Bevrani, Hassan and Mitani, Yasunori and Tsuji, Kiichiro (2002) Robust low-order load frequency controller in a deregulated environment. In *Proceedings 5th Asia-Pacific Conference on Control and Measurement (APCCM)*, Dali, China.

Robust Low-order Load Frequency Controller In a Deregulated Environment

Hassan Bevrani, Yasunori Mitani and Kiichiro Tsuji

Dept of Electrical Engineering,
Graduate School of Engineering, Osaka University
2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

Abstract – **The electric power industry is in transition from large and regulated utilities to an industry that will incorporate competitive companies selling unbundled power at lower rates. The new structure of electric power systems, which includes separate companies with an open access policy demands novel control strategies to maintain the stability and eliminates the frequency error. Under current organization several approaches have already been proposed.**

This paper addresses the design and introduce of reduced load frequency controller based on μ-synthesis theorem for a possible structure in the new deregulated open access environment. We used the singular values of the observability matrix of the high order μ-controller for reducing the controller order .

1. INTRODUCTION

Any power system has a fundamental control problem of matching real power generation to load plus losses, a problem called Load Frequency Control (LFC) or frequency regulation. The purpose of Load Frequency Control is tracking of load variation while maintaining system frequency and tie line power interchanges close to specified values. Reference [1], give a detailed discussion of LFC.

Deregulation structure considers the system as an area that includes separate generation, transmission and distribution companies with an open access policy. In this new structure, each control area has its own generation and transmission network, and distribution company is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors by securing as much transmission and generation capacity as needed.

The classical load frequency controllers are designed and tuned for the particular operating point of power system. Closed-loop stability and acceptable performance is only achieved for slight deviation from the nominal operating point. That is why the classical controllers can not satisfy the new structure objectives. Under current organizations, several notable approaches based on optimal, H^{∞}, μ -synthesis, neural networks and other control theorems have already been proposed [2-15].

[16], discusses and compares of several LFC scenarios and issues in power system operation after deregulation. Also, the authors [9] have proposed a high order μ load frequency controller for the scenario presented here. In this paper, based on obtained results in [9] we will present a robust low-order load frequency controller.

Because of our tight design objectives with considering several simultaneous uncertainties and wide range of input disturbances, the order of out coming robust controller by using μ-synthesis will be too high. A wide variety of methods for the order reduction have been proposed over the last two decades [17-22]. In the opinion of many investigators of model reduction, two developments have dramatically changed the status of the model reduction theory. These are the methods of Moor balanced realization [17] and optimal Hankel-norm approximation [18]. The main advantage of these two methods is that they address the problem of Kalman minimal realization theory. Specifically, since the rank of a matrix is a relative number, by observability grammians or the Hankel matrix of the system can be determined.

In this paper, a reduced order of High order μ-based load frequency controller that is given in [9], is obtained using a Kalman observability matrix of the high-order μ controller.

2. MODEL DESCRIPTION

Based on the new structure, let us consider a simple distribution company and its suppliers as shown in Fig. 1, [8-9]. In this example the distribution company (DISCO) buys firm power from one generation company (GENCO 2) and enough power from other generation company (GENCO 1) to supply its load and support the LFC task. Transmission company (TRANSCO 1) delivers power from GENCO 1. TRANSCO 1 is also contracted to deliver power associated with the LFC problem.

In the structure proposed the DISCO are to be responsible for tracking the load and hence performing the load frequency control task by securing as much transmission and generation capacity as needed. Connections of the DISCO to other companies are considered as disturbances (d1).

For simplicity assume that GENCOs 1 and 2 have one generator each. The state space realization of the distribution area as presented in [8], has the following form:

$$\dot{x} = Ax + Bu + Dw \tag{1}$$

where,

$$x^T = [\Delta f_1 \quad \Delta P_{M1} \quad \Delta P_{V1} \quad \Delta\delta_1 - \Delta\delta_2 \quad \Delta f_2 \quad \Delta P_{M2} \quad \Delta P_{V2}]$$
$$w^T = [\Delta P_L \quad d_1]\ ; \quad u = \Delta P_{ref1}$$

