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

[1]K. P. Singh Parmar, [2]S. Majhi, Member, IEEE, and [3]D. P. Kothari, Senior Member, IEEE

***Abstract*—In this paper, the dynamical response of the load frequency control problem in an interconnected power system is improved with a pragmatic viewpoint. In practice, access to all the state variables of system is not possible and also their measurements are not feasible. Usually only a reduced number of state variables or linear combinations thereof, are available. To resolve this difficulty, in this paper optimal output feedback method is proposed which uses only the measurable state variables. The optimal control is determined by minimizing a performance index under the proposed output feedback conditions.**

The effectiveness of the method is demonstrated on the two equal area interconnected thermal power system. The results indicate that the proposed controller exhibits better performance. In fact, the control system designed on this method satisfies the load frequency control requirements with a reasonable dynamic response. The proposed method has several desirable properties such as good sensitivity and robustness behavior.

***Index Terms*—Area control error, Load frequency control, Optimal control, PI Output feedback.**

I. NOMENCLATURE

ACE_i area control error of area i

P_{rti} rated power capacity of area i

f nominal system frequency

D_i system damping of area i

T_{SG} speed governor time constant

T_T steam turbine time constant

T_{PS} power system time constant

R governor speed regulation parameter

K_{PS} power system gain

B frequency bias parameter

β_i ith area frequency response characteristics

$a_{12} = \frac{P_{rt1}}{P_{rt2}}$

T_{12} synchronizing coefficient

$w_i = \Delta P_{Di}$ incremental load change in area i

II. INTRODUCTION

THE successful operation of interconnected power system requires the matching of total generated power with total load demand and associated system losses. The operating point of a power system changes with time, and hence, these systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas, which may yield undesirable effects [1] [19]. In the power system, any sudden load perturbations cause the deviation of tie line exchange and the frequency fluctuations. There are two variables of interest, namely, frequency and tie line power exchanges. Their variations are weighted together by a linear combination to a single variable called the area control error (ACE). The 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 [1] [3]. The main aim of the LFC is to maintain the frequency of each area and tie line power flow at specified levels by adjusting the Real power outputs of generators so as to accommodate fluctuating load demands [8] [20].

A lot of studies have been made about LFC over last decades. To improve the transient response, various control strategies, such as linear feedback, full state feedback control and Kalman estimator method have been proposed [10] [11] [16]. 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 intelligent algorithms or robust methods [3]. The proposed methods show good dynamical responses, but some of them suggest complex and or high order dynamical controllers, which are not practical for industry practices yet. In multi area power system, dynamic response is difficult to obtain by the transfer

1st Author is Assistant Director (Technical) with Centre for Advanced Management & Power Studies, National Power Training Institute, Faridabad, India,121003(Phone:+919654260217,email:kpsingh_jss@rediffmail.com)

2nd Author is Professor and Head of the Department of Electronics and Communication Engineering, Indian Institute of Technology, Guwahati, Assam, India 781039 (email:smajhi@iitg.ernet.in)

3rd Author is Former Director (in charge) of IIT, Delhi. He is currently Vice Chancellor of VIT University, Vellore (TN), India, 632014 (email:dpk0710@yahoo.com)

978-1-4244-7781-4/10/$26.00 ©2010 IEEE

function approach because of complexity of blocks and multi input and multi output situation. A more organized and more conveniently carried out analysis is through the state space approach [1]. Probably the most important contribution modern optimal control theory has made to the control engineer is the ability to handle a large multivariate control problem with ease. The engineer has only to represent the control system in state variable form and specify the desired performance mathematically in terms of a cost to be minimized. A unique or best controller in the sense of minimizing the cost may be designed by applying well proven theories and techniques [1]. Application of the optimal control theory to power system has shown that an optimal load frequency controller can improve the dynamic stability of a power system [10].

