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Multi-Area Load Frequency Control in a Deregulated Power System Using Optimal Output Feedback Method

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Abstract-- **In this paper, the dynamical response of the load-frequency control problem in the deregulated environment is improved with a pragmatic viewpoint. In the practical environment, access to all of the state variables of system is limited and measuring all of them is also impossible. To solve this problem, in this paper the optimal output feedback method is proposed. In the output feedback method, only the measurable state variables within each control area is required to use for feedback. The optimal control law is determined by minimizing a performance index under the output feedback conditions leading to a coupled matrix equation.**

The proposed method is tested on a two-area power system with different contracted scenarios. The results of the proposed controller are compared with the full-state feedback method. The results are shown that when the power demands changed, the output feedback method have a good ability to tracking of contracted and/or non-contracted demands. In fact, this method provides a control system that satisfied the load frequency control requirements and with a reasonable dynamic response.

I. NOMENCLATURE

ACE	Area Control Error
APF	Area Participation Factor
CPF	Contract Participation Factor
DISCOs	Distribution Companies
GENCOs	Generation Companies
ΔP_M	Power generation of GENCOs
ΔP_d	Un-contracted demand or area load disturbance
ΔP_L	Contracted demand of DISCOs
ΔP_{Loc}	Local contracted demand
d_n	Total demand
T_{12}	Tie line synchronizing coefficient between areas

II. INTRODUCTION

IN recent years, major changes have been introduced into the structure of electric power utilities all around the world. The reason for this was to improve efficiency in the operation of the power system by means of deregulating the industry and opening it up to private competition. In this new framework, consumers will have an opportunity to make a choice among competing providers of electric energy. The net effect of such changes will mean that the transmission, generation and distribution systems must now adapt to a new set of rules dictated by open markets.

In the power system, any sudden load perturbations cause the deviation of tie-line exchanges and the frequency fluctuations. So, load frequency control (LFC) is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. The main goal of the load frequency control of a power system is to maintain the frequency of each area and tie-line power flow within specified tolerance by adjusting the MW outputs of LFC generators so as to accommodate fluctuating load demands.

With the restructuring of electric markets, Load-Frequency Control requirements should be expanded to include the planning functions necessary to insure the resources needed for LFC implementation are within the functional requirements. So all of the methods that may be proposed must be having a good ability to tracking contracted or non-contracted demands and can be used in a practical environment.

A lot of studies have been made about LFC in a deregulated environment over the last decades. These studies try to modify the conventional LFC system to take into account the effect of bilateral contracts on the dynamics [1]-[2] and improve the dynamical transient response of system under competitive conditions [3]-[6]. To improve the transient response, various control strategies, such as linear feedback, optimal control and Kalman estimator method, have been proposed [3], [4]. However, these methods are idealistic or need some information of the system states, which are very difficult to access completely.

There have been continuing efforts in designing LFC with better performance using intelligence algorithms or robust methods [5]–[6]. The proposed methods show good dynamical

responses, but some of them suggest complex and or high order dynamical controllers [6], which are not practical for industry practices yet.

In this paper, the dynamical response of the load-frequency control problem in the deregulated environment is improved with a pragmatic viewpoint. Because in the practical environment (real world), access to all of the state variables of system is limited and the measuring all of them is impossible. To solve this problem, the optimal output feedback method is proposed. In the output feedback method, only the measurable state variables within each control area are required to use for feedback. In this method when the system is subjected to wide changes in the operating conditions, the effect of changes in parameters and inputs of system on the feedback gains, is very low. The optimal control law is determined by minimizing a performance index under the output feedback conditions. So the matrix equations are solved in optimal manner to find the best output feedback gain and design a good controller. The proposed method is tested on a two-area power system with two contracted scenarios. The results of the proposed controller are compared with full-state feedback control. The results are shown that when the power demands changed, the state feedback method is so sensitive and have a weak ability to tracking un-contracted demands (in the case of LFC with disturbance input ΔP_d), whereas the proposed method is so rational technique with so good tracking of contracted and/or un-contracted demands.