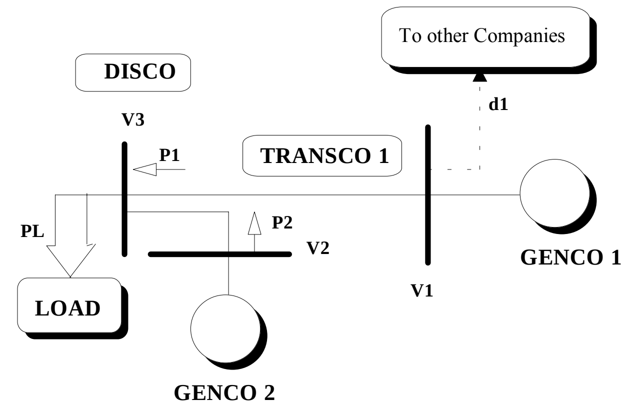

Fig. 1. A distribution company and its suppliers

Coefficients of equation (1) are given bellow:

A =

$$\begin{bmatrix} -\frac{D_1}{T_{P1}} & \frac{1}{T_{P1}} & 0 & -\frac{\alpha}{T_{P1}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{M1}} & \frac{K_{M1}}{T_{M1}} & 0 & 0 & 0 & 0 \\ -\frac{K_{H1}}{R_1 T_{H1}} & 0 & -\frac{1}{T_{H1}} & 0 & 0 & 0 & 0 \\ 2\pi & 0 & 0 & 0 & -2\pi & 0 & 0 \\ 0 & 0 & 0 & \frac{\alpha}{T_{P2}} & -\frac{D_2}{T_{P2}} & \frac{1}{T_{P2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{M2}} & \frac{K_{M2}}{T_{M2}} \\ 0 & 0 & 0 & 0 & -\frac{K_{H2}}{R_2 T_{H2}} & 0 & -\frac{1}{T_{H2}} \end{bmatrix}$$

$$\alpha = \frac{T_1 T_2}{(T_i + T_2)}, T_{Pi} = \frac{2H_i}{f_0}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{K_{H1}}{T_{H1}} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$D^T = \begin{bmatrix} -\frac{T_1}{(T_1 + T_2) T_{P1}} & 0 & 0 & 0 & -\frac{T_2}{(T_1 + T_2) T_{P2}} & 0 & 0 \\ -\frac{1}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and,

Δ : Deviation from nominal value

f_o : Nominal frequency

f_i : Frequency

δ_i : Rotor angle

P_M : Turbine (mechanical) power

d_i : Disturbance (power quantity).

P_V : Steam valve power

P_{refi} : Reference set point (control input)

In order to simulation, system parameters and data are given in Table 1, according to [8-9].

TABLE 1

DATA FOR THE SIMULATION

Quantity	**GENCO 1**	**GENCO 2**
Rating (MW)	1000	800
Constant of Inertia: H(sec)	5	5
Damping: D (pu MW/Hz)	0.02	0.015
Droop characteristic (%)	4	5
Generator's: $T_p = 2H / f_0$	0.2	0.2
Turbine's Time Constant: T_M	0.5	0.5
Governor's Time Constant: T_H	0.2	0.1
Gains: K_M, K_H	1	1
Synchronizing coefficients: T_i	0.2	0.1

3. μ -BASED CONTROLLER DESIGN, [9]

The first step is formulate the LFC problem as an μ controller design problem. The state-space model is based on equation (1), and, let the output variables be given by the Area Control Error (ACE), as given in [9].

The objective is to design a controller that will result in a stable closed-loop system and minimize the effects of the worst disturbances or exogenous inputs on the output variables. To meet our objective, we consider the closed-loop interconnection system as shown in figure 2.

Note that there are three uncertainty blocks and associated weighting functions. The block Δu model the multiplicative uncertainty while the blocks $\Delta p1$ and $\Delta p2$ are the fictitious uncertainties added to assure robust performance. The robust controller K(s) must be computed to meet design objectives. An important issue in regard to selection of the weights is the degree to which they can guarantee the satisfaction of design objectives. For the problem at hand a suitable set of weighting functions is:

$$w_u(s) = \frac{2.5(s+315)}{(s+1000)} \quad ; \quad w_{p1}(s) = \frac{2\times10^{-5}s}{2\times10^{-7}s+1} \tag{2}$$

$$w_{p2}(s) = \frac{s+0.2}{40(s+0.001)}$$

For more details on finding of these weighting functions refer to [9].