In this paper, the dynamical response of the LFC problem is improved with a practical point of view. Because practically access to all of the state variables of system is limited and measurement of all of them is not feasible. A controller design is presented in this paper to overcome this problem. The control problem is a multiobjective optimization task, namely the regulation of the state trajectories and minimizing the control efforts. The elements of the weights on the states (Q) and the controls (R) are indicators of the relative importance of each of them with respect to others. The design matrices Q and R are defined by most appropriate design consideration of minimizing the excursions of state variables/vectors to be controlled about their steady values**.** It is well known that changing these matrices can modify the transient behavior of the closed system. The proposed PI optimal output feedback method is evaluated on a two-area power system .The results of the proposed controller are compared with the optimal full state feedback control and Integral optimal output feedback control by means of computer simulations. The result indicate that this proposed method improved the dynamic response of system considered and provides a control system that satisfied the LFC requirements.

III. MATHMATICAL BACKGROUND

Modern control theory is to be applied to design an optimal load frequency controller for a two-area system [21]. In accordance with modern control terminology ΔP_{ref1} and ΔP_{ref2} will be referred to as control inputs u_1 and u_2. In the conventional approach u_1 and u_2 were provided by the integral of ACEs. In modern control theory approach u_1 and u_2 will be created by a linear combination of all the system states (full state feedback approach) or a linear combination of states to be controlled/measurable states (output feedback approach) [1][21].

The Generalized linear model of the power system may be described in state space form as

$$\dot{x} = Ax + Bu \qquad (1)$$

with $x(0) = x_0$

$$y = Cx \qquad (2)$$

Where

x is a state vector of dimension n×1, n no. of states

u is a control vector of dimension m×1, m no. of control variables

y is a output vector of dimension p ×1, p no of output variables

A, B and C are constant matrices with appropriate dimensions.

The performance of the system is specified in terms of a cost that is to be minimized by the optimal controller.

$$J = \frac{1}{2}\int_0^\infty \left(x^T Q x + u^T R u\right)dt \qquad (3)$$

Where

Q is nXn positive semi definite symmetric state cost weighting matrix

R is mXm positive semi definite symmetric control cost weighting matrix

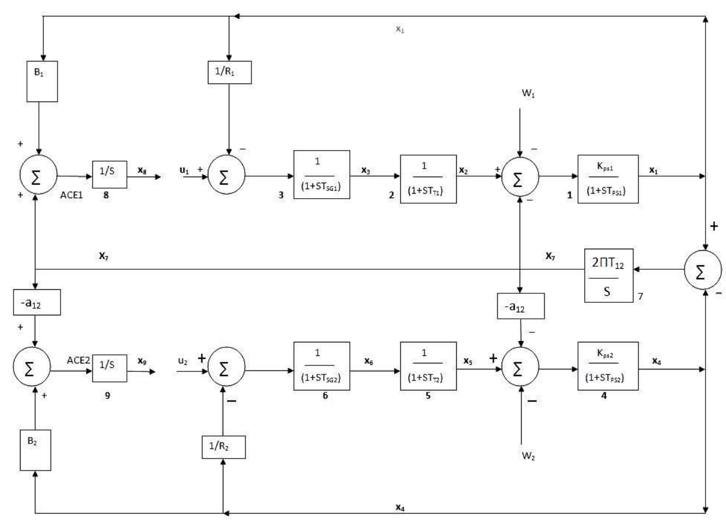

Fig. 1. State space model of a two area interconnected Power System.

The matrices Q and R are defined for the problem under consideration through the following design considerations [1] [8]:

1. Excursions of ACEs about their steady values are minimized. The steady values of ACEs are of course zero.
2. Excursions of $\int ACEdt$ about the steady values are minimized. The steady values of $\int ACEdt$ are of course constants.
3. Excursions of control vector about their steady values are minimized. The steady value of the control vector is of course a constant.

The optimal controller that minimizes the cost of the system in state variable form is a function of the present states of the system weighted by the components of a constant gain matrix K_1 of dimension mXn and can be defined by

$$u = -K_1 x \qquad (4)$$

K_1 can be obtained from the solution of the reduced matrix Riccati equation given below.

$$A^T P_1 + P_1 A - P_1 B R^{-1} B^T P_1 + Q = 0 \quad (5)$$

$$K_1 = R^{-1} B^T P_1 \quad (6)$$

The acceptable solution of K_1 is that for which the system remains stable. For Stability all the eigen values of the matrix $(A - BK_1)$ should have negative real parts. From equation (4), we get the optimal control of our choice.

