practices.

This paper addresses a new decentralized control strategy based on robust H_∞ control technique formulated as a Linear Matrix Inequalities (LMI) problem using a modified LFC scheme in the restructured power system. To achieve decentr-alization, the interfaces between control areas and new input signals according to possible contracts are treated as a set of disturbance signals. The motivation of using this control strategy is flexibility of the synthesis procedure for modeling uncertainty, direct formulation of performance objectives and practical constraints. Due to its practical merit, the proposed control scheme is a decentralized LFC and requires only the Area Control Error (ACE), which is a linear combination of frequency (ΔF) and tie-lines power (ΔP_{tie}) deviations. When a decentralized LFC is applied, by reducing the system size, H_∞ norm is easier to dampen. Thus, H_∞ control is more effective in the decentralized control schemes. Following the idea presented in [10] a generalized model for LFC scheme is developed based on possible contracted scenarios. Using the generalized LFC scheme the proposed control strategy is for-mulated as a

LMI problem [14] and solved via optimization routines provided with MATLAB's LMI control toolbox [15] to obtain desired robust decentralized controller.

A four-area power system is considered as a test system. The results are compared with the conventional PI controller which is widely used in practical industry. To demonstrate effectiveness of proposed method two scenarios of possible contracts under larger load disturbances in the presence of modeling uncertainties and Generation Rate Constraints (GRC) have been simulated. The simulation results show that the proposed method can achieve good robust performance for all admissible uncertainties and load disturbances.

This paper is organized as follows. Technical background including H_∞ control design by LMI approach is given in section 2. The general dynamic model of LFC scheme in a deregulated electricity market is presented in section 3. Section 4 describes the problem formulation for a given control area. The proposed strategy is applied to a four-area power system as a case study in section 5. In section 6, some simul-ation results are given to illustrate robustness of the proposed controllers. Finally, the conclusions are presented in section 7.

2. Technical background

During the last two decades, robust control theory has been used for control of systems with different uncertainties and disturbances such as plant parameter variations, system mod-eling errors, measurement noises and external disturbances. One major objective of robust control is to synthesize a contr-oller that would guarantee internal stability of the system in the presence of bounded perturbation. This section presents the H_∞ control design via LMI approach, which is less com-plex than standard frequency domain approaches that required substantial mathematical computational effort. Consider a linear time invariant system *P(s)* with following state-space realization.

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_z x + D_{11} w + D_{21} u \\ y &= C_y x + D_{21} w \end{aligned} \qquad (1)$$

Where x is the state variable vector, w is the disturbance and other external vector and y is the measured output vector. It is assumed (A, B_2) is stabilizable and (A, C_y) is detectable.

The robust H_∞ controller problem is to find a controller *K(s)* as shown in Fig.1, such that the resulting close loop system is internally stable and the H_∞ norm form w to z smaller than γ, a specified positive number, i.e. :

$$\|T_{zw}(s)\|_\infty < \gamma \qquad (2)$$

The state spare realization of *K(s)* is given by:

$$\begin{aligned} \dot{\xi} &= A_k \zeta + B_{ky} \\ u &= C_k \zeta + D_k y \end{aligned} \qquad (3)$$

Consider the following state space realization for close loop system in order to synthesis on H_∞ controller via LMI approach.

$$\begin{aligned} \dot{x}_{cl} &= A_{cl} x_{cl} + B_{cl} w \\ z &= C_{cl} x_{cl} + D_{cl} w \end{aligned} \qquad (4)$$

where,

$$x_{cl} = \begin{bmatrix} x \\ \zeta \end{bmatrix}, A_{cl} = \begin{bmatrix} A + B_2 C_k C_y & B_2 C_k \\ B_k C_y & A_k \end{bmatrix}, B_{cl} = \begin{bmatrix} B_1 + B_2 C_k D_{21} \\ B_k D_{21} \end{bmatrix}$$

$$C_{cl} = [C_z + D_{12} C_y \quad D_{12} C_k], D_{cl} = [D_{11} + D_{12} D_k D_{21}]$$

The following lemma [14] relates H_∞ control design to LMI.

Lemma 1: The closed loop RMS gain for $T_{zw}(s)$ does not exc-eed γ if and only if there are:

$$\begin{bmatrix} A_{cl} X_\infty + X_\infty A_{cl}^T & B_{cl} & X_\infty C_{cl}^T \\ B_{cl}^T & -I & D_{cl}^T \\ C_{cl} X_\infty & D_{cl} & -\gamma^2 I \end{bmatrix} < 0 \qquad (5)$$

$$X_\infty < 0 \qquad (6)$$

An optimal H_∞ control design can achieve by minimizing the guaranteed robust performance index γ subject to the constr-aints given by the matrix inequalities (5) and (6). An efficient algorithm for solving this problem is available in the LMI control toolbox for MATLAB [15].

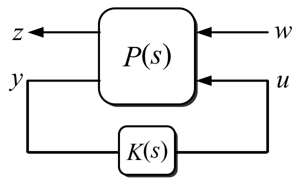


Fig. 2. The H_∞ control structure

3. LFC scheme in a restructured system

The traditional power system industry has a vertically Integr-ated Utility (VIU) structure, which supplies power to the customers at regulated rates. In the deregulated power syst-ems, the VIU no longer exists, however, the common LFC objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area remained. The deregulated power system consists of three companies, GENCOs, TRANCOs and DISCOs with an open access policy. In the new structure, GENCOs may or may not participate in the LFC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. This makes various combinations of possible contract scenarios between DISCOs and GENCOs. All the transa-ctions have to be cleared by the ISO or the other responsible organizations. Thus, it is required that a new model for LFC scheme is developed in order to account effects of possible load following contracts on dynamics. Here, we introduce the concept of an '*Augmented Generation Participation Matrix*' (AGPM) to express these possible contracts following the idea presented in Ref. [10]. The AGPM shows the participation factor of a GENCO in the load following contract with a DISCO. The rows and columns of AGPM matrix is equal with total number of GENCOs and DISCOs in the overall power system, respectively. Consider the number of GENCOs and DISCOs in area i be n_i and m_i in a large scale power system with N control area. The structure of AGPM is given by:

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix}$$

where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

$$s_i = \sum_{k=1}^{i-1} n_i \,,\; z_j = \sum_{k=1}^{j-1} m_j \;, \quad i,j = 2,\cdots,N \quad \& \quad s_1 = z_1 = 0$$

Which in gpf_{ij} refer to '*generation Participation factor*' and shows the participation factor GENCO i in total load follo-wing requirement of DISCO j based on the possible cont-racts. The sum of all entries in each column of AGPM is unity. The diagonal submatrices of AGPM correspond to local demands and off diagonal submatrices correspond to demands of DISCOs in one area to GENCOs in another area.

