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Simulation of Two-Area AGC System in a Competitive Environment Using Reduced-Order Observer Method

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Keywords—Automatic generation control, restructured power system, reduced order-observer, optimal full-state feedback

Abstract—In this paper, a reduced-order observer controller is proposed to solve the automatic generation control problem in a deregulated power system that operates under deregulation based on the bilateral policy scheme. In the practical environment (real world), access to all of the state variables of system is limited and measuring all of them is also impossible. So when we have fewer sensors available than the number of states or it may be undesirable, expensive, or impossible to directly measure all of the states, using a reduced-order observer is proposed. A proposed design, which is presented in this paper, has been developed in order to over-come this problem.

The proposed strategy is tested on a two-area power system and compared with the optimal full-state feedback method by means of simulation. The results are shown that this method improved the dynamic response of system and provides a control system that satisfied the load frequency control requirements.

I. NOMENCLATURE

B	Frequency bias
ACE	Area Control Error
R	Droop characteristic
LFC	Load Frequency Control
apf	Area participation factor
DPM	Disco Participation Matrix
cpf	Contract participation factor
AGC	Automatic Generation Control
T _T	Turbine time constant
T _G	Governor time constant
K _P	Power system equivalent gain
T _P	Power system equivalent time constant
ΔP _M	Power generation of GENCOs

ΔP _L	Contracted demand of DISCO
GENCOs	Generation Companies
DISCOs	Distribution Companies
TRANSCO	Transmission Company
VIU	Vertically Integrated Utility
ISO	Independent System Operator
EMS	Energy Management systems
T ₁₂	Tie-line synchronizing coefficient between areas

II. INTRODUCTION

DURING the past years, the experiences of the electric power industry have been heavily conditioned by economic regulation. 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. This is a global trend and similar structural changes have occurred elsewhere in other industries, i.e. in the telecommunications and airline transportation industries. 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. The electricity power utilities in many countries have been, or are being, restructured.

This new development in the power system restructuring requires innovations in the Energy Management systems (EMS). The introduction of market system requires a lot of changes in power system operations. Especially, the EMS should be innovated to be adapted to electricity market systems.

In the power system, any sudden load perturbations cause the deviation of tie-line exchanges and the frequency fluctuations. So, load frequency control is a very important issue in power system operation. LFC is also simultaneous

automatic generation control. Automatic Generation Control is a means of automatically controlling the outputs of power-generating units to accomplish economic dispatch, and maintain system frequency and power flows over tie lines at desired levels. AGC is performed at energy control centers or energy coordination centers using energy management systems. The AGC is one of main functions of EMS, and is also required to be innovated for the adaptation to the market systems with several kinds of the bidding strategies. Its basic theory is much consolidated and well known [1]–[5]. With the restructuring of electric markets, AGC requirements should be expanded to include the market contracts and planning functions. So Automatic Generation Control is one of the ancillary services traditionally associated with the activity of electricity generation and the additional modifications were made at the AGC controller to meet the requirements of deregulation processes. Thus, the AGC system keeps track of the momentary active power imbalance, detects it, corrects it and communicates an adequate amount of the balance energy service basis, to the market operating system.

During the last decade several proposed AGC scenarios have attempted to adapt traditional AGC schemes to the change of environment in the power systems under deregulation [6]–[13]. Some of these studies try to modify the conventional AGC system to take into account the effect of bilateral contracts on the dynamics [6]–[8] or try to improve the dynamical transient response of system under competitive conditions [9]–[13]. The conventional control strategy for the LFC problem is to take the integral of the ACE as the control signal. An integral controller provides zero steady state deviation, but it exhibits poor dynamic performance. To improve the transient response, various control strategies, such as linear feedback, optimal control and Kalman estimator method, have been proposed [9], [10]. There have been continuing efforts in designing LFC with better performance using intelligence algorithms or robust methods [11]–[13]. The proposed methods show good dynamical responses, but some of them suggest complex and or high order dynamical controllers.