So for it was assumed that all the states are available for feedback. Practically it is very difficult and costly to measure and to have readily available information of all the states in most of the large power systems. Usually reduced number of state variables or a linear combination thereof is available. The output feedback controller is as described below

$$u = -Ky \quad (7)$$

where K is an output feedback gain matrix of dimension (m×p). In the optimal control scheme the control inputs are generated by means of feedbacks from all the controlled output states with feedback constants to be determined in accordance with optimality criterion. The linear model given by equation (1) and (2) can be arranged as

$$\dot{x} = (A - BKC)x = A_C x \quad (8)$$

The PI may be expressed in terms of K as

$$J = \frac{1}{2}\int_0^{\infty} \left(x^T (Q + C^T K^T R K C \right) x dt \quad (9)$$

The design problem is now to select the gain K so that J is minimized subject to dynamical constraint

$$\dot{x} = (A - BKC)x \quad (10)$$

This dynamical optimization problem may be converted into an equivalent static one that is easier to solve. After applying the suitable optimization techniques, we obtain the following Optimal Gain Design Equations:

$$0 = A_c^T P + P A_c + C^T K^T R K C + Q \quad (11)$$

$$0 = A_c S + S A_c^T + X \quad (12)$$

$$K = R^{-1} B^T P S C^T (C S C^T)^{-1} \quad (13)$$

where

$A_c = A - BKC$

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

If initial states are assumed to be uniformly distributed on the unit sphere, then $X=I$, X is a n×n symmetric matrix. In many applications *x(0)* may not be known, this dependence is typical of output feedback design. It is usual to sidestep this problem by minimizing not the PI but its expected value [17], $X = E\{J\}$

$$E\{J\} = \frac{1}{2} E\{x^T(0) P x(0)\} = \frac{1}{2} tr(PX) \quad (14)$$

The Optimal cost can be given by

$$J_O = tr(PX) \quad (15)$$

The equations (11) and (12) are Lyapunov equations and the equation (13) is an equation for the gain K. To obtain the output feedback gain K minimizing the J_O, these three coupled equations may be solved by some iterative technique [17].

IV. SYSTEM INVESTIGATED

The AGC system investigated consists of two interconnected thermal generating areas of equal size. There are identical governors and non-reheat type thermal turbines considered in both of the areas. The linearised models of governors and non-reheat turbines are considered for study [9]. Fig.1 shows the AGC model with state variables. A bias setting *Bi=βi* is considered in both areas. MATLAB version 7.0 has been used to obtain dynamic response for Δf_1, Δf_2, ΔP_{tie} for 1% step load perturbation in either area. The typical system parameters considered are given in appendix. For formulating the state variable model, the conventional feedback loops are opened as shown in Fig. 1. State variables are defined as the outputs of all the blocks having either an integrator or a time constant. The system has n=9 state variables, $x_1 = \Delta f_1$, $x_4 = \Delta f_2$, $x_2 = \Delta P_{T1}$, $x_5 = \Delta P_{T2}$, $x_8 = \int ACE_1 dt$, $x_9 = \int ACE_2 dt$ and the linear combinations thereof, refer fig.1.State variables $x_1 = \Delta f_1$, $x_4 = \Delta f_2$, $x_8 = \int ACE_1 dt$ and $x_9 = \int ACE_2 dt$ are taken as controlled output feedback signal for the design of PI output feedback controller and state variables $x_8 = \int ACE_1 dt$ and $x_9 = \int ACE_2 dt$ are taken as controlled output feedback signal for obtaining the Integral optimal output controller gain.

The optimums gains of full state controller, Integral output feedback controller and PI output feedback controller have been obtained by running the MATLAB codes generated on the basis of methods described in mathematical background. The computer simulations are carried out with the optimum gains obtained.