III. DEREGULATED POWER SYSTEM FOR LFC WITH TWO AREAS

In the competitive environment of power system, the vertically integrated utility (VIU) no longer exists. Deregulated system will consist of GENCOs, DISCOs, transmission companies (TRANSCOs) and independent system operator (ISO). However, the common AGC goals, i.e. restoring the frequency and the net interchanges to their desired values for each control area, still remain. The power system is assumed to contain two areas and each area includes two GENCOs and also two DISCOs as shown in Fig. 1 and the block diagram of the generalized LFC scheme for a two area deregulated power system is shown in Fig. 2. A DISCO can contract individually with any GENCO for power and these transactions are made under the supervision of ISO.

To make the visualization of contracts easier, the concept of a "DISCO participation matrix" (DPM) will be used [2]; Essentially, DPM gives the participation of a DISCO in contract with a GENCO. In DPM, the number of rows has to be equal to the number of GENCOs and the number of columns has to be equal to the number of DISCOs in the system. Any entry of this matrix is a fraction of total load power contracted by a DISCO toward a GENCO. As a result, total of entries of column belong to $DISCO_i$ of DPM is $\sum_i cpf_{ij} = 1$. The corresponding DPM for the considered power system having two areas and each of them including two DISCOs and two GENCOs is given as follows:

$$DPM = \begin{array}{c} Area1 \\ \\ Area2 \end{array} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \begin{array}{c} G \\ E \\ N \\ C \\ O \end{array}$$

Where cpf represents ''contract participation factor'' and is like signals, that carry information as to which GENCO has to follow load demanded by which DISCO.
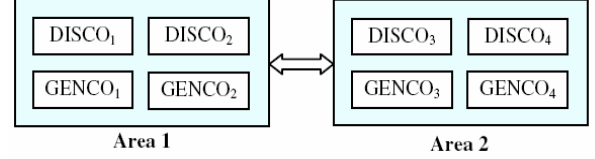

Fig. 1. The configuration of the power system

The actual and scheduled steady state power flow on the tie line are given as

$$\Delta P_{tie1-2,scheduled} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj} \quad (1)$$

$$\Delta P_{tie1-2,actual} = (2\pi.T_{12}/s).(\Delta f_1 - \Delta f_2) \quad (2)$$

And at any given time, the tie line power error $\Delta P_{tie1-2,error}$ is defined as

$$\Delta P_{tie1-2,error} = \Delta P_{tie1-2,actual} - \Delta P_{tie1-2,scheduled} \quad (3)$$

This error signal is used to generate the respective ACE signals as in the traditional scenario [2].

$$ACE_1 = B_1\Delta f_1 + \Delta P_{tie1-2,error} \quad (4)$$

$$ACE_2 = B_2\Delta f_2 + \Delta P_{tie2-1,error} \quad (5)$$

The closed loop system in Fig. 2 is characterized in state space form as

$$\dot{x} = A.x + B.u \quad (6)$$

$$y = C.x \quad (7)$$

A fully controllable and observable dynamic model for a two-area power system is proposed, where x is the state vector and u is the vector of power demands of the DISCOs.

$$u = [\Delta P_{L1} \quad \Delta P_{L2} \quad \Delta P_{L3} \quad \Delta P_{L4} \quad \Delta P_{d1} \quad \Delta P_{d2}]^T$$

$$x = [\Delta f_1 \quad \Delta f_2 \quad \Delta P_{m1} \quad \Delta P_{m2} \quad \Delta P_{m3} \quad \Delta P_{m4}$$

$$\int ACE_1 \quad \int ACE_2 \quad \Delta P_{tie1-2,actual}]^T$$

The deviation of frequency, turbine output and tie-line power flow within each control area are measurable outputs that can be used for output feedback.