Fig. 1 shows the block diagram of a generalized LFC sche-me for control area i in a restructured structure. The nomenc-lature used is given in Appendix A. Dashed dot-lines show the demand signals based on possible contracts and interfaces between areas. These new information sig-nals were absent in the traditional LFC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE partici-pation factor in the LFC task and $\sum_{j=1}^{n_i} apf_{ji} = 1$. From Fig.1, it can see that d_i, ζ_i, η_i and ρ_i as four input disturbance channels are considered for decentralized LFC design and defined as follows:

$$d_i = \Delta P_{Loc,i} + \Delta P_{di} \quad , \quad \Delta P_{Loc,i} = \sum_{j=1}^{m_i} (\Delta P_{Lj} + \Delta P_{ULj}) \tag{7}$$

$$\eta_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} T_{ij} \Delta f_j \tag{8}$$

$$\zeta_i = \sum_{\substack{k=1 \\ k \neq i}}^{N} \Delta P_{tie,ik,schdueled} \tag{9}$$

$$\Delta P_{tie,ik,schdueled} = \sum_{j=1}^{n_i} \sum_{t=1}^{m_k} apf_{(s_i+j)(z_k+t)} \Delta P_{L(z_k+t)} - \sum_{t=1}^{n_k} \sum_{j=1}^{m_i} apf_{(s_k+t)(z_i+j)} \Delta P_{L(z_i+j)} \tag{10}$$

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i \tag{11}$$

$$\rho_i = [\rho_{1i} \ldots \rho_{ki} \ldots \rho_{n_i i}]^T \ , \quad \rho_{ki} = \Delta P_{m,k-i} \tag{12}$$

$$\Delta P_{m,k-i} = \sum_{j=1}^{z_{N+1}} gpf_{(s_i+k)j} \Delta P_{Lj} \quad , k = 1,2,\cdots,n_i \tag{13}$$

$\Delta Pm,ki$ is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state.

According to Fig.1, the state-space model for control area i can be obtained as:

$$\begin{aligned} \dot{\boldsymbol{x}}_i &= \boldsymbol{A}_i \boldsymbol{x}_i + \boldsymbol{B}_{iu} \boldsymbol{u} + \boldsymbol{B}_{iw} \boldsymbol{w}_i' \\ \boldsymbol{y}_i &= \boldsymbol{C}_i \boldsymbol{x}_i + \boldsymbol{D}_{iw} \boldsymbol{w}_i' \end{aligned} \tag{14}$$

where,

$$x_i^T = [x_{ai} \ x_{1i} \ldots x_{ki} \ldots x_{n_i i}], \ u_i = \Delta P_{ci} \ , y_i = ACE_i$$

$$x_{ai} = [\Delta f_i \ \Delta P_{tie,i}] , x_{ki} = [\Delta P_{Tki} \ \Delta P_{Vki}] , k = 1,\ldots,n_i$$

$$w_i'^T = [d_i \quad \eta_i \quad \xi_i \quad \rho_i] , \rho_i = [\rho_{1i} \ldots \rho_{ki} \ldots \rho_{n_i i}]$$

$$A_i = \begin{bmatrix} A_{11i} & A_{12i} \\ A_{21i} & A_{22i} \end{bmatrix} \ , \quad A_{11i} = \begin{bmatrix} 1/T_{Pi} & -K_{Pi}/T_{Pi} \\ \sum_{j=1\& j\neq i}^{N} Tji & 0 \end{bmatrix}$$

$$A_{12i} = \underbrace{\begin{bmatrix} \begin{pmatrix} K_{Pi}/T_{Pi} & 0 \\ 0 & 0 \end{pmatrix} & \cdots & \begin{pmatrix} K_{Pi}/T_{Pi} & 0 \\ 0 & 0 \end{pmatrix} \end{bmatrix}}_{n_i blocks}$$

$$A_{21i} = [DP_{1i}^T \ldots DP_{ki}^T \ldots DP_{n_i i}^T] , A_{22i} = diag(TG_{1i},\ldots,TG_{ki},\ldots,TG_{n_i i})$$

$$DP_{ki} = \begin{bmatrix} 0 & 0 \\ -1/(R_{ki}T_{Hki}) & T_{Hki} \end{bmatrix} , TG_{ki} = \begin{bmatrix} -1/T_{Tki} & 1/T_{Tki} \\ 0 & -1/T_{Hki} \end{bmatrix}$$

$$B_{iu}^T = [0_{2\times 1}^T \quad B_{1iu}^T \ldots B_{kiu}^T \ldots B_{n_i iu}^T] , B_{kiu} = [0 \quad apf_{ki}/T_{Hki}]$$

$$B_{iw}^T = [B_{aiw}^T \quad B_{1iw}^T \ldots B_{kiw}^T \ldots B_{n_i iw}^T]$$

$$B_{aiw} = \begin{bmatrix} -K_{Pi}/T_{Pi} & 0 & 0_{1\times(n_i+1)} \\ 0 & -1 & 0_{1\times(n_i+1)} \end{bmatrix} , B_{kiw} = \begin{bmatrix} 0_{1\times 3} & 0 \ \ldots \ 0 \ \ldots \ 0 \\ 0_{1\times 3} & b_{1i} \ldots b_{ki} \ldots b_{n_i i} \end{bmatrix} , b_{ji} = \begin{cases} -1/T_{Hki} & j = k \\ 0 & j \neq i \end{cases}$$

$$C_i = [C_{ai} \quad 0_{1\times 2n_i}] , C_{ai} = [B_i \quad 1] , D_{wi} = [0_{1\times 2} \quad -1 \quad 0_{1\times n_i}]$$

4. Decentralized H_∞ control synthesis

The main goal in each control area is maintaining the area frequency and tie line power interchanges close to specified values in the presence of model uncer-tainties and disturbances. In order to achieve our ob-jectives and formulate the LFC problem via a H_∞ control design, we propose the control strategy as shown in Fig. 3 for a given control area (Fig. 2). This figure shows the main framework and synthesis strat-egy for designing desired controller. In restructured power systems, each control area contains different kinds of uncertainties because of plant parameter variations and system modeling error due to some approximations in model linearization and unmod-eled dynamics. Usually, the uncertainties in power system can be modeled as multiplicative and/or addi-tive uncertainties [16]. In Fig. 3 the Δu_i block mod-els the structured uncertainties as a multiplicative type and Wu_i is the associated weighting function.