System matrices for two-area system under study are

$$A = \begin{bmatrix}
-\frac{1}{T_{PS1}} & \frac{K_{PS1}}{T_{PS1}} & 0 & 0 & 0 & 0 & -\frac{K_{PS1}}{T_{PS1}} & 0 & 0 \\
0 & -\frac{1}{T_{T1}} & \frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{R_1 T_{SG1}} & 0 & -\frac{1}{T_{SG1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{T_{PS2}} & \frac{K_{PS2}}{T_{PS2}} & 0 & a_{12}\frac{K_{PS2}}{T_{PS2}} & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{T_{T2}} & \frac{1}{T_{T2}} & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{R_2 T_{SG2}} & 0 & -\frac{1}{T_{SG2}} & 0 & 0 & 0 \\
2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 \\
B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & B_2 & 0 & 0 & -a_{12} & 0 & 0
\end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{1}{T_{SG1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{SG2}} & 0 & 0 & 0 \end{bmatrix}$$

V. Simulation Results

The optimum values of controller gains for (1) full state feedback, (2) Integral optimal output feedback and (3) PI Optimal output feedback controller are obtained by minimizing the performance Index as described in mathematical back ground. Dynamic responses of the system are obtained for 1% step load perturbation in area-1 through computer simulation. The data for the system considered for this study has been given in Appendix. The dynamic responses are as depicted in Fig.2, Fig.3 and Fig.4.It has been observed that output feedback controllers gives better dynamic responses as compared to full state feedback response. However Dynamic responses obtained through PI and Integral output feedback controllers are more and less same.

VI. Conclusion

In this paper the proposed controller is tested on a two equal area interconnected power system and its dynamic responses are compared with optimal full state feedback controller and Integral optimal output feedback controller. Although the paper discusses about two-area interconnected power system, the proposed method can theoretically be extended for multi-area interconnected power system involving analytical and computational complexities. The state feedback controllers introduce indirectly proportional/integral/derivative control actions.

Frequency deviation response of area-1 and area-2 and Tie line power deviation response to 1% step load perturbations in area-1 with (1) full state feedback, (2) Integral optimal output feedback and (3) PI Optimal output feedback controller have been obtained. It is observed that optimal output feedback controller gives better dynamic response that satisfies the requirements of LFC. The controller design is simple and systematic.

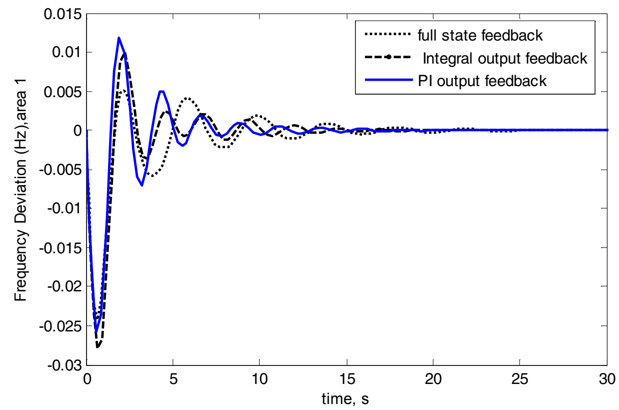

Fig. 2. Frequency deviation response of area-1 to 1% step load perturbation in area-1 with (1) full state feedback, (2) Integral optimal output feedback and (3) PI Optimal output feedback controller.

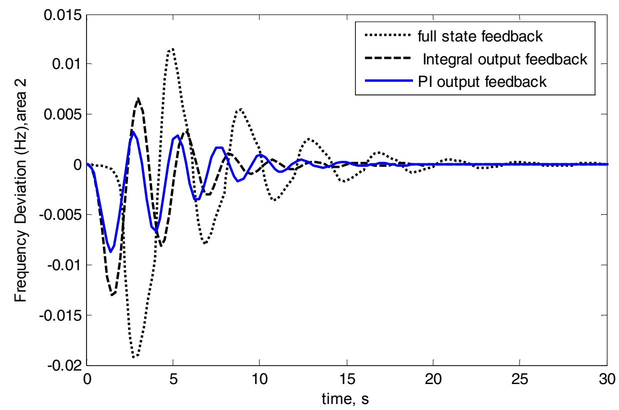

Fig. 3. Frequency deviation response of area-2 to 1% step load perturbation in area-1 with (1) full state feedback, (2) Integral optimal output feedback and (3) PI Optimal output feedback controller.