The dotted and dashed lines show the demand signals based on the possible contracts between GENCOs and DISCOs that carry information as to which GENCO has to follow a load demanded by that DISCO. These new information signals were absent in the traditional LFC scheme. As there are many GENCOs in each area, the ACE signal has to be distributed among them due to their ACE participation factor in LFC.
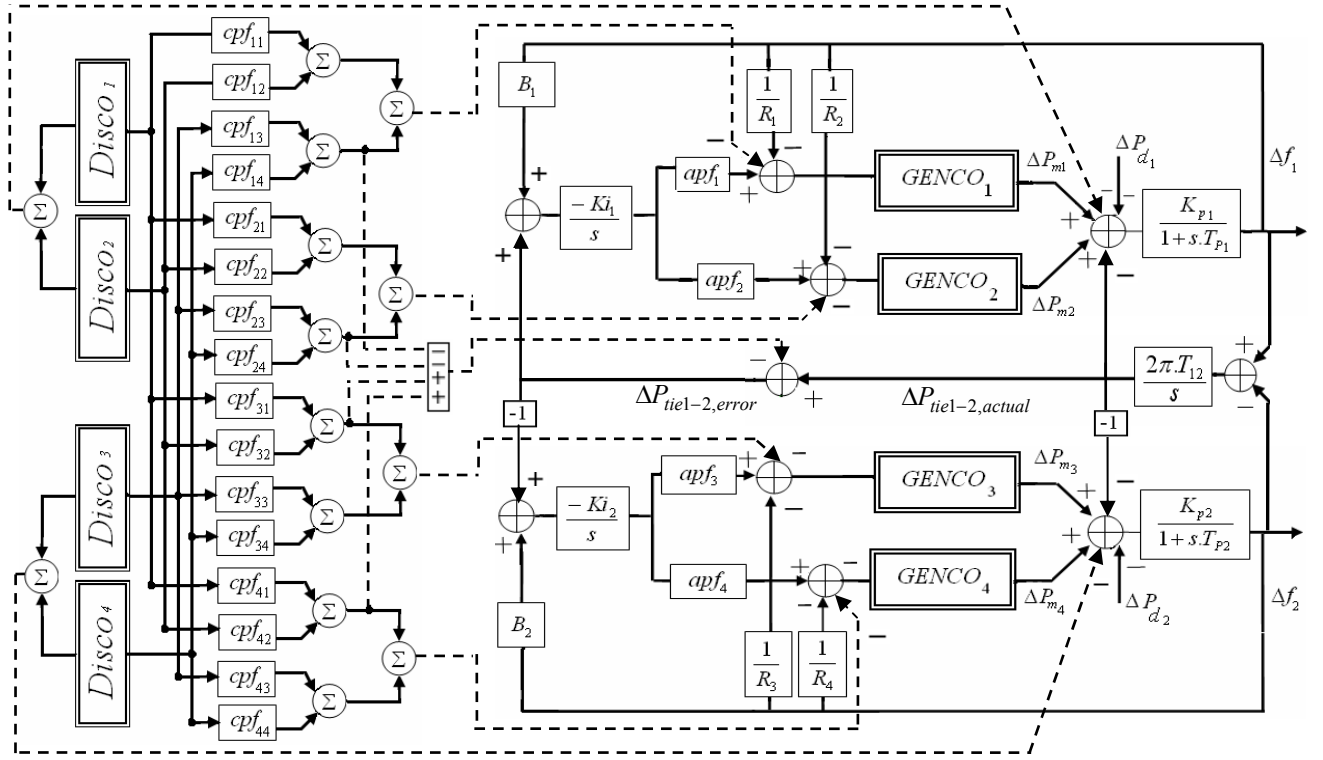
Fig. 2. Modified LFC system in a deregulated environment

We can write:

$$d_n = \Delta P_{Loc,n} + \Delta P_{dn} \tag{8}$$

$$\Delta P_{Loc,n} = \sum_j \Delta P_{Lj} \tag{9}$$

$$\Delta P_{dn} = \sum_j \Delta P_{dj} \tag{10}$$

IV. CONTROLLER DESIGN

In this paper, to improve the dynamical response of system, optimal output feedback method is proposed, but to have a complete research, full-state feedback method are compared with proposed method too.