In this paper, the dynamical response of the AGC problem in the competitive environment is improved with a practical viewpoint. Because in the real world, access to all of the state variables of system is limited and measuring all of them is also impossible. So when we have fewer sensors available than the number of states or it may be undesirable, expensive, or impossible to directly measure all of the states, using a reduced-order observer will be useful and practical. A proposed design, which is presented in this paper, has been developed in order to over-come this problem. The proposed method is evaluated on a two-area power system under a contracted scenario. The results of the proposed controller are compared with the optimal full state feedback control by means of computer simulations.

The results are shown that this proposed method improved the dynamic response of system and provides a control system that satisfied the load frequency control requirements.

III. RESTRICTED POWER SYSTEM FOR AGC 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 [3]; Essentially, DPM gives the participation of a DISCO in contract with a GENCO.

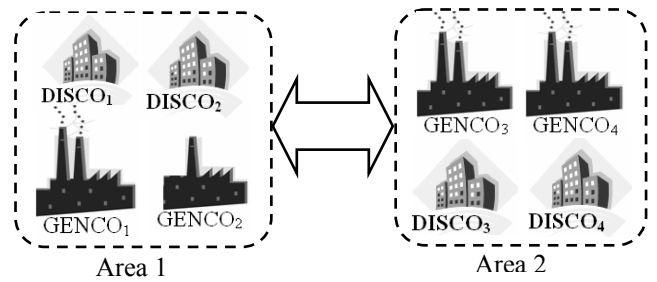


Fig. 1. The configuration of the power system

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 to the considered power system having two areas and each of them including two DISCOs and two GENCOs is given as follows:

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

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.