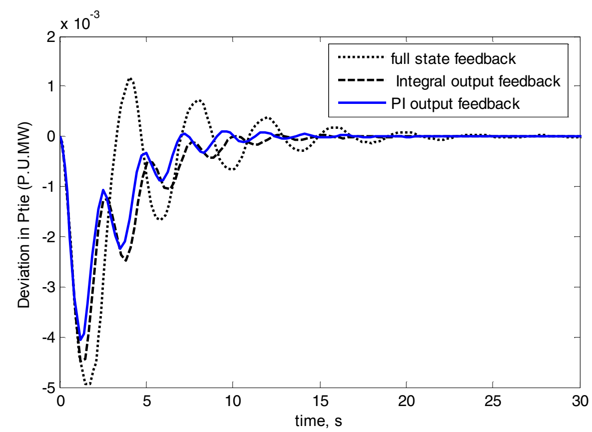

Fig. 4. Tie line power deviation response of two-area system to 1% step load perturbation in area-1 with (1) full state feedback, (2) Integral optimal output feedback and (3) PI Optimal output feedback controller.

APPENDIX

System Parameters

$$P_{rt1} = P_{rt2} = 2000MW$$

$$f = 60Hz$$

$$D_1 = D_2 = 0.00833\, puMW / Hz$$

$$T_{SG1} = T_{SG2} = 0.08s$$

$$T_{T1} = T_{T2} = 0.5s$$

$$T_{PS1} = T_{PS2} = 20s$$

$$R_1 = R_2 = 2.4Hz / puMW$$

$$K_{PS1} = K_{PS2} = 120s$$

$$B_1 = B_2 = \left(\frac{1}{R_1} + D_1 \right)$$

$$a_{12} = 1$$

$$2\pi T_{12} = 0.215$$

REFERENCES

[1] D.P. Kothari and I.J. Nagrath, Modern Power System Analysis,3rd ed, Singapore, McGraw Hill, 2003

[2] S.Majhi, Advanced Control Theory-a relay feedback approach,1st ed, Cengage Learning Asia ,2009

[3] Ibraheem, P. Kumar and D.P. Kothari, "Recent philosophies of automatic generation control strategies in power systems," *IEEE Trans Power Syst* 20 (1), pp.346–357, 2005.

[4] S.Majhi, "Relay based identification of time delay processes," IFAC Journal of Process Control,vol.17,Issue2, pp. 93-101,Feb 2007

[5] S.Majhi, "Relay based identification of a class of non minimum phases SISO Processes," IEEE Transactions on Automatic Control, Vol.52, No.1, pp.134-139,Jan 2007.

[6] D.P.Kothari and K.P.Singh Parmar, "A Novel Approach for Eco-Friendly and Economic Power Dispatch Using MATLAB," IEEE conf. proceedings, PEDES 2006, New Delhi, India

[7] D.P.Kothari and K.P.Singh Parmar, "Environment-Friendly Thermal Generating Unit Commitment," National power systems conference -2006 proceedings, Roorkee, India.

[8] O.I. Elgerd, Electric Energy System Theory: an introduction (2nd ed.), McGraw-Hill, New York (1983),pp 310-360

[9] P. Kundur, *Power System Stability & Control*. Tata McGraw Hill, New Delhi, Fifth reprint 2008,pp 581-626

[10] C.E. Fosha and O.I. Elgerd, The megawatt frequency control problem: a new approach via optimal control theory, *IEEE Trans Power Appl Syst* 89 (4), pp. 563–577, 1970.

[11] O.I. Elgerd and C. Fosha, Optimum megawatt frequency control of multi-area electric energy systems, *IEEE Trans Power Appl Syst* 89 (4), pp. 556–563, 1970.

[12] M. Aldeen and H. Trinh, Load frequency control of interconnected power systems via constrained feedback control schemes, *Int J Comput Elect Eng* 20 (1), pp. 71–88, 1994.