- *Optimal Output Feedback Control*

For the system that is defined by equations (6) and (7), feedback control law is:

$$u = -K.y \tag{11}$$

The objective of this regulator for the system may be attained by minimizing a performance index *(J)* of the type:

$$J = 1/2 \int [x^T(t).Q.x(t) + u^T(t).R.u(t)]dt \tag{12}$$

Or

$$J = 1/2 \int x^T (Q + C^T K^T R K C) x \ dt \tag{13}$$

By substituting equation (11) into (6), the closed-loop system equation are found to be

$$\dot{x} = (A - BKC)x = A_c.x \tag{14}$$

This dynamical optimization may be converted to an equivalent static one as follow that is easier to solve. So a

constant, symmetric, positive-semidefinite matrix *P* can be defined, as:

$$d(x^T Px)/dt = -x^T (Q + C^T K^T R K C)x \tag{15}$$

$$J = 1/2 \ x^T(0)Px(0) - 1/2 \ \lim_{t \to \infty} x^T(t).P.x(t) \tag{16}$$

Assuming that the closed-loop system is stable so that *x(t)* vanishes with time, this becomes:

$$J = 1/2 \ x^T(0)Px(0) \tag{17}$$

If *P* satisfies (15), then we may use (14) to see that:

$$-x^T (Q + C^T K^T R K C)x = d(x^T Px)/dt = \dot{x}^T Px + x^T P\dot{x}$$
$$= x^T (A_c^T P + PA_c)x \tag{18}$$

$$g \equiv A_c^T P + PA_c + C^T K^T R K C + Q = 0 \tag{19}$$

We may write (17) as:

$$J = 1/2 \ .tr(PX) \tag{20}$$

Where the $n \times n$ symmetric matrix *X* is defined as:

$$X = E\{x(0).x^T(0)\} \tag{21}$$

So the best *K* must be selected, to minimize (13) subject to the constraint (19) on the auxiliary matrix *P*. To solve this modified problem, Lagrange multiplier approach will be used and the constraint will be adjoined by defining this Hamiltonian:

$$H = tr(PX) + tr(gS) \tag{22}$$

Now to minimize (20), partial derivatives of *H* with respect to all the independent variables *P*, *S* and *K* must be equal to zero.

$$0 = \partial H / \partial S = A_c^T P + PA_c + C^T K^T R K C + Q \tag{23}$$

$$0 = \partial H / \partial P = A_c S + S A_c^T + X \quad (24)$$

$$0 = 1/2 \cdot (\partial H / \partial K) = RKCSC^T - B^T PSC^T \quad (25)$$

To obtain the output feedback gain K with minimizing the (12), these three coupled equations (23), (24) and (25) must be solved simultaneously. The first two of these are Lyapunov equations and the third is an equation for the gain K. If R is positive definite and is nonsingular, then (25) may be solved for K [8]:

$$K = R^{-1} B^T PSC^T (CSC^T)^{-1} \quad (26)$$

To solve these equations, an iterative algorithm can be used.

V. SIMULATION RESULTS

In this section, to illustrate the performance and robustness of the proposed control against parametric uncertainties and un-contracted loads variations, simulations are performed for two scenarios of possible contracts under various operating conditions and large load demands. For performance comparison, the full-state feedback control is also simulated and the results are presented. The simulations are done using MATLAB platform. The power system parameters are given in Tables 1 and 2 (Appendix).