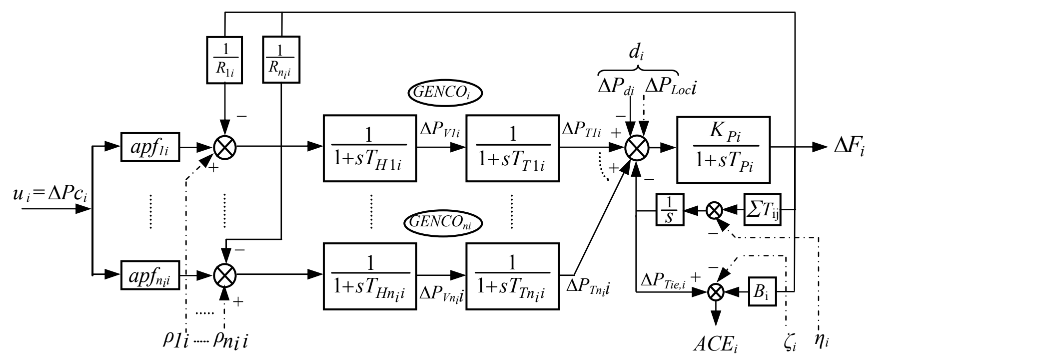


Fig. 2. The generalized LFC scheme for area i in the deregulated environment

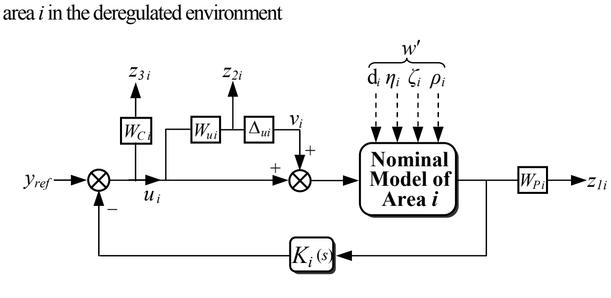


Fig. 3. The proposed synthesis framework

According to the requirements of performance and practical constraint on control actions, two weighting function W_{Ci} and W_{Pi} are added to the control area model. The W_{Ci} on the control input sets a limit on the allowed control signal to penalize fast change and large overshoot in the control action. The weight W_{Pi} at the output sets the performance goal i.e.: tracking regulation error on the output area control signal. Thus, it is expected that proposed strategy satisfy the main objectives of the LFC problem under possible contract variations and model uncertainties. It be noted that for rejecting disturbances and assuring a good tracking property, W_{Ci} and W_{Pi} must be selected such that the singular value of sensitivity transfer function from u_i to y_i be reduced at low frequency [17]. Design problem formulation into the robust general structure is shown in Fig. 4. $P_o(s)$ and $K_i(s)$ denote the nominal area model as given by (14) and controller, respectively. Also, y_i is the measured output (performed by area control error), u_i is the control input and w_i includes the perturbed, disturbance and reference signals in the control area.

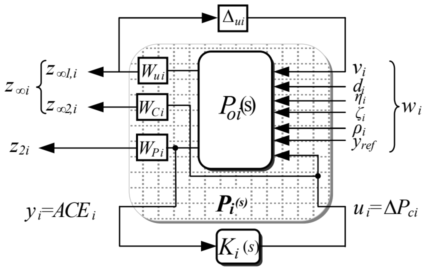


Fig. 4. Formulation of H_∞ based control design problem

In Fig. 4, $P_i(s)$ is generalized plant (GP) that includes area-i's nominal model and associated weighting functions. In order to design of the robust controller the GP is formulated as following state space model:

$$\begin{aligned} \dot{x}_{GPi} &= A_{GPi}x_i + B_{1i}w_i + B_{2i}u_i \\ z_i &= C_{zi}x_{GPi} + D_{11i}w_i + D_{21i}u_i \\ y_i &= C_{yi}x_{GPi} + D_{21i}w_i \end{aligned} \qquad (15)$$

where,

$$w_i^T = [v_i \quad d_i \quad \eta_i \quad \zeta_i \quad \rho_i \quad y_{ref}], z_i^T = [z_{1i} \quad z_{2i} \quad z_{3i}] \qquad (16)$$

Now, the synthesis problem is designing the robust controller $K_i(s)$ as shown in Fig. 4, such that the resulting close loop system is internally stable and the H_∞ norm from w_i to z_i less than γ_i. Specifically, first the control design is formulated as a general LMI and then the H_∞ control problem is solved using the function "*hiflmi*" provides by the MATLAB LMI control toolbox [15]. This function gives an optimal H_∞ controller through minimizing the guaranteed robust performance index (2) subject to the constraints given by the matrix inequality (5) and returns the controller $K_i(s)$ with optimal robust performance index. In summery, the proposed method consists of the following steps:

Step 1: Compute the state space model for the given control area

Step 2: Identify the uncertainty weighting function for the given area according to dynamical model.

Step 3: Identify the performance weighting function of W_{Pi} and W_{Ci}.

Step 4: Formulation of generalized plant ($P_i(s)$) as a general LMI and solving it using LMI approach to obtain the optimal H_∞ controller.

Step 5: Reduce the order of result controller by using standard model reduction techniques.

It is should be noted that the order of found controller by this procedure is the same as size of generalized plant that is typically high in general. In order to the complexity of computation in the case of high order power systems, appropriated model reduction techniques might be applied to the obtained controller model.

The proposed strategy in this section guarantees the desired robust performance for multi area power system in deregulated environment in the presence of model uncertainties, load changes and system nonlinearities. In the next section, the proposed H_∞ controllers based on LMI technique is developed for a four area power system and compared with the PI controller, which widely used in practical industry nowadays.

5. Case study

A power system, which consists of four control areas interconnected through a number of tie lines as shown in Fig. 5, is considered as a test system to illustrate the effectiveness of the modeling strategy and the proposed idea. It is assumed that each control area includes two GENCOs and two DISCOs except areas two and four have one DISCOs. The power system parameters are given in Tables 1 and 2.