[13] M. Aldeen and J.F. Marsh, Observability controllability and decentralized control of interconnected power systems, *Int J Comput Elect Eng* 16 (4), pp. 207–220, 1990.

[14] W S Levin,M Athans, "On the determination of the optimal constant output feedback gains for linear Multivarialbe systems,"IEEE Trans. On Automatic Control,vol AC-15,no.1,1970.

[15] Elyas R and Sadeh J, Simulation of two- area AGC system in a competitive environment using reduced order observer method, *IEEE Trans Power Appl Syst*), pp. 27–33, 2008.

[16] F.Liu,Y.H.Song etal ,"Optimal load frequency control in restructured power systems, "IEE Proc. Generation, Transmission and Distribution, vol 150,no.1, pp87-95, Jan 2003.

[17] F.Llewis and V.L.Syrmos,Optimal Control,Prentice hall,Englewood cliffs,New Jersy,1995

[18] M.L. Kothari, J. Nanda, D.P. Kothari and D. Das, "Discrete mode automatic generation control of a two area reheat thermal system with new area control error," *IEEE Trans Power Appl Syst* 4 (2), pp. 730–738, 1989.

[19] B.Tyagi and S.C.Srivastava, "A LQG based load frequency controller in a competitive electricity environment", Int.J.Emerging Electic Power syst(online),vol(2),2005,available:http://www.bepress.com/ijeeps/vol2/iss2/art1044.

[20] J.Nanda,L.C.Saikia, "Comparision of performances of several types of classical controller in Automatic generation control for interconnected multi-area Thermal system",AUPEC,2008.

[21] *K. P. Singh Parmar, S. Majhi and D. P. Kothari,* "Automatic Generation Control of an Interconnected Hydrothermal Power System", IEEE Conf. proceedings, INDICON 2010,Kolkata,India.

K.P.Singh Parmar is Assistant Director (Technical), Centre for Advanced Management and Power Studies, NPTI, Faridabad, India. He has worked as an Assistant Professor with the Electrical Engineering Department, JSS Academy Of Technical Education, NOIDA(UP),India. He obtained his BE(Hons) from Govt. Engineering College Rewa (MP) and M.Tech. from Indian Institute of Technology Delhi and has been involved in teaching, training, consultancy and research since 2001.He has taught various subjects of Electrical Engineering including Electric machines, Power systems, Electric drives, Control systems, Electric Networks and Systems, Basic System Engineering and Operation & Maintenance in Transmission and Distribution System .Mr Parmar is a life member of ISTE, India and member of IETE, India. His research interests include AGC, Power quality, Energy conservation, Unit commitment, wind and solar energy. Presently, he is a research scholar at IIT Guwahati.

S.Majhi is currently Professor and Head of the Department of Electronics and Communication Engineering at Indian Institute of Technology, Guwahati, India. A Ph. D. from Sussex University, England. He has been awarded the Commonwealth Scholarship and the Alexander von Humboldt Research Fellowship for his doctoral and postdoctoral research programmes. He is a life member of Systems Society of India and Indian Society for Technical Engineers and member, IEEE. He has published and presented more than 80 research papers in reputed National and International journals and conferences. His research interests include relay control systems, design of automatic controllers, model identification, and application of control theory to communication systems.

D.P.Kothari is Former Director (in charge) of IIT, Delhi. He is currently Vice Chancellor of VIT University, Vellore (TN), India. He was a visiting Fellow in 1982-83 and in 1989 at the Royal Melbourne institute of Technology, Melbourne, Australia. He obtained his BE, ME and Ph.D. degrees from BITS, Pilani and has been involved in teaching and research since 1977 at IIT, Delhi. He has published and presented more than 640 papers in prestigious National and International journals and conferences. Dr.Kothari is also a Fellow of the Institution of Engineers (India) and senior member, IEEE. He has co-authored more than 25 books including Power system Engineering, Modern Power system Analysis, Basic Electrical Engineering and Electric Machines. His research interests include power system control, optimization, unit commitment, reliability and energy conservation.