A. Scenario 1: transaction based on free contracts

In this scenario, DISCOs have the freedom to have a contract with any GENCO in their or other areas. So all the DISCOs contract with the GENCOs for power base on following DPM:

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

It is considered that each DISCO demands 0.1 *pu MW* total power from GENCOs as defined by entries in *DPM* and each GENCO participates in AGC as defined by following *apf*:

$$apf_1 = 0.75 \quad , \quad apf_2 = 1 - apf_1 = 0.25$$
$$apf_3 = 0.5 \quad , \quad apf_4 = 1 - apf_3 = 0.5$$

The simulation results for this case are given in Figs. 3–5, respectively. As shown in Fig. 3, in the steady state, any GENCO generations must match the demand of the DISCOs in contract with it, as expressed as follows:

$$\Delta P_{mi} = \sum_j cpf_{ij} \Delta P_{Lj} \quad (27)$$

So for this scenario, we have:

$$\Delta P_{m1} = 0.105 \quad pu \ MW \ , \quad \Delta P_{m2} = 0.045 \quad pu \ MW$$
$$\Delta P_{m3} = 0.195 \quad pu \ MW \ , \quad \Delta P_{m4} = 0.055 \quad pu \ MW$$

Using the proposed method, the frequency deviation of each area and the tie-line power have a good dynamic response in comparing with initial system without controller (Figs. 4, 5).
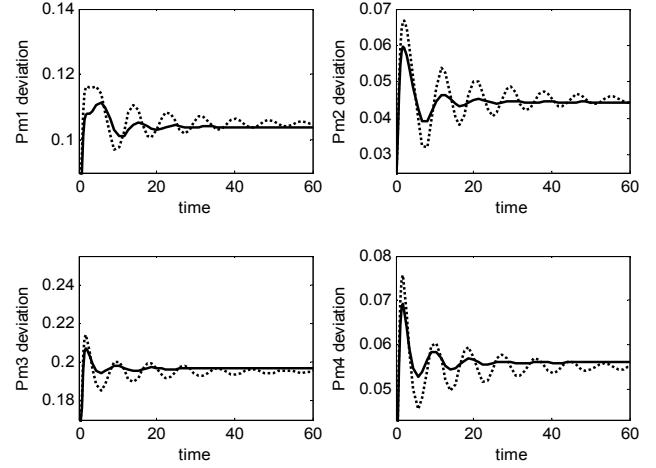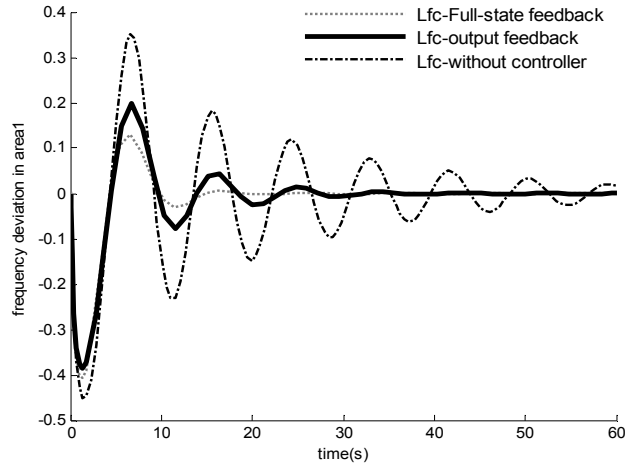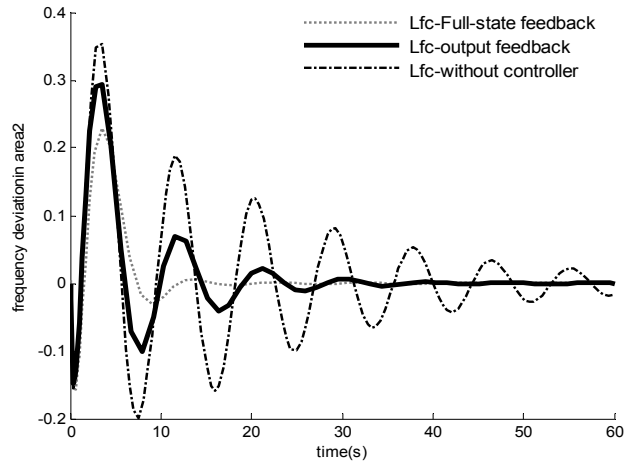