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

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

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

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

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

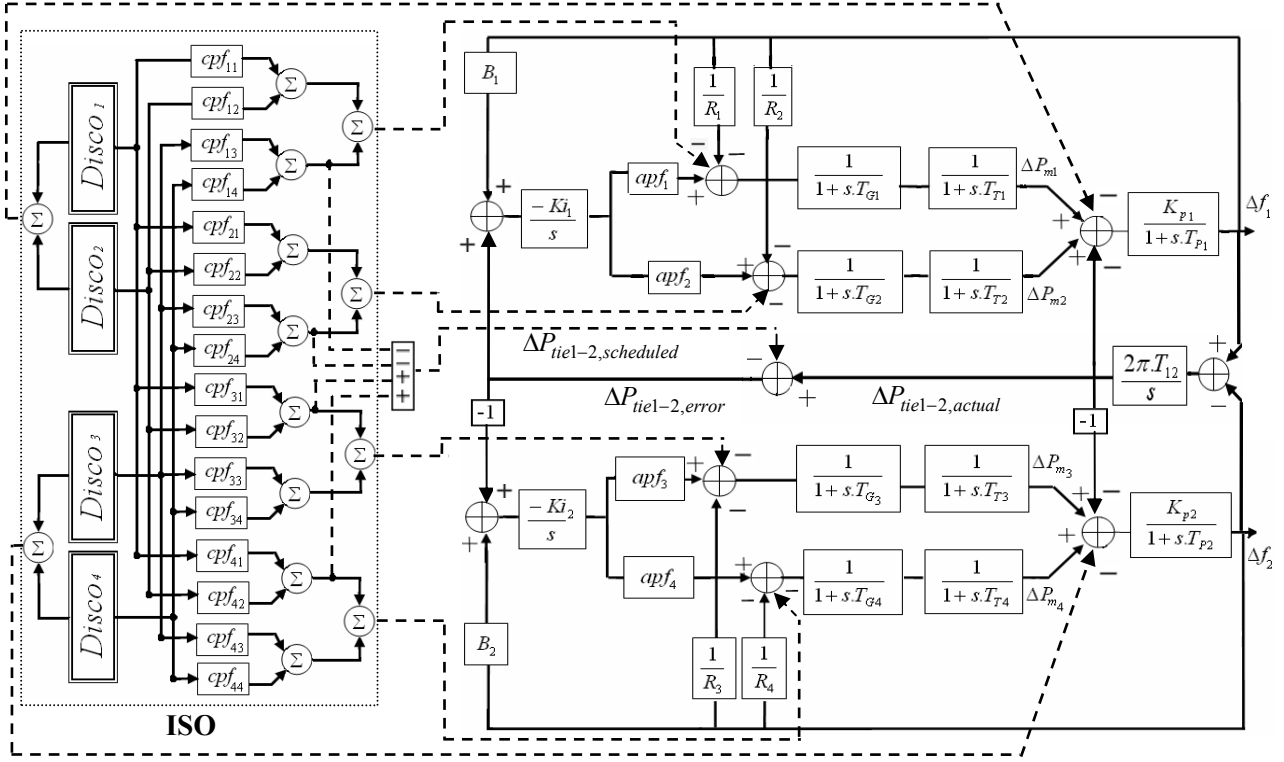


Fig. 2. Modified LFC system in a deregulated environment for this study

This error signal is used to generate the respective ACE signals as in the traditional scenario [3].

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

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

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

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

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

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.

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

$$x = [\Delta f_1 \quad \Delta f_2 \quad \Delta P_{G1} \quad \Delta P_{G2} \quad \Delta P_{G3} \quad \Delta P_{G4}$$

$$\Delta P_{m1} \quad \Delta P_{m2} \quad \Delta P_{m3} \quad \Delta P_{m4} \quad \int ACE_1 \quad \int ACE_2 \quad \Delta P_{tie1-2,actual}]^T$$

The deviation of frequency, turbine output and tie-line power flow within each control area are measurable outputs, other states are not measurable and must be estimated to use for reduced-order method.

The dotted and dashed lines (in Fig. 2) 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.

IV. CONTROLLER DESIGN

In this paper to improve the dynamical response of system pragmatically, reduced order observer method is proposed, but to have a complete research, optimal full state feedback control is designed and the results are compared. When feedback control law is $u = -K \cdot x$, if some of the state variables in vector x is not measurable, observers may be used [10]. A full order observer estimates all the states in a system, regardless whether they are measurable or not but when some of the state variables are measurable using a reduced-order observer is so better.

- *Reduced-Order Observer Controller:*

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

$$u = -K \cdot y \quad (8)$$

We suppose that only some of the state variables are measurable. These are defined as output variable such as:

$$y_{p \times 1} = C_{p \times n} \cdot x_{n \times 1} \quad , p < n \quad (9)$$

The interesting case is when we have less sensors available (p) than the number of states (n), $p < n$.

Suppose we can measure some of the state variables contained in x , and the state vector x is partitioned into two sets, x_1 : variables that can be measured directly, x_2 : variables that cannot be measured directly.

$$\begin{cases} \dot{x}_1 = A_{11} \cdot x_1 + A_{12} \cdot x_2 + B_1 \cdot u \\ \dot{x}_2 = A_{21} \cdot x_1 + A_{22} \cdot x_2 + B_2 \cdot u \end{cases} \quad (10)$$

and the observation equation is:

$$y = C_1 \cdot x_1 \quad (11)$$

Where C_1 is square and nonsingular matrix. The full order observer for the states is then:

$$\begin{cases} \dot{\hat{x}}_1 = A_{11} \cdot \hat{x}_1 + A_{12} \cdot \hat{x}_2 + B_1 \cdot u + L_1 \cdot (y - C_1 \cdot \hat{x}_1) \\ \dot{\hat{x}}_2 = A_{21} \cdot \hat{x}_1 + A_{22} \cdot \hat{x}_2 + B_2 \cdot u + L_2 \cdot (y - C_1 \cdot \hat{x}_1) \end{cases} \quad (12)$$

But we do not need to solve first observer equation for x_1 because these states can be solved directly using equation (11):

$$\hat{x}_1 = x_1 = C_1^{-1} \cdot y \quad (13)$$

In this case the observer for those states that cannot be measured directly is designed as follows:

$$\dot{\hat{x}}_2 = A_{21} \cdot C_1^{-1} \cdot y + A_{22} \cdot \hat{x}_2 + B_2 \cdot u \quad (14)$$

