OPTIMAL POWER SYSTEM STABILIZATION VIA OUTPUT FEEDBACK EXCITATION CONTROL

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This paper presents a modified optimal controller for an interconnected power system. The design method does not need the specification of weighting matrices. The eigenvalues of electromechanical and exciter modes would be shifted to a pre-specified vertical strip. For practical implementation, the proposed method designs using an optimal reduced order model whose state variables are torque angles and speeds. The reduced order model retains their physical meaning and is used to design output feedback controller that takes into account the realities and constraints of the electrical power systems. Effectiveness of this controller is evaluated and examples, one machine infinite bus system and a multimachine system, are given to illustrate the advantages and effectiveness of the proposed approach.

Key words: dynamic stability, strip eigenvalue assignment, excitation control, power system stabilizer, reduced order model

1. Introduction

The poor damping of electromechanical oscillation is symptomatic of intrinsic weaknesses in the power system. In some interconnections the situation is worsened by the growth of inter-utility wheeling, which is dictated by the economical constraints in modern power systems. These factors combine to bring the typical operating state closer than ever to the system stability limits and to make the damping of electromechanical oscillations a recurrent problem in the several power systems. Since the introduction of new control systems to the uncertain and multivariable environment of complex power systems is a slow process, which incurs a variety of risks, the full utilization of existing power system stabilizers (PSS) is essential for the enhancement of overall system stability on the present level of system development[1-9].

Excitation control has received a great deal of attention in the past and will receive increasing attention in the future as major means to improve the damping of a power system. The present excitation control design is generally based on the natural mechanical mode oscillation frequency ($s = j\omega_n$), without considering the damping of the machines. A more suitable technique in which a complex frequency ($s = \sigma_i + j\omega_i$) is used has been developed[8,11], but the question of determining the appropriate complex frequency to use has not yet been solved.

Power system have been growing in size and complexity with increasing interconnection between systems. An increase in the damping of the system response is desirable, not only because it reduces the fluctuations in the controlled variables and hence improving the quality of the electric service, but mainly because this damping is translated into an increase in the power transmission stability limits. Higher stability limits bring significant economic savings as the need for the expansion of the transmission system can be postponed.

Supplementary excitation control, commonly referred to as PSS, has become an important means to enhance the damping of low-frequency oscillations in the range 0.5 to 2 Hz, i.e. dynamic or steady-state stability of power systems[1-2]. Considerable efforts have been placed on the synthesis of power system stabilizer in multimachine power systems[3-9].

The design of PSS can be formulated as an optimal linear regulator control problem. However, the implementation of this technique requires the design estimators. This approach increases the implementation cost and reduces the reliability of the control system. These are the reasons that a control scheme use only some desired

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state variables such as torque and speeds. Optimal control theory has been widely used in industrial applications. In recent years, the modal control design has been used in power systems to shift the dominant eigenvalues. Different methods have been proposed to assign eigenvalues by modifying the weighting matrix of the quadratic performance index. Optimal and suboptimal control strategies on the basis of linear system theory using various system states and measurable output as input to the controller have also been attempted[10, 11].

Although the closed-loop system constructed by using the optimal control theory has some advantages, there are still many problems to solve. One of the most serious is that it is rather difficult to specify the control performance described in terms of a quadratic performance index. The weighting matrices usually would be decided based on trial and error to give satisfactory performance. It is difficult to determine the weighting matrices of the performance index[11].

This paper is presented for finding a linear quadratic controller such that the optimal closed-loop system has eigenvalues lying within a vertical strip in the complex s-plane[12]. Aiming at improving system stability the design method does not need the specification of the weighting matrices. In this work, the desired positions of the eigenvalues are achieved without convergence problems. One basic difficulty of the state feedback control is that it is usually impractical since some of system states can not be measured. An output feedback controller is preferred. The output feedback gains are obtained from optimal reduced order method[13] and strip eigenvalue assignment[12].

These drawbacks can be avoided by using the technique proposed in this papers. The optimal reduced order models are used to design the power system stabilizers and to pre-specify the eigenstructure of the system. Study results reveal that by using output feedback only, the eigenvalues assignment based on the proposed method is more stable than that based on the former method[13]. This results from that the output feedback gains that obtained from transformation of the state feedback matrix can be retain the physical meanings of the output state.

2. Strip Eigenvalue Assignment

Consider a linear time-invariant controllable system which is described in the state space by:

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

$$y(t) = Cx(t) \tag{2}$$

where x(t), u(t), and y(t) are the $n \times 1$ state vector, $m \times 1$ input vector, and $p \times 1$ output vector, respectively. A, B, and C are constant matrices of appropriate dimensions.