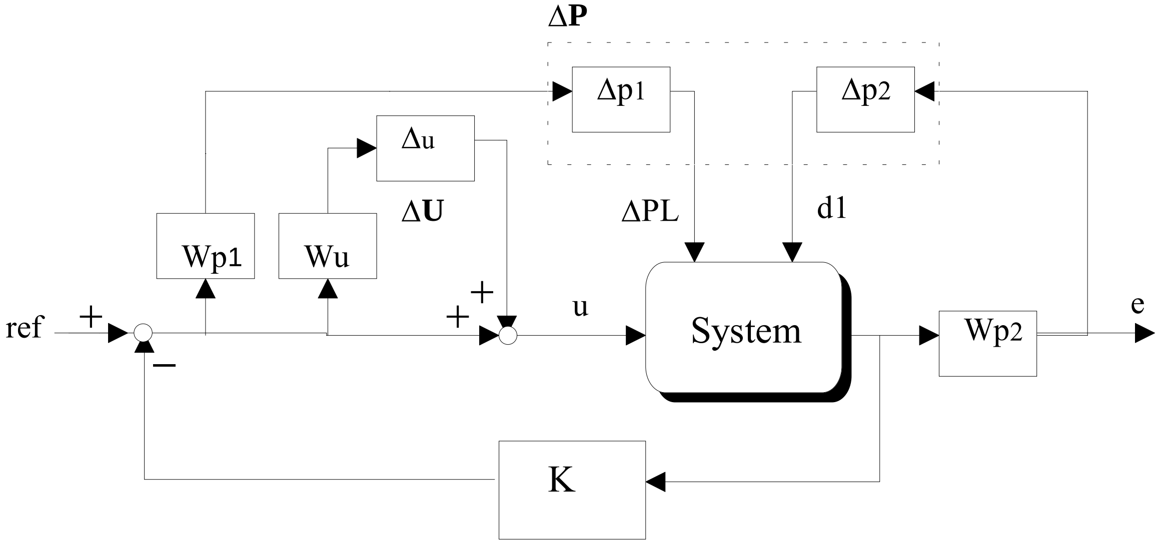

Figure 2: The block diagram for μ-synthesis

Our next task is to isolate the uncertainties from the nominal plant model and redraw the system in the standard M-Δ block from shown in figure 3.

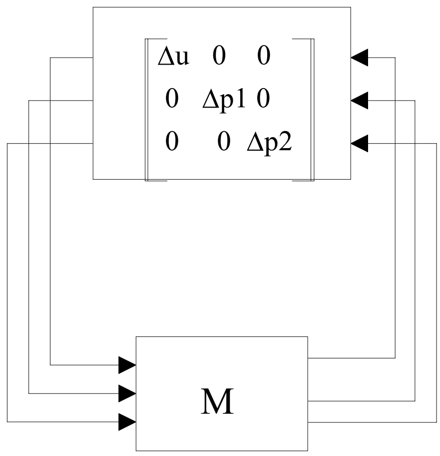

Fig 3 Standard M-Δ block

The block labeled M, consists of the nominal plant, controller K(s), the weighting functions and scaling factors. Having setup our robust synthesis problem in terms of the standard μ-theory, we use the μ-analysis and synthesis toolbox, to obtain a solution. The 10^{th} order controller K(s), is found at the end of the third D-K iteration yielding the value of about 0.9843 on the upper bound on μ. The state space realization of the reduced order controller is:

$$\begin{aligned} \dot{\hat{x}} &= \hat{A}\hat{x} + \hat{B}y \\ u &= \hat{C}\hat{x} + \hat{D}y \end{aligned} \tag{3}$$

4. ORDER REDUCTION

An important issue concerning the structure of the resulting compensator is its high order. This is expected in view our tight design objectives with considering several simultaneous uncertainties and wide range of input disturbances. Indeed, most robust controllers obtained via this approach display this feature.

Order reduction techniques have to be used to reduce controller's complexity and make practical implementation feasible. There are many methods to aid in reducing the order of the systems [17-22]. MATLAB software, provide several commands to aid in reducing the order of a system, such as, Balanced realization model reduction (*sysbl*), Residualization method (*resid*), Frequency weighted balanced reduction (*sfrwtbld*) and Relative error model reduction (*srelbal*).