Fig. 3. GENCOs power change (pu MW): Solid (Optimal output feedback), Dotted (without controller)

(a)

(b)

Fig. 4. (a) Frequency deviation in area 1 (rad/s), (b) Frequency deviation in area 2 (rad/s): Dotted (Full-state feedback control), Solid (Optimal output feedback), Dot-dashed (Without controller)

The off diagonal blocks of the DPM correspond to the contract of a DISCO in one area with a GENCO in another area.
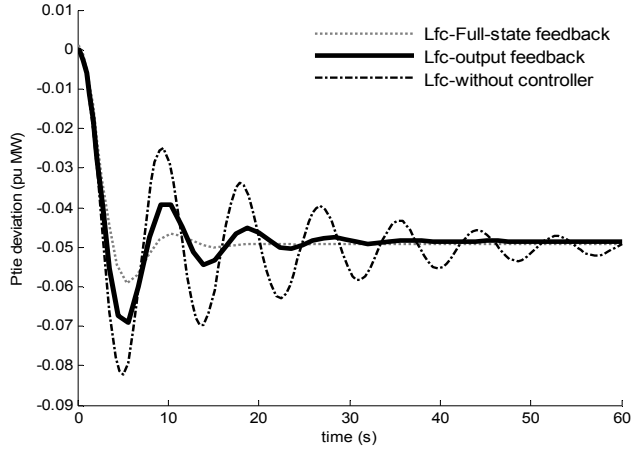
Fig. 5. Deviation of tie line power flow (pu MW): Dotted (Full-state feedback control), Solid (Optimal output feedback), Dot-dashed (Without controller)

As Fig. 5 shows, the tie-line power flow properly converges to the specified value of equation (1) in the steady state, i.e.

$$\Delta P_{tie1-2,scheduled} = -0.05 \quad pu$$

B. Scenario 2: contract violation

In this case, DISCOs may violate a contract by demanding more or less power than that specified in the contract. This excess power is reflected as a local load of the area (un-contracted demand). In this section, it is assumed that in addition to the specified contracted load demands DISCO$_1$ in area 1, demand 0.1 *pu MW* as large un-contracted loads. The *DPM* is the same as in scenario 1 and the un-contracted load in each area is taken up by the GENCOs in the same area and the tie-line powers are the same as in scenario 1 in the steady state (Figs. 5, 8). The purpose of this scenario is to test the effectiveness of the proposed controller against uncertainties and large load disturbances ΔP_d. Using full-state feedback control dynamic response of system will improved so well, but base on these simulations (scenario 2) we will see that this method have a weak ability to tracking un-contracted demands changes. The power system responses for this scenario are shown in Figs. 6–8.

The un-contracted load of DISCO$_1$, is taken up by the GENCOs of their areas according to the ACE participation factors in the steady state. So for this scenario, the actual generated power of the GENCOs in the areas in the steady state must match the demand of the DISCOs as expressed as follows:

$$\Delta P_{mi} = \sum_j cpf_{ij}\Delta P_{Lj} + apf_i \ \Delta P_{dn} \qquad (28)$$

$$\Delta P_{dn} = \sum_j \Delta P_{dj} \qquad (29)$$

As shown in Fig. 6, using equations (28) and (29), the actual generated power of the GENCOs in the areas in the steady state is given by $\Delta P_{d1} = 0.1 \quad pu$, $n, j = 1$
And

$$\Delta P_{m1} = 0.105 + (0.75 \times 0.1) = 0.18 \quad puMW$$

$$\Delta P_{m2} = 0.045 + (0.25 \times 0.1) = 0.07 \quad puMW$$

$$\Delta P_{m3} = 0.195 \quad puMW \quad , \quad \Delta P_{m4} = 0.055 \quad puMW$$