This is a dynamic system of the same order as the number of state variables that cannot be measured directly. The dynamic behavior of this reduced order observer is governed by the eigenvalues of A_{22} , a matrix over which the designer has no control. Since there is no assurance that the eigenvalues of A_{22} are suitable, we need a more general system for the reconstruction of x_2 . We take:

$$\dot{\hat{x}}_2 = L \cdot y + z \quad (15)$$

where:

$$\dot{z} = F \cdot z + G \cdot y + H \cdot u \quad (16)$$

Define the estimation error as follows:

$$e = x - \hat{x} = \begin{bmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} 0 \\ e_2 \end{bmatrix} \quad (17)$$

and we get:

$$\begin{aligned} \dot{e}_2 &= \dot{x}_2 - \dot{\hat{x}}_2 \\ &= A_{21} \cdot x_1 + A_{22} \cdot x_2 + B_2 \cdot u - L \cdot \dot{y} - \dot{z} \\ &= A_{21} \cdot x_1 + A_{22} \cdot x_2 + B_2 \cdot u \\ &\quad - LC_1 \cdot \dot{x}_1 - F \cdot z - G \cdot y - H \cdot u \\ &= A_{21} \cdot x_1 + A_{22} \cdot x_2 + B_2 \cdot u - LC_1 (A_{11} \cdot x_1 + \\ &\quad A_{12} \cdot x_2 + B_1 \cdot u) - F(\hat{x}_2 - L \cdot y) - G \cdot y - H \cdot u \end{aligned} \quad (18)$$

Since:

$$\hat{x}_2 - L \cdot y = x_2 - e_2 - L \cdot y = x_2 - e_2 - LC_1 \cdot x_1 \quad (19)$$

we get:

$$\begin{aligned} \dot{e}_2 &= F e_2 + (A_{21} - LC_1 A_{11} - G C_1 + F L C_1) x_1 \\ &\quad + (A_{22} - LC_1 A_{12} - F) x_2 + (B_2 - LC_1 B_1 - H) u \end{aligned} \quad (20)$$

In order for the error to be independent of x_1 , x_2 , and u , the matrices multiplying x_1 , x_2 , and u must vanish:

$$\begin{cases} F = A_{22} - LC_1 A_{12} \\ H = B_2 - LC_1 B_1 \\ G = (A_{21} - LC_1 A_{11}) C_1^{-1} + F L \end{cases} \quad (21)$$

Then:

$$\dot{e}_2 = F \cdot e_2 \quad (22)$$

And for stability of the observer dynamic system, the eigenvalues of F must lie in the left hand-side of s plane. Therefore, we see that the problem of reduced order observer is similar to the full order observer with $(A_{22} - LC_1 A_{12})$ playing the role of $(A - LC)$. The block diagram of this reduced-order observer is shown in Fig. 3.

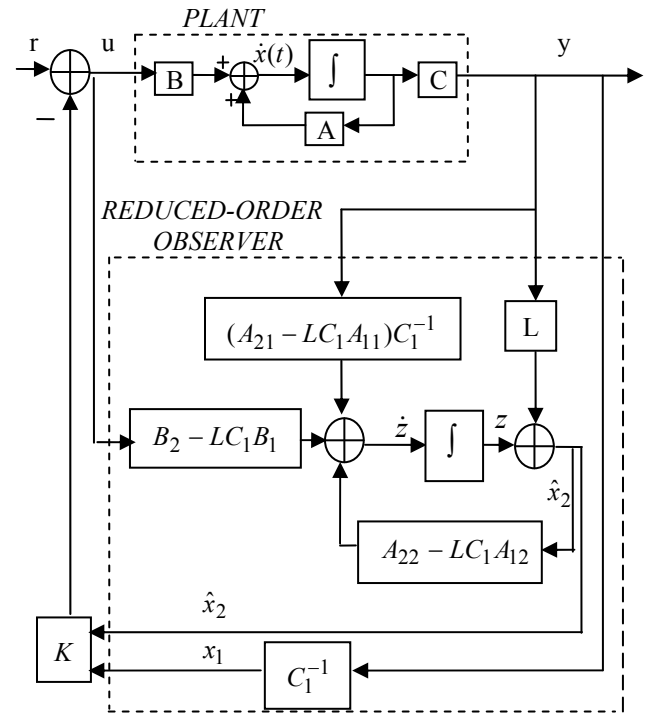


Figure 3: Block diagram of reduced order observer

V. SIMULATION RESULTS

In this section, to illustrate the performance of the proposed controller against load variations, simulations are performed for one scenario of possible contracts under various operating conditions and large load demands and it is assumed that all of the changes in load demands occur in bilateral contract and there is no any violation of contracted demands.