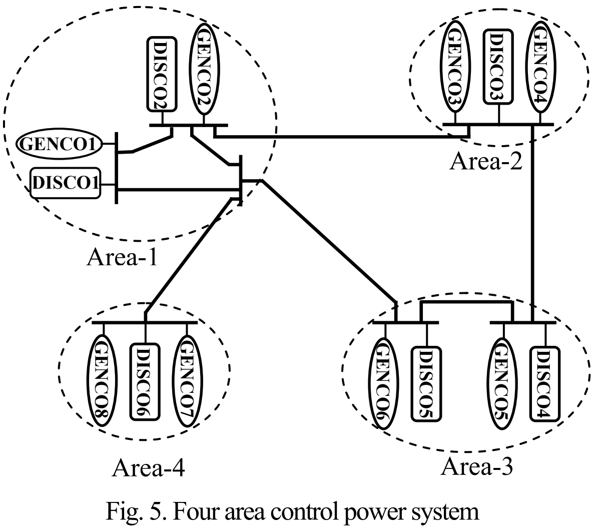


Fig. 5. Four area control power system

Table 1. GENCOs parameter

MVA_{base} (1000MW) Parameter	GENCOs (*k in area i*)							
	1-1	*2-1*	*1-2*	*2-2*	*1-3*	*2-3*	*1-4*	*2-4*
Rate (MW)	800	1000	1100	1200	1000	1000	800	1000
T_T (sec)	0.36	0.42	0.44	0.40	0.36	0.40	0.38	0.40
T_H (sec)	0.06	0.07	0.06	0.08	0.07	0.08	0.085	0.08
R (Hz/pu)	2.4	3.3	2.5	2.4	3	2.4	2	2.4

apf	*0.5*	*0.5*	*0.6*	*0.4*	*0.5*	*0.5*	*0.5*	*0.5*

Table 2. Control area parameters

Parameter	Area -1	Area -2	Area -3	Area -4
K_P (Hz/pu)	120	112.5	125	115
T_P (sec)	20	25	20	25
B (pu/Hz)	0.425	0.385	0.359	0.425
T_{ij} (pu/Hz)	$T_{12}=T_{13}=T_{14}=T_{23}=0.545$			

Simulation results and eigenvalue analysis show that the open loop system performance is affected by changing in the K_{pi}, T_{pi}, B_i and T_{jj} more significantly than changes of other parameters. Thus, to illustrate the capability of the proposed strategy in this example, in the view point of uncertainty our focus will be concentrated on variation of these parameters. Hence, for the given power system, we have set our objectives to area frequency regulation and assuring robust stability and performance in the presence of specified uncertainties, load disturbances or exogenous inputs as follows:

1. Holding stability and robust performance for the overall power system and each control area in the presence of 25% uncertainty for the K_{pi}, T_{pi}, B_i and T_{jj}.
2. Minimizing the effects of new input disturbances (η_i, ζ_i, ρ_i) from outside areas on output signals.
3. Getting zero steady state error and good tracking for load demands and disturbances.
4. Maintaining acceptable overshoot and settling time on the frequency deviation signal in each control area.
5. Setting the reasonable limit on the control action signal in the change speed and amplitude view point.

Following, we will discuss application of the proposed strategy on the given power system to achieve the above objectives for each control area separately. Because of similarity and to save space, the first controller synthesis will described in detail and for the other control areas, only the final results will be presented.

5.1. Selection of weighting function for one control area

Uncertainty weights selection: As is mentioned in the previous section, we can consider the specified uncertainty in each area as a multiplicative uncertainty associated with a nominal model. Let $\hat{P}_i(s)$ denote the transfer function from the control input u_i to control output y_i at operating points other than the nominal point. Following a practice common in robust control, we will represent this transfer function as:

$$\hat{P}_i(s) = P_{oi}(s)(1 + \Delta u_i(s) W_{ui}(s)) \tag{17}$$

Then the multiplicative uncertainty block can be expressed as:

$$|\Delta u_i(s) W_{ui}(s)| = \left|(\hat{P}_i(s) - P_{oi}(s)) / P_{oi}(s)\right|;\ P_{oi}(s) \neq 0 \tag{18}$$

W_{ui} is a fixed weighting function containing all the information available about the frequency distribution of the uncertainty, and where $\Delta u_i(s)$ is stable transfer function representing model uncertainty. furthermore, without loss of generality (by absorbing any scaling factor into $W_{ui}(s)$ if necessary, it can be assumed that:

$$|\Delta u_i(s)|_\infty = \sup|\Delta u_i(s)| \leq 1 \tag{19}$$

Thus $W_{ui}(s)$ is such that its respective magnitude Bode plot covers the Bode plot of all possible plants. Using (18) some sample uncertainties corresponding to different values of K_{pi}, T_{pi}, B_i and T_{jj} are shown in Fig.6 for one area. We can see that multiplicative uncertainties have a peak around the 7 rad/s. based on this figure the following multiplicative uncertainty weight was chosen for control design as:

$$W_{u1} = \frac{18.49s^2 + 25.35s + 24.87}{s^2 + 1.81s + 47.77} \tag{20}$$

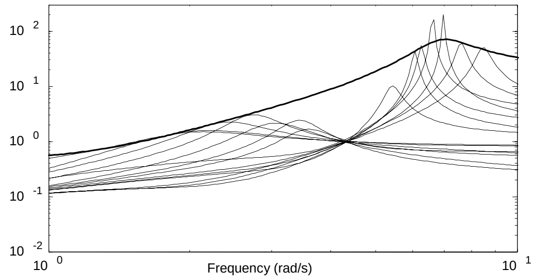


Fig. 6. Uncertainty plot due to change of K_{pi}, T_{pi}, B_i and T_{jj} (Dashed-dot) and $W_{ui}(s)$ (Solied)