The results of frequency deviations and tie line power flow are shown in Figs. 7-8, respectively (for scenario 2). These figures also are comparing the performance of the full-state feedback control with the proposed controller.
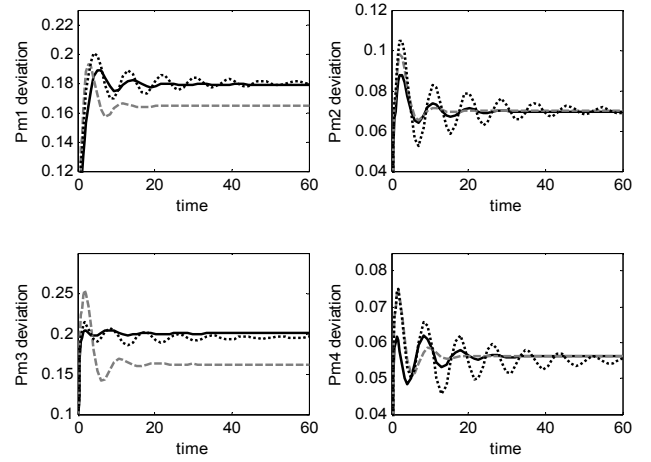

Fig. 6. GENCOs power change (pu MW): Solid (Optimal output feedback), Dashed (Full-state feedback control), Dotted (Without controller)
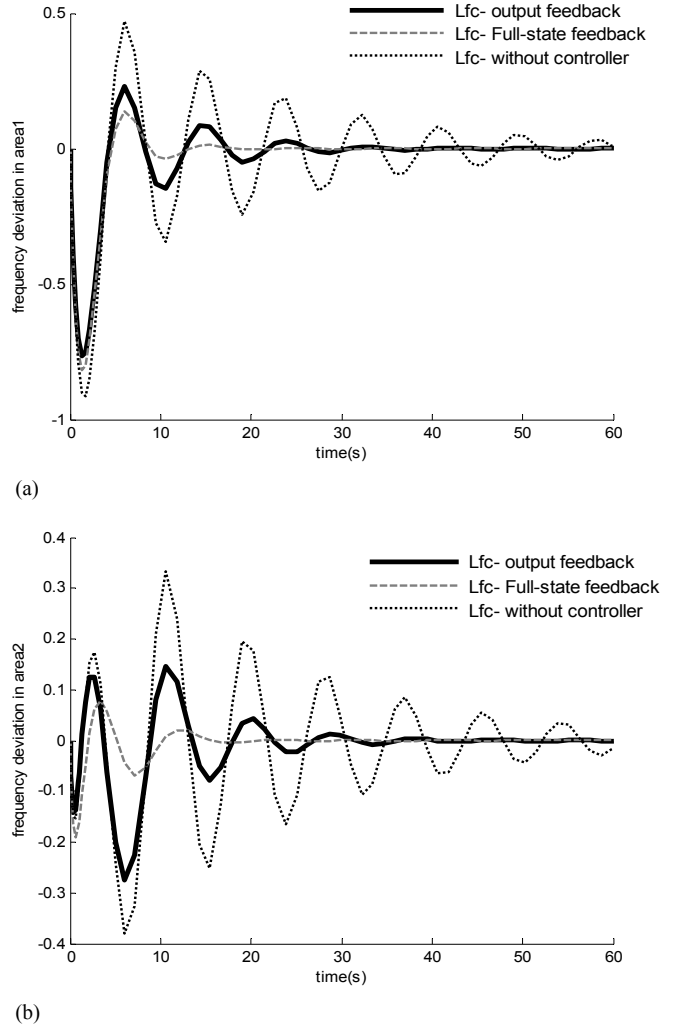

(a)

(b)