In this scenario the performance of the proposed controller is compared with full state feedback controller. The simulations are done using MATLAB platform. The power system parameters are given in Tables 1 and 2 (Appendix).

A. Scenario : 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 based on following DPM:

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

Base of this DPM, GENCO₂ doesn't have any contract with other DISCOs. So it is considered that each DISCO demands 0.1 pu MW total power from other GENCOs as

defined by entries in DPM and these GENCOs participates in AGC as defined by following apf :

$$\begin{aligned} apf_1 &= 0.75, & apf_2 &= 1 - apf_1 = 0.25 \\ apf_3 &= 0.5, & apf_4 &= 1 - apf_3 = 0.5 \end{aligned}$$

If un-contracted loads are absent, ACE participation factors affect only the transient behavior of the system and it does not affect steady state behavior.

As shown in Fig. 4, in the steady state, any GENCO generation must match the demand of the DISCOs in contract with it, as expressed as follows:

$$\Delta P_{mi} = \sum_j cpf_{ij} \Delta P_{Lj} \quad (23)$$

So for this scenario, we have:

$$\begin{aligned} \Delta P_{m1} &= 0.5 (0.1) + 0.25 (0.1) + 0 + 0.3 (0.1) \\ &= 0.105 \text{ puMW} \end{aligned}$$

$$\Delta P_{m2} = 0.0 \text{ puMW}$$

$$\Delta P_{m3} = 0.22 \text{ puMW}$$

$$\Delta P_{m4} = 0.075 \text{ puMW}$$

The results for this case are given in Figs. 4–6. 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.

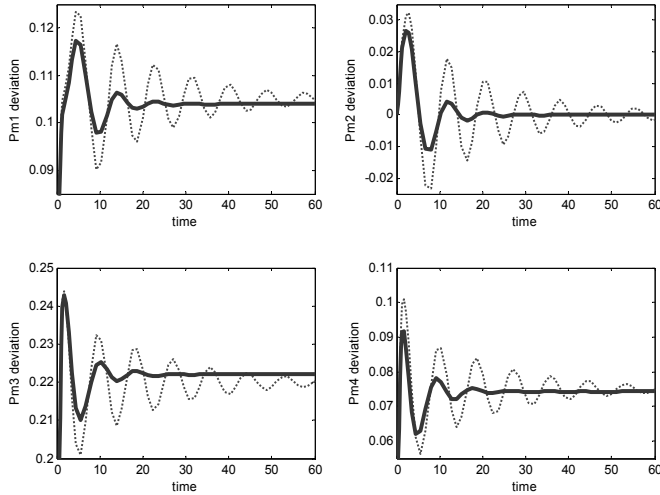
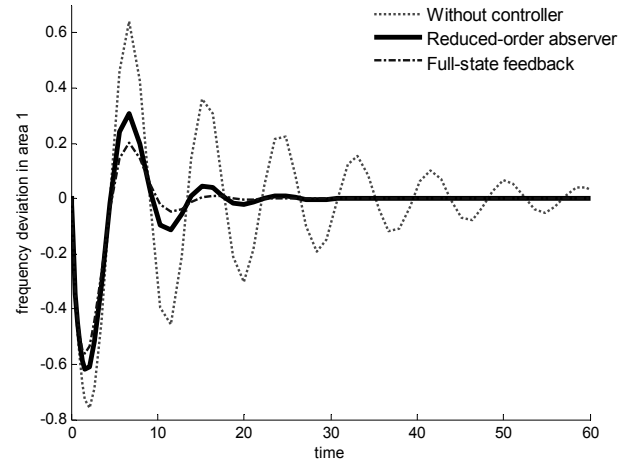