In the design of a conventionally optimal control system, the control vector is given by

$$u(t) = -Kx(t) \tag{3}$$

where K is the $m \times n$ state feedback control matrix designed to minimize the following quadratic performance index :

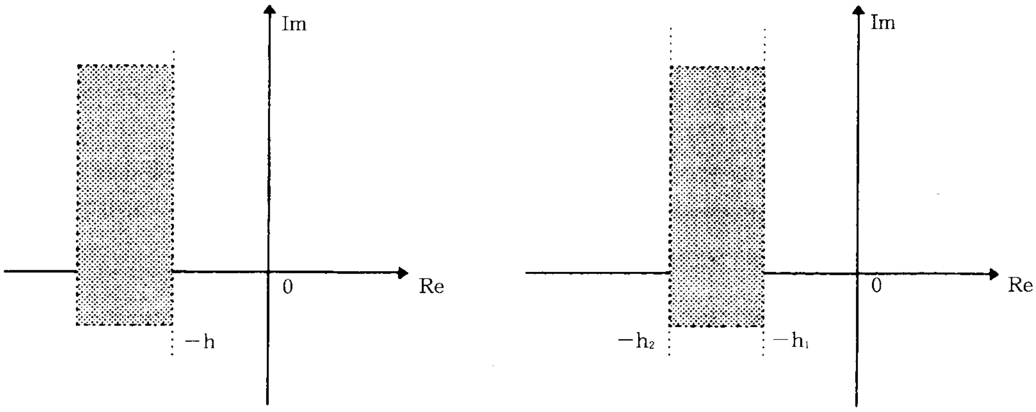
$$J = \frac{1}{2}\int_0^\infty (x^TQx + u^TRu)dt \tag{4}$$

In eqn.(4) the weighting matrices Q and R are $n \times n$ non-negative and $m \times m$ positive definite symmetric matrices, respectively. The feedback gain in eqn.(3) is K $(=R^{-1}B^TP)$ with P being a symmetric positive definite matrix, which is solution of the following algebraic matrix Riccati equation,

$$A^TP + PA - PBR^{-1}B^TP + Q = 0_n \tag{5}$$

and the eigenvalues of $A-BK$, denoted by $\Lambda(A-BK)$, will lie in the open left half plane of the complex s-plane.

In conventionally optimal system analysis, the gain in eqn.(3) is designed by roughly selecting weighting matrices according to physical reasoning. Because of complexity, the matrices Q and R are commonly chosen as diagonal matrices. The eigenvalues of the closed-loop system are denoted by $\Lambda(A-BK) = [\lambda_1, \lambda_2, \cdots, \lambda_m, \lambda_{m+1}, \cdots, \lambda_n]$. In order to improve the system performance,



(a) Vertical Line (b) Vertical Strip

Fig.1 Complex S-Plane

the eigenvalue λ_1 through λ_m will be selected and shifted to a desired region. To achieve this results the weighting matrix R in the eqn.(5) is set to be an identity matrix for equal weighting of the m control inputs, and the weighting matrix Q must be given previously.

In the above procedures, generally, the weighting matrices Q and R must be given previously. But in large power system, it is not easy to determine those weighting matrices. The weighting matrices usually are determined by trial and error to obtain satisfactory performances. To overcome this difficulty, a novel approach for designing the optimal eigenvalues assignment will be proposed in the following discussion. The design method in this paper shifts the closed-loop eigenvalues to a pre-specified vertical strip without the need of weighting matrices.

Let (A,B) be the pair of the open-loop system matrices in eqn.(1) and $h \geqq 0$ represent the prescribed degree of relative stability. Then the closed-loop matrix $A_c = A - BR^{-1}B^T\tilde{P}$ has all its eigenvalues lying on the left side of the -h vertical line as shown in Fig. 1(a), where the matrix $\tilde{P}$ is the solution of the following Riccati equation[12];

$$(A+hI_n)^T\tilde{P}+\tilde{P}(A+hI_n)-\tilde{P}BR^{-1}B^T\tilde{P}+Q=0_n \quad (6)$$

Note that in eqn.(6) with $Q = 0_n$, the unstable eigenvalues of $A + hI_n$ are shifted to their mirror image positions with respect to the -h vertical lie, which are the eigenvalues of the closed-loop system matrix A_c.