To dispense with using type of order reduction technique, the reduced model should represent the original model with sufficient accuracy such that performance objectives can be met using the reduced model instead of the original one in a given frequency bandwidth.

In this section a method based on the singular values of the observability matrix of the high order μ-controller is applied to reduce the size of the controller [15]. $\hat{x}$ in (3), is the $\hat{n}\times1$ state vector of the controller, the size of the controller is too high. Now a reduced order controller of size $n_r \langle \hat{n}$ is obtained using Kalman observable canonical form. To transform the state space model of the controller to a Kalman observable canonical form, singular value decomposition of the observability matrix Q of the controller is used:

$$Q = obs(\hat{A}, \hat{C}) = U\Sigma\Sigma^T$$
$$= \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_1 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} \qquad (4)$$

where,

$$\Sigma_1 = diag\{\sigma_1 \ \sigma_2 \ \cdots \ \sigma_{n_r}\}$$
$$\Sigma_2 = diag\{\sigma_{n_r+1} \ \cdots \ \sigma_n\}$$

and, $\sigma_{n_r} \geq \sigma_{n_r+1}$.

Equation (4) determines the size of the reduced order model of the controller. The matrix V is used as a similarity transformation to obtain a Kalman observable canonical form whose state variable are:

$$\tilde{x} = V^T \hat{x} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = \begin{bmatrix} V_1^T \tilde{x} \\ V_2^T \tilde{x} \end{bmatrix} \qquad (5)$$

The controller description in the new coordinate system is:

$$\dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}y$$
$$u = \tilde{C}\tilde{x} + \tilde{D}y \qquad (6)$$

where,

$$\tilde{A} = V^T \hat{A} V = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} \\ \tilde{A}_{21} & \tilde{A}_{22} \end{bmatrix};$$
$$\tilde{B} = V^T \hat{B} = \begin{bmatrix} \tilde{B}_1 \\ \tilde{B}_2 \end{bmatrix}; \ \tilde{C} = \hat{C}V = \begin{bmatrix} \tilde{C}_1 & \tilde{C}_2 \end{bmatrix}; \ \tilde{D} = \hat{D}.$$

Finally, a reduce order controller whose size is the size of $\tilde{x}_1$, is obtained from equations (5) and (6):

$$\dot{\tilde{x}}_1 = \tilde{A}_{11}\tilde{x}_1 + \tilde{B}_1 y$$
$$u = \tilde{C}_1 \tilde{x}_1 + \tilde{D}y \qquad (7)$$

For the power system of figure 1, the singular values of the observability matrix of the original controller are:

$$\Sigma = diag\{6812.49, \ 1124.21, \ 114.01, \ 67.10,$$
$$13.098 \ \ 0.07, \ 0.069, \ 0.04, \ 0.01, \ 0.00011\}$$

It is seen that the first five singular values are too larger than the next singular values. Therefore a fifth order model is considered. Based on (7), the result reduced controller has the following form:

$$\dot{\hat{x}}_r = \hat{A}_r \hat{x}_r + \hat{B}_r y$$
$$u = \hat{C}_r \hat{x}_r + \hat{D}_r y \qquad (8)$$

where,

$$\hat{A}_r = \tilde{A}_{11}$$
$$= \begin{bmatrix} -0.04410 & -0.52651 & -0.0039 & -0.0026 & 0.00011 \\ 7.160210 & 1.75090 & 0.01440 & 0.00960 & -0.0002 \\ -10.6597 & -1.2173 & -0.2735 & -0.7682 & 0.00151 \\ 20.42300 & 3.11930 & 2.11070 & 0.30110 & -0.0389 \\ -11.5881 & -1.5331 & -0.6935 & 0.25780 & -0.8128 \end{bmatrix},$$

$$\hat{B}_r = \tilde{B}_1 = \begin{bmatrix} 0.02260 \\ -0.1594 \\ 0.25240 \\ -0.4780 \\ 0.27290 \end{bmatrix}, \ \hat{D}_r = \tilde{D} = \begin{bmatrix} 1.4880 \end{bmatrix};$$

$$\hat{C}_r = \tilde{C}_1 = \begin{bmatrix} -37.4023 & -8.5980 & -1.8977 & 0.08011 & -0.3272 \end{bmatrix}.$$

5. SIMULATION RESULTS

Analysis of the reduced order controller shows that the upper bound on μ remains less than one. In other word, this yield a stable closed-loop system. But reduction of order, effects on output response. Figures 4-5 show this fact, following a 10% load increase in the distribution system.