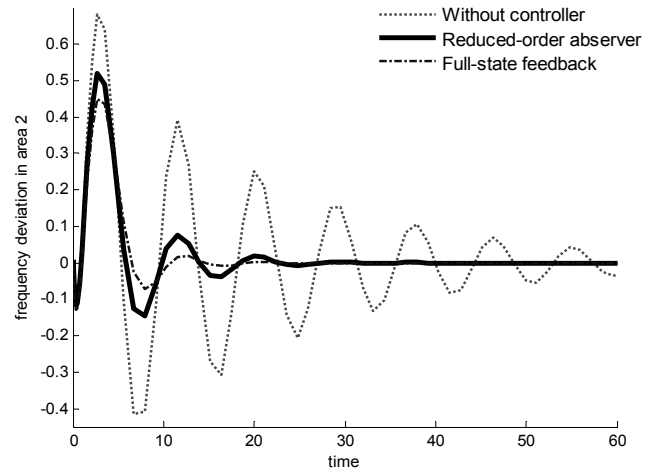
Fig. 4. GENCOs power change (pu MW): Solid (With reduced-order observer control), Dotted (without controller).

The results of frequency deviations and tie line power flow are shown in Figs. 5 and 6, respectively. These figures also are comparing the performance of the proposed controller with the optimal full-state feedback.

The off diagonal blocks of the DPM correspond to the contract of a DISCO in one area with a GENCO in another area. As Fig. 6 shows, the tie line power flow properly converges to the specified value of equation (1) in the steady state (Fig. 6), i.e. $\Delta P_{tie1-2,scheduled} = -0.095 \text{ puMW}$



(a)



(b)

Fig. 5. (a) Frequency deviation in area1 (rad/s), (b) Frequency deviation in area2 (rad/s): Dotted (Without controller), Solid (Reduced-order observer control), Dot-dashed (Optimal full-state feedback)

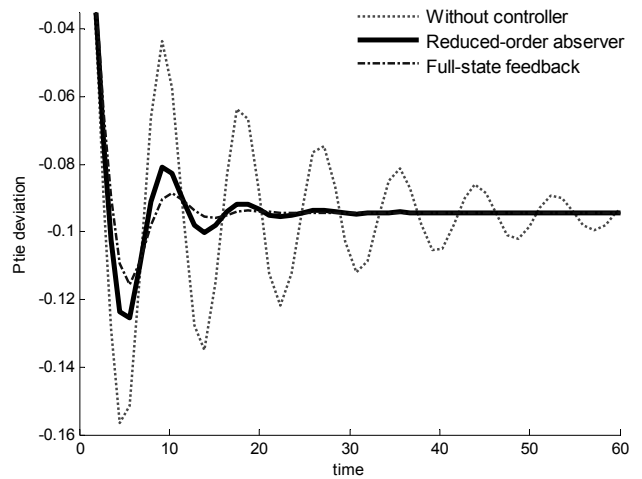


Fig. 6. Deviation of tie line power flow (pu MW): Dotted (Without controller), Solid (Reduced-order observer control), Dot-dashed (Optimal full-state feedback)

VI. CONCLUSION

In this paper, automatic generation control of the power system after deregulation including bilateral contracts is investigated. In a practical environment some of the state variable in AGC system such as output of governors, *ACE* or integration of *ACE*, are not measurable. Because of this, a reduced order observer is proposed for estimation of un-measurable states.

In order to demonstrate the effectiveness of the proposed method, the control strategy described in section IV, is applied to the power system described in section III.

This controller by using the states that are estimated, allocates generating unit's output according to a deregulation scenario. The performance of the proposed controller is evaluated through the simulation of two area power system.

Analysis reveals that the proposed technique gives good results and uses of this method reduce the peak deviations of frequencies, tie-line power, time error and inadvertent interchange. It can be concluded that the application of reduced-order observer controller to AGC of interconnected power system will be provided a practical viewpoint. Also this method can be used in a large AGC power system as a local estimator.

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VIII. 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
$T_I(s)$	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	

IX. BIOGRAPHIES



Elyas Rakhshani was born in Mashhad, Iran in 1982. He received the B.Sc. degree in the power engineering from Islamic Azad University of Iran, Birjand branch, Iran in 2004 and M.Sc. degree in Control Engineering from Islamic Azad University of Iran, Gonabad branch, Iran in 2008. His research interests are Power System Control, Dynamics and Operation, Optimal Control and neural computing.



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.