Fig. 7. (a) Frequency deviation in area1 (rad/s), (b) Frequency deviation in area 2 (rad/s): Solid (Optimal output feedback), Dashed (Full-state feedback control), Dotted (Without controller)
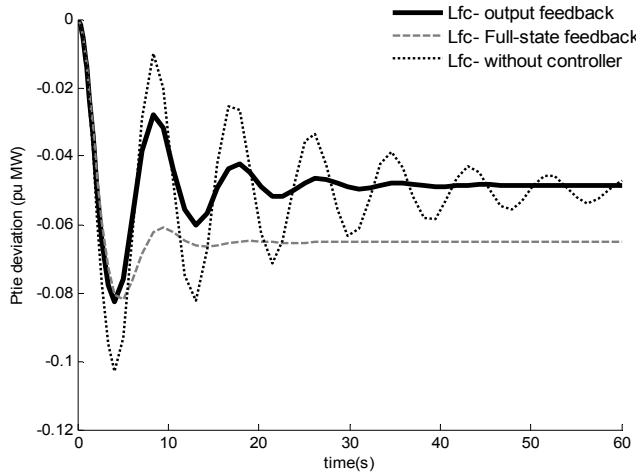
Fig. 8. Deviation of tie line power flow (pu MW): Solid (Optimal output feedback), Dashed (Full-state feedback control), Dotted (Without controller)

The simulation results shown that the proposed optimal output feedback controller track the un-contracted load changes and achieve good robust performance better than the full-state feedback controllers for a wide range of load disturbances (Figs. 6-8).

VI. CONCLUSION

Modified LFC after deregulation, is an important issue in the power system studies. A new optimal controller for the LFC problem in deregulated power systems is proposed using the modified LFC scheme in this paper.

In research of LFC problem, a special attention should be given to the load frequency control requirements and ability of used controller in tracking of load changes under the market conditions and must be know that some of the state variables are not accessible for measuring in a practical environment. So with a pragmatic viewpoint, an optimal output feedback controller is presented for satisfy all of this conditions. The proposed method is tested on a two-area power system with different contracted scenarios. The results of the proposed controller are compared with the full-state feedback controller too.

The superiority in implementing such controller resides in its simplicity, that is, no need for un-measurable states, and telemetry problem and is suitable for on-line applications. The results are shown that when the power demands changed, the full-state feedback method is so sensitive and have a weak ability to tracking un-contracted demands, whereas the output feedback method is so rational technique with so good tracking of contracted and/or un-contracted demands.

Proposed strategy is very effective and guarantees good robust performance against parametric uncertainties, load and parameter changes.

In fact, this method provides a control system that satisfied the load frequency control requirements and with a reasonable dynamic response.

VII. APPENDIX

The parameter values of the power system are given in Tables 1 and 2:

Table 1
GENCOs parameter

GENCOs Parameters	Area1		Area2	
	GENCO$_1$	GENCO$_2$	GENCO$_3$	GENCO$_4$
$T_T(s)$	0. 32	0. 30	0. 03	0. 32
$T_G(s)$	0. 06	0. 08	0. 06	0. 07
$R\ (Hz/pu)$	2.4	2.5	2.5	2.7

Table 2
Control area parameters

Control area parameters	Area1	Area2
$K_P\ (pu/Hz)$	102	102
$T_P\ (s)$	20	25
$B\ (pu/Hz)$	0. 425	0. 396
$T_{ij}\ (pu/Hz)$	0. 245	

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IX. BIOGRAPHIES

Javad Sadeh was born in Mashhad, IRAN in 1968. He received the B.Sc. and M.Sc. in electrical engineering from Ferdowsi University of Mashhad in 1990 and 1994 respectively and the Ph.D from Sharif University of Technology, Tehran Iran with the collaboration of the electrical engineering laboratory of the National Polytechnic Institute of Grenoble (INPG), France in 2000. Since then he served as an assistant professor at the Ferdowsi University of Mashhad. His research interests are Power System Protection, Electromagnetic Transients in Power System and Restructuring.

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