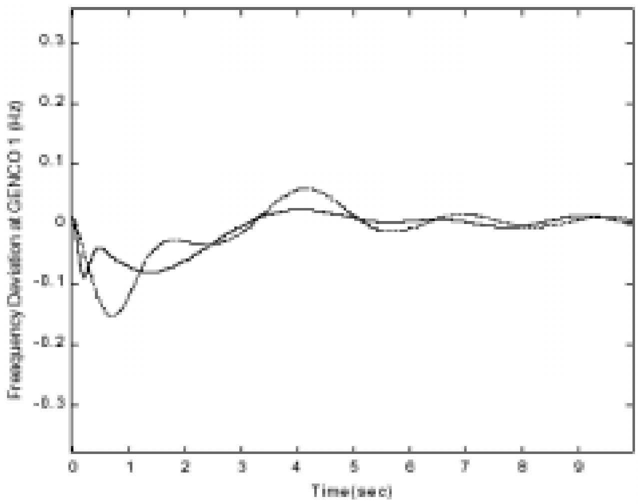

Fig 4 Frequency deviation at GENCO 1; using original controller (solid), using reduced controller (dashed)

Figure 6 shows the changes in power coming to the distribution company from generation companies, following a 10% load increase in the distribution system. In figure 6, upper curves show the power that coming from GENCO 1 and lower curves belong to GENCO 2.

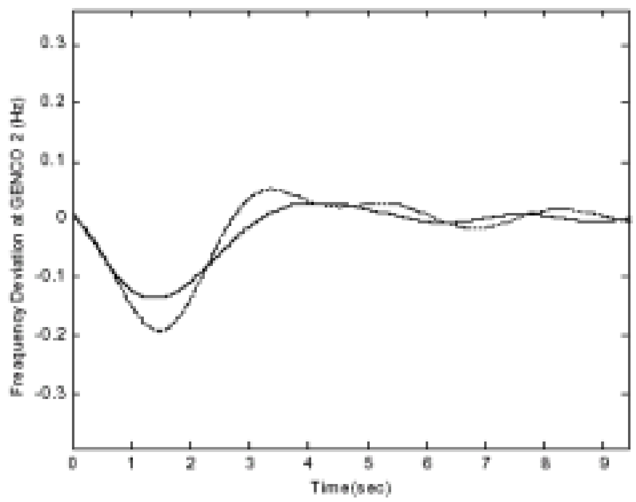

Fig 5 Frequency deviation at GENCO 2; using original controller (solid), using reduced controller (dashed)

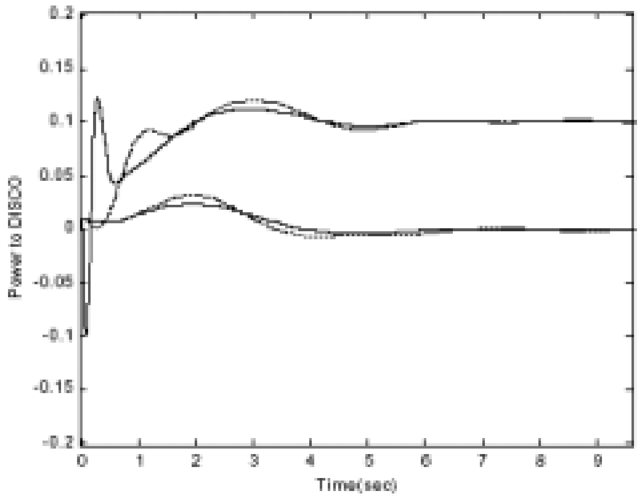

Fig 6 Change in power supplied to power system; using original controller (solid), using reduced controller (dashed)

6. CONCLUTION

This paper presents a robust low-order load frequency controller in a deregulated environment to overcome the problem of load variation and disturbances. The reduction of high-order controller is proposed by using singular value decomposition of the its observability matrix.

A simple test system is given to demonstrate the effectiveness of the proposed methodologies.

7. REFERENCES

[1] N. Cohn, Control of Generation and Power Flow on Interconnected Power Systems, New York: John Wiley & Sons, 1961.