Assume that h_1 and h_2 are two positive real values to determine an open vertical strip of $[-h_2, -h_1]$ on the negative real axis as shown in Fig. (1b) and give an n×n matrix $\tilde{A}=A+h_1 I$. The control law changed to be

$$u(t)=p\tilde{K}x(t) \quad (7)$$

with the feedback gain $\tilde{K}=R^{-1}B^T\tilde{P}$. The matrix $\tilde{P}$ is the solution of the following modified Riccati equation :

$$\tilde{A}^T\tilde{P}+\tilde{P}\tilde{A}-\tilde{P}BR^{-1}B^T\tilde{P}=0_n \quad (8)$$

The gain ρ is selected by

$$\rho=\frac{1}{2}+\frac{h_2-h_1}{2.\mathrm{tr}(\tilde{A}^+)}=\frac{1}{2}+\frac{h_2-h_1}{\mathrm{tr}(B\tilde{K})} \quad (9)$$

where $\mathrm{tr}(\tilde{A}^+)=\sum_{i=1}^{n^+}\lambda_i^+=\frac{1}{2}B\tilde{K}$ and $\lambda_i^+ (i=1,2,\cdots,n^+)$ are the eigenvalues of $\tilde{A}$ in the right half-plane of the complex s-plane. The optimal closed-loop system becomes

$$\dot{x}(t)=(A-\rho B\tilde{K}) \quad (10)$$

Equation (10) consists of a set of eigenvalues which lie inside the vertical strip of the $[-h_2, -h_1]$ as shown in Fig. (1b). In eqn.(8) for equal weighting of the m control inputs, we can let R be unity matrix. These solving the Riccati eqn.(8) does not need a Q matrix, so it is easy to design an optimal controller for power system oscillation damping.

3. Optimal Reduced Order Model

Since the reduced order model derived in Ref.13 is used in the following study, the process of evaluating the reduced order model is abbreviated as follows without proof.

The reduced order model is the derived using the following system whose first m variables are the desired variables z, which are speeds and torque angles in the proposed approach. The similarity transformation T is obtained in Ref.13.

$$\dot{\hat{x}}=\hat{A}\hat{x}+\hat{B}u \quad (11)$$

$$z=[I_m,0]\hat{x} \quad (12)$$

where

$\hat{x}=Tx$
$\hat{A}=TAT^{-1}$
$\hat{B}=TB$
$I_m=m\times m$ identity matrix

Assume that the eigenvalues of $\hat{A}$ are distinct, this will actually be the case in the power system.

Let $V=[V_1, V_2,\cdots, V_n]$ where V_i is the right eigenvector of A associated with λ_i. Let $W=V^{-1}$,

Define $\phi=W\hat{x}$

Then

$$\dot{\phi}=\Lambda\phi+\Gamma u \quad (13)$$

$$z=D\phi \quad (14)$$

where

$\Lambda=W\hat{A}V=$ diagonal$(\lambda_1, \lambda_2,\cdots, \lambda_n)$
$\Gamma=W\hat{B}$
$D=[I_m,0]V$

These equations can be arranged and written in partition form as :

$$\dot{\phi}_1=\Lambda_1\phi_1+\Gamma_1 u \quad (15)$$

$$\dot{\phi}_2=\Lambda_2\phi_2+\Gamma_2 u \quad (16)$$

$$z=D_1\phi_1+D_2\phi_2 \quad (17)$$

where

Λ_1 contains modes to be retained

Λ_2 contains modes to be eliminated

Assume the reduced order system we are sought to determine will be of the form as follows :

$$\dot{z}=Fz+Gu \quad (18)$$

The evaluation algorithm of F and G proposed in Ref.13 are abbreviated as follows :

$$F=D_1\Lambda_1 D_1^{-1} \quad (19)$$

Let V_m be the modal matrix associated with eqn.(19).

Define

$$\bar{F}=V_m^{-1}FV_m \quad (20)$$

$$\bar{G}=V_m^{-1}G \quad (21)$$

$$\bar{C}=V_m^{-1}D_2 \quad (22)$$

$$\bar{\Gamma}_1=V_m^{-1}D_1\Gamma_1 \quad (23)$$

Then

$$\bar{S}=\bar{C}\Lambda_2-\bar{F}\bar{C} \quad (24)$$

$$\Lambda=-(\bar{F}+\bar{F}^T)^{-1} \quad (25)$$

$$R=-\Lambda\bar{S} \quad (26)$$

Let $\alpha_i=\lambda_{m+i}, i=1,2,\cdots,n-m$.

Then $\Lambda_2=$ diagonal$(\alpha_1, \alpha_2,\cdots, \alpha_{n-m})$

The$(i,j)^{th}$ element of the mxp matrix is given by:

$$\Phi_{ij}=\frac{R_{ij}}{\lambda_i^*+\alpha_j} \quad (27)$$

where the subscript*denotes complex conjugate.

$$\Delta=\Lambda^{-1}\Phi \quad (28)$$

Let $\bar{K}=\bar{\Gamma}_1+\bar{C}\Gamma_2$ (29)

Then $\bar{G}=\bar{K}+\Delta\Gamma_2$ (30)

And $G=V_m\bar{G}$ (31)

4. Output Feedback Excitation Control

To avoid the drawback demonstrated in the above section; we should use the optimal reduced