Fig.6 clearly shows that attempting to cover the sharp peak around the 7 rad/s will result in large gaps between the weight and uncertainty at other frequency. On other hand a tighter fit at all frequencies using higher order transfer function will result in high order controller. The weight (20) used in our design give a conservative design at around the 7 rad/s, low and high frequency, but it provides a good trade off between robustness and controller complexity. Using the same method, the uncertainty weighting function for area 2, 3 and 4 are calculated as follows:

$$W_{u2} = \frac{19.41s^2 + 23.8s + 18.41}{s^2 + 1.7s + 35.13}$$

$$W_{u3} = \frac{16.28s^2 + 20.18s + 21.39}{s^2 + 2.26s + 38.72} \tag{21}$$

$$W_{u4} = \frac{8.55s^2 + 17.2s + 19.76}{s^2 + 1.03s + 35.02}$$

Performance weights selection: As we discussed in section 4, in order to guarantee robust performance and satisfy the control objectives of LFC problem, we need to choose the performance weights W_{Ci} and W_{Pi} which are associated with control effort and control area error minimization, respectively. The selection of W_{Ci} and W_{Pi} entails a trade off among different performance requirements, particularly good regulation versus peak control action. The weight on the control input W_{Ci} must be chosen close to a differentiator to penalize fast change and large overshoot in the control input. The weight on the output error W_{Pi} must be close to an integrator at low frequencies in order to get zero steady state error, good tracking and disturbances rejection. Finally, it be noted that for rejecting disturbances and assuring a good tracking property, W_{Ci} and W_{Pi} must be selected such that singular value of sensitivity function be reduced at low frequency. More details on how these weights are chosen are given in [18-19]. Based on the above discussion, a suitable set of performance weighting functions for one control area is chosen as:

$$W_{P1} = \frac{0.64s + 0.04}{50(s + 0.0001)}\ ,\quad W_{C1} = \frac{0.01s}{0.0001s + 1} \tag{22}$$

5.2. H_∞ control design based on LMI

According to the synthesis methodology presented in section 2, a decentralized robust H_∞ controller is designed for one control area. The problem formulation and control framework are explained in section 4.

The next step in robust design problem is to redraw the system in the framework as shown in Fig. 4 by using the uncertainty description and developed performance weights. Due to this framework the state space model of generalized plant is computed similar to (15) and control design is reduced to a general LMI formulation. Then the H_∞ control problem is solved using function "*hinflmi*" provided by MATLAB LMI control toolbox [15] to obtain desired controller.

The order of resulting controller is the same as the size of generalized plant (here 10). The controller is reduced to a 5^{th} order with no performance degradation using the standard Henkel norm approximation. The Bode plots of the full order and reduced order controllers are shown in Fig.7. The transfer function of the reduced order controller is given as:

$$K_1(s) = 6.33\times 10^{-5}\,\frac{s^4+10.95s^3+49.95s^2+236.67s+300.24}{s^5+4.97s^4+12.81s^3+13.57s^2+8.62s+0.0038} \quad (23)$$

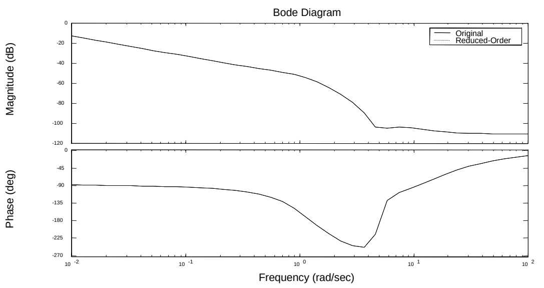


Fig. 7. Bode plot comparison of original and reduced order controller $K_1(s)$

Using the same procedure and setting similar objectives as discussed above the set of suitable weighting function for the other control area synthesis are given in Table 3. The resulting controllers can be approximated by low order controllers as follows:

$$K_2(s) = -6.86\times 10^{-4}\,\frac{s^4-1.88s^3+3.74s^2-42.13s-48.66}{s^5+5.39s^4+16.91s^3+16.8s^2+9.91s+0.0065} \quad (24)$$

$$K_3(s) = 1.53\times 10^{-4}\,\frac{s^4+6.96s^3+32.77s^2+128.88s+103.11}{s^5+4.73s^4+10.11s^3+10.06s^2+5.71s+0.0031}$$

$$K_4(s) = 1.63\times 10^{-3}\,\frac{s^4+4.3s^3+15.7s^2+71.83s+28.05}{s^5+12.20s^4+29.38s^3+33.06s^2+11.86s+0.0078}$$

Table 3. The set of weighting functions

Weight	Area- 2	Area- 3	Area- 4
W_{Pi}	$\frac{0.64s+0.03}{25(s+0.0003)}$	$\frac{0.64s+0.03}{30(s+0.0003)}$	$\frac{0.64s+0.05}{40(s+0.0005)}$
W_{Ci}	$\frac{0.04s}{0.0001s+1}$	$\frac{0.05s}{0.001s+1}$	$\frac{0.5s}{0.0001s+1}$

6. Simulation results

A four-area power system described in section 5 is used as a test system to illustrate behavior of the proposed LFC strategy. In the simulation study, the linear model of a turbine $\Delta P_{VKi}/\Delta P_{TKi}$ in Fig. 1 for each GENCO is replaced by a nonlinear model of Fig. 8 (with $\pm$ 0.015 limits). This is to take GRC into account i.e. the practical limit on the area of change in the generating power of each GENCO. It is noted that GRC would influence the dynamic responses of the system signifycantly and lead to longer overshoot and longer settling time.

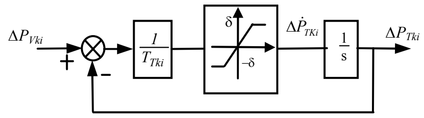


Fig. 8. A nonlinear turbine model with GRC

In this section, the performance of proposed H_∞ controller is compared with conventional PI controller, which is widely used for LFC problem in industry nowadays. Some simulations are carried out for two scenarios of possible contracts under large load disturbances and the following operating conditions.

Case A: The uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} decrease 25% from nominal values.

Case B: The uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} increase 25% from nominal values.

Senario1: *Poolco based Transaction*

In this case GENCOs only participate in load following control of their areas. It is assumed that large step load is demanded by DISCOs 1, 2, 3,4 and 6. i.e.:

$\Delta P_{L1}=50\,MW$, $\Delta P_{L2}=50\,MW$, $\Delta P_{L3}=100\,MW$,
$\Delta P_{L4}=50\,MW$, $\Delta P_{L6}=100\,MW$,

A case of Poolco based contracts between DISCOs and available GENCOs is simulated based on the following AGPM:

$$AGPM^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Power system responses for opera-ting condition case A are depicted in Fig. 9. Using the proposed method, the frequency deviation, area control error quickly goes to zero and the tie line powers and generated powers of GENCOs properly converge to specified values. Since there no contracts of power between GENCOs and DISCOs in other areas, the scheduled steady state power flow based on (10), over the tie-line are zero as shown in Fig. 9. Also it shows the actual generated powers of the GENCOs reach the desired values in the steady state due to (13). i.e.:

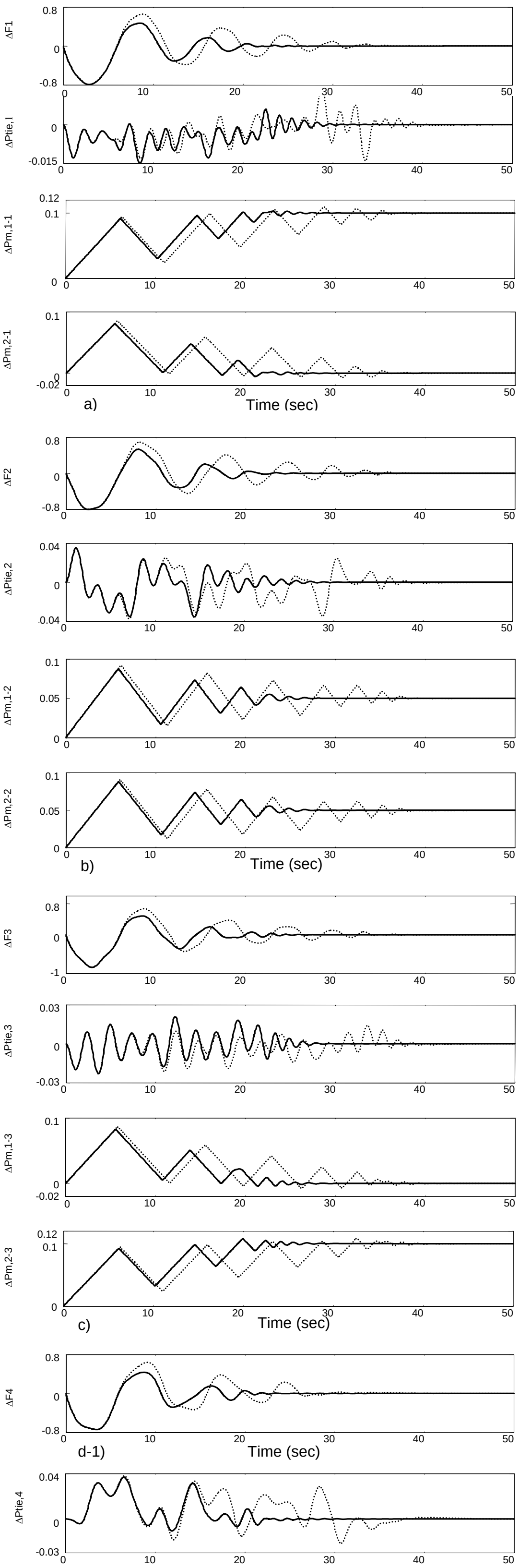
$$\Delta P_{m,1-1} = \sum_{j=1}^{6} apf_{ij}\Delta P_{Lj} = apf_{11}\Delta P_{L1} + apf_{12}\Delta P_{L2} + apf_{13}\Delta P_{L3} + apf_{14}\Delta P_{L4}$$
$$+ apf_{15}\Delta P_{L5} + apf_{16}\Delta P_{L6} = 1\times 0.06 + 1\times 0.04 + 0 + 0 + 0 + 0 = 0.1\,pu$$

And similarly,

$\Delta P_{m,2-1} = \Delta P_{m,1-3} = \Delta P_{m,2-4} = 0$, $\Delta P_{m,1-2} = \Delta P_{m,2-2} = 0.05$,

$\Delta P_{m,2-3} = \Delta P_{m,1-4} = 0.1\,pu$,

As the first GENCOs in area 3 and the second GENCOs in areas 1 and 4 no participate in the LFC task, hence, their change in generated power is zero in the steady state.



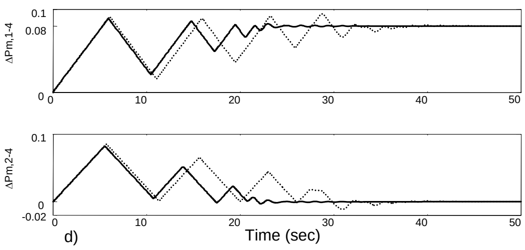


Fig. 9. Power system responses to scenario 1, Soiled ($H\infty$), Dotted (*PI*): a) Area 1 b) Area 2 c) Area 3 d) Area4

<u>Scenario 2</u>: Combination of Poolco Based and Bilateral Transactions

In this case, DISCOs have the freedom to have a contract with any GENCOs. Consider the all the DISCOs contract with the available GENCOs in their and other areas for power as per the following AGPM and requesting load demands:

$$AGPM^T = \begin{bmatrix} 0.4 & 0 & 0.4 & 0 & 0.2 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0.4 & 0 & 0 & 0 & 0.4 \\ 0 & 0 & 0.4 & 0 & 0 & 0.6 & 0 & 0 \\ 0 & 0.4 & 0 & 0.2 & 0.4 & 0 & 0 & 0 \\ 0.8 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

ΔP_{L1}=100 MW, ΔP_{L2}=50 MW, ΔP_{L3}=100 MW, ΔP_{L4}= 80 MW, ΔP_{L5}= 60 MW, ΔP_{L6}=100 MW,

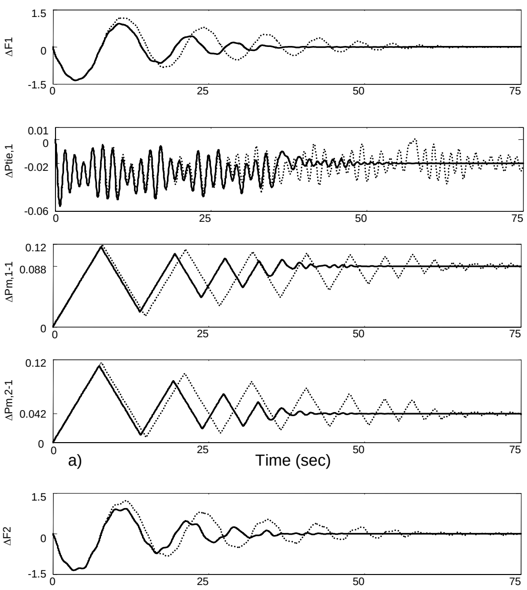
The system in Fig. 5 is simulated using the above data for operating condition case *B* and the results are depicted in Fig. 10. From (10) the scheduled power tie line in four areas is:

$\Delta P_{tie,1}$ = -0.02, $\Delta P_{tie,2}$ = 0.016, $\Delta P_{tie,2}$ =-0.016, $\Delta P_{tie,1}$ =0.02 pu

Fig. 10 shows the actual tie line powers properly converge to the above values using the proposed method. Also the actual generated powers of GENCOs properly reach the desired values (13) in the steady state. i.e.:

$\Delta P_{m,1\text{-}1}$= 0.088, $\Delta P_{m,1\text{-}2}$= 0.042, $\Delta P_{m,2\text{-}1}$= 0.08, $\Delta P_{m,2\text{-}2}$= 0.036, pu

$\Delta P_{m,3\text{-}1}$= 0.052, $\Delta P_{m,1\text{-}2}$= 0.072, $\Delta P_{m,2\text{-}1}$= 0.1, $\Delta P_{m,2\text{-}2}$= 0.02, pu



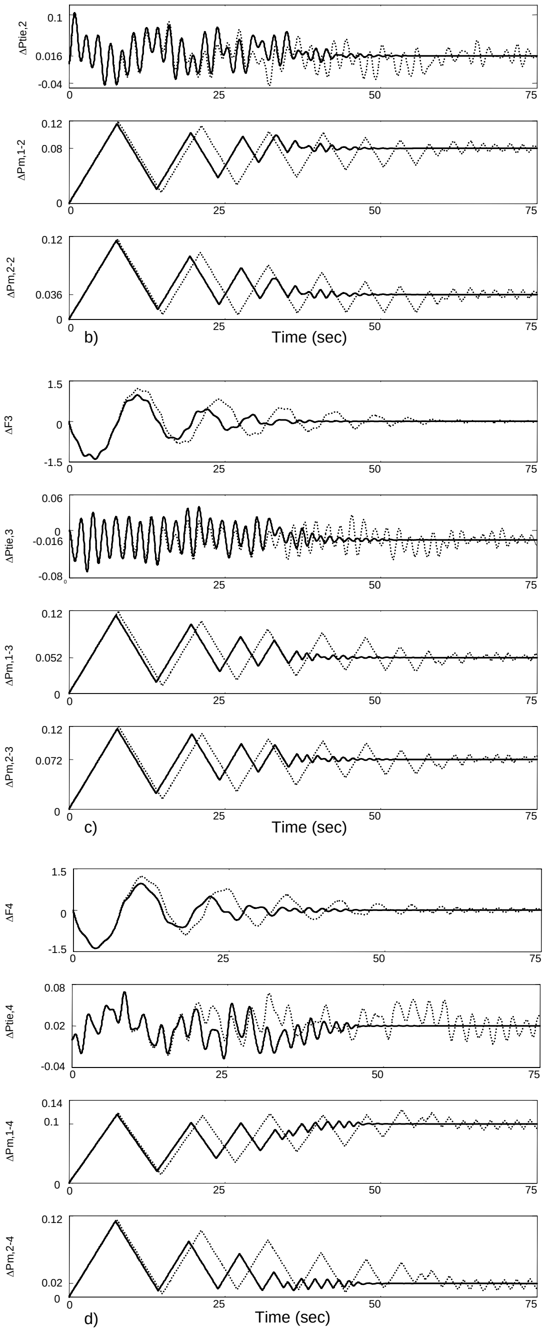


Fig. 10. Power system responses to scenario 2, Soiled ($H\infty$), Dotted (PI): a) Area 1 b) Area 2 c) Area 3 d) Area4

The simulation results in the above scenarios indicate that the proposed control strategy can ensure the robust performance such as frequency tracking and disturbance attenuation for possible contracted scenarios under modeling uncertainties and large area load demands in the presence of GRC.

To demonstrate robust performance of the proposed control strategy, the performance index Figure of Demerit (FD) based on system performance characteristics (suitably weighted) is being used as:

$$FD = (OS \times 10)^2 + (US \times 5)^2 + (t_s \times 0.4)^2 \tag{25}$$

Overshoot (OS), undershoot (US) and settling time (for 5% band of the total step load demand in area 1) of frequency deviation area 1 are considered for evaluation of FD. The numerical results of the performance robustness for two above scenarios in two cases of operating conditions are listed in Table 4. Examination of this Table reveals that the performance of the proposed controller is better than to PI controller.

Table 4. Performance index FD

Method	Scenario 1		Scenario 2	
	Case A	Case B	Case A	Case B
H_∞	145.558	207.043	268.482	497.973
PI	298.816	473.432	574.312	1066.816

7. Conclusion

In this paper a new decentralized robust H_∞ control strategy formulated as a LMI technique has been proposed using the modified LFC scheme in a deregulated power system. To achieve decentralization, the interface between control area and the effects of possible contracts are treated as a set of new disturbance signals in each control area. Synthesis problem introduce appropriate uncertainties for consideration of practical limits and has enough flexibility for setting the desired level of robust performance.

A four-area power system was used as a test system and the proposed decentralized controller has been tested for all types of load following contracts under various operating conditions in the presence of GRC. The results were compared with the result of PI controllers. The simulation results show that the proposed controller not only is effective and gives good dynamical responses compared to PI controller, but also can ensure the robust performance, such as precise reference frequency tracking and disturbance attenuation under possible contracted scenarios for a wide range of area load disturbances. The system performance characteristics in terms of '*figure of demerit*' reveal that the proposed control strategy can be an appropriate control scenario for the real world deregulated power systems.

Appendix A

A.1: Nomenclature

- F area frequency
- P_{Tie} net tie-line power flow turbine power
- P_T turbine power
- P_V governor valve position
- P_C governor set point
- ACE area control error
- apf ACE participation factor
- Δ deviation from nominal value
- K_P subsystem equivalent gain
- T_P subsystem equivalent time constant
- T_T turbine time constant
- T_H governor time constant
- R droop characteristic
- B frequency bias

T_{ij}	tie line synchronizing coefficient between area i and j
P_d	area load disturbance
P_{Lj}	contracted demand of Disco j
P_{ULj}	uncontracted demand of Disco j
$P_{m,ji}$	power generation of GENCO j in area i
P_{Loc}	total local demand
η	area interface
ζ	scheduled power tie line power flow deviation ($\Delta P_{tie,i,\ scheduled}$)

A.2. Gain of PI controllers:
$K_1 = K_2 = K_3 = K_4 = 0.6,$

References:

[1] N. Jaleeli, L. S. Van Slyck, D. N. Ewart, L. H. Fink, and A.G. Hoffmann, "Understanding automatic generation control", *IEEE Trans. on Power Systems*, vol. 7 (3), pp. 1106 - 1122, 1992.

[2] V. Donde, A. Pai and I. A. Hiskens "Simulation and optimization in a AGC system after deregulation", *IEEE Trans. on Power Systems*, vol. 16 (3), pp. 481 - 489, 2003.

[3] J. Kumar, N. G. Hoe and G. Sheble "AGC simulator for price-based operation Part I: Modeling", *IEEE Trans. on Power Systems*, vol. 12 (2), pp. 527 - 532, 1997.

[4] R. D. Christie and A. Bose, "Load frequency control issues in power system operations after deregulation", *IEEE Trans. on Power Systems*, vol. 11 (`3), pp. 1191 - 1200, 1996.

[5] K.Y. Lim, Y. Wang, and R. Zhou, "Robust decentralized load frequency control of multi-area power systems", *IEE Proc. on Gener. Transm. Distrib.* , vol. 143 (5), pp. 377 - 386, 1996.

[6] M. H. Kazemi, M. Karrari and M. B. Menhaj, "Decentralized robust adaptive-output feedback controller for power system load frequency control", *Electrical Engineering*, vol. 84 (2), pp. 75-83, 2002.

[7] A. Feliachi, "Optimal decentralized load frequency control", *IEEE Trans. on Power Systems*, 2, pp. 379 - 384, 1987.

[8] C. M. Liaw, and K. H. Chao, "On the design of an optimal automatic generation controller for interconnected power systems" Int. J. Control, vol. 58, pp. 113 - 127, 1993.

[9] H. L. Zeynelgil, A. Demiroren and N. S. Sengor, "The Application of ANN technique to automatic generation control for multi-area power system", *Electrical Power and Energy Systems*, vol. 24, pp. 545 - 354, 2002.

[10] F. Liu, Y. H. Song, J. Ma. and Q. Lu, "Optimal load frequency control in restructured power systems", *IEE Proc. on Gener. Transm. Distrib.* , vol. 150 (1), pp. 87 - 95, 2003.

[11] D. Rerkpreedapong, A. Hasanovic and A. Feliachi, "Robust load frequency control using genetic algorithms and linear matrix inequalities", *IEEE Trans. on Power Systems*, vol. 18 (2), pp. 855 - 861, 2003.

[12] A. Feliachi, "On load frequency control in a deregulated environment", *IEEE Inter. Conf. on Control Applications*, pp. 437 - 441, 1996.

[13] H. Bevrani, Y. Mitani, and K. Tsuji, "Robust decentralized AGC in a restructured power system", *Energy Conversion and Management*, vol. 45, pp. 2297 - 2312, 2004.

[14] P. Gahinet, and P. Apkarian, "A linear matrix inequality approach to H_∞ control", *Int. J. Robust Nonlinear Control*, vol. 4, pp. 421 - 448, 1994.

[15] P. Gahinet A. Nemirovski, A. J. Laub and M. Chilali. "*LMI control toolbax*", The Mathworks Inc., South Natick, 1995.

[16] *M. B. Djukanovic, M. H. Khammash and V. Vittal,* "Sensitivity based structured singular value approach to stability robustness of power systems", *IEEE Trans. on Power Systems*, vol. 15 (2), pp. 825 - 830, 2000.

[17] H. Shayeghi and M. Karrari, "Theory of µ synthesis for power systems load frequency control", *Journal of Electrical Engineering*, vol. 51, pp. 258 - 263, 2000.

[18] *K. Zhou and J. C. Doyle,* "*Essentials of robust control*", Englewood cliffs, New Jercy, Prentice Hall, pp. 88 - 94, 1999.

[19] M. Karrari, H. Shayeghi, M. B. Menhaj and M. Abedi, "Design of H_∞ load frequency controller in electric power systems", *Amirkabir Journal of Science & Technology*, vol. 11 (41), pp.79-88, 1999.

BIOGRAPHIES

H. Shayeghi received the B.S. and M.S.E. degrees in electrical engineering from KNT University and Amirkabir University of Technology in 1996 and 1998, respectively. He is currently a PH. D. candidate at the Iran University of Science and Technology, Tehran, Iran. His research interests are in the application of robust control, artificial intelligence to power system control design and power system restructuring.

H. A. Shayanfar received the B.S. and M.S.E. degrees in electrical engineering in 1973 and 1979, respectively. He is received the PH. D degree in electrical engineering from Michigan State University, U.S.A., in 1981. Currently, He is a Full Professor at Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research interests are in the application of artificial intelligence and robust methods to power system control design, dynamic load modeling, power system observability studies and voltage collapse.

İDARƏ OLUNMAYAN ENERJİ SİSTEMLƏRİNDƏ YÜK TEZLİYİNİN XƏTTİ MATRİS QEYRİBƏRABƏRLİYİNDƏN İSTİFADƏ ETMƏKLƏ MƏRKƏZLƏŞDİRİLMƏMİŞ DAYANIQLI NƏZARƏTİ

ŞAYEHİ H., ŞƏYANFƏR H.A.

Məqalədə idarə olunmayan enerji sistemlərində yük tezliyinin xətti matris qeyribərabərliyindən istifadə etməklə mərkəzləşdirilməmiş dayanıqlı nəzarətinə yeni yanaşma verilmişdir.

ДЕЦЕНТРАЛИЗОВАННЫЙ УСТОЙЧИВЫЙ КОНТРОЛЬ ЧАСТОТЫ НАГРУЗКИ В РАЗРЕГУЛИРОВАННОЙ ЭНЕРГЕТИЧЕСКОЙ СИСТЕМЕ С ИСПОЛЬЗОВАНИЕМ ЛИНЕЙНЫХ МАТРИЧНЫХ НЕРАВЕНСТВ

Г. ШАЕГИ, Г.А. ШАЯНФАР

В статье сформулирована новая стратегия децентрализованного устойчивого контроля с использованием модифицированной схемы разрегулированной энергетической системы.