[2] E. J. Davison, N. K. Tripathi, "The Optimal Decentralized Control of a Large Power System: Load and Frequency Control" *IEEE Trans. On Automatic Control,* vol.. AC-23, 1978.

[3] M. S. Calovic, "Automatic Generation Control: Decentralized Area-Wise Optimal Solution", *Electric Power Systems Research,* Vol. 7, 1984.

[4] Y. M. Park, K. L. Lee, "Optimal Decentralized Load Frequency Control *", Electric Power Systems Research*, Vol. 7, 1984.

[5] A. Feliachi, "Optimal Decentralized Load Frequency Control", *IEEE Trans. on Power Systems*, vol. PWRS-2, No. 2, 1987.

[6] C. M. Liaw and K. H. Chao, "On the Design of an Optimal Automatic Generation Controller for Interconnected Power System ", *Int. Journal of Control*, vol. 58, 1993.

[7] T. C. Yang, H. Cimen and Z. T. Ding, "A New Robust Decentralized Power System Load Frequency Controller Design Method", in *Proceedings of ICARCV*, Singapore, 1996.

[8] A. Feliachi, "On Load Frequency Control in a Deregulated Environment *", in Proceedings of the IEEE Inter. Conf. on Control Applications*, Derborn, Sept. 1966, pp. 437-441.

[9] H. Bevrani, "Robust Load Frequency Control in a Deregulated Environment: A μ-Synthesis Approach", *in Proceedings of the IEEE Conf. on Control Applications*, USA, 1999, pp. 616-621.

[10] H. Bevrani, M. Teshnehlab and H. Bevrani, " Load Frequency Controller Design In a Deregulated Environment Using Flexible Neural Networks *", in Proceedings of the* 15th. Int. Power System Conf., Tehran, Iran, 2000, pp. 1-8.

[11] B. H. Bakken and O. S. Grande, " Automatic Generation Control in a Deregulated Power System ", *IEEE Trans. on Power Systems*, vol. 13, no. 4, Nov. 1998.

[12] H. Bevrani, "Application of Kharitonov's Theorem and its Results to Load Frequency" *Barg - Journal of Electrical Science and Technology (in Persian*), No. 24, Iran, Sept. 1998, pp.82-95.

[13] H. Bevrani, " Load Frequency Controller Design Using Neural Networks*", in Proceedings of the Seminar on Power Plant Control & Instrumentation,* WREC, Kermanshah, Iran, Oct. 2000, pp. 84-90.

[14] R. D. Christie, A. Bose, " Load Frequency Control Issues in Power System Operation after Deregulation, *", in Proceedings of the IEEE CCA Conference,* Dearborn, 1996, pp. 432-437.

[15] A. Feliachi, " Reduced H-inf Load Frequency Controller in a Deregulated Power System Environment*", in Proceedings of the 36th Conf. On Decision and Control*, California USA, 1997, pp. 3100-3101.

[16] H. Bevrani, A. Rezazadeh and M. Teshnehlab, " Camparision of Existing LFC Approaches In a Deregulated Environment Using Flexible Neural Networks *", in Proceedings of IEE Conf. On Power System Management and Control (PSMC),*London, 2002.

[17] B. Moor, " Principal Component analysis in Linear System: Controllability, Observability and Model Reduction", *IEEE Trans. On Automatic Control*, vol. 26, no. 1, 1981.

[18] K. Glover, " All Optimal Hankel-Norm Approximation of Linear Multivariable Systems", *Int. Journal of Control,* vol. 39, No. 6, 1984.

[19] B. Anderson and Liu, "Control Reduction: Concept and Approach," *Int. Journal of Control*, 1989.

[20] D. F. Enns, " Model Reduction with Balanced Realization: An Error Bound and Frequency Weighted generalization*", in Proceedings of the 23th Conf. On Decision and Control,* 1984.

[21] Fen Wu, " Solutions to Frequency Weighted optimal H∞-Model Reduction Problem*", in Proceedings of the* American Control Conf. , vol. 6, 1997.

[22] A. Zilouchian, et. al., " Model Reduction of Large Scaled Systems via Frequency-Domain Balanced Structures Problem," *", in Proceedings of the* American Control Conf. , vol. 6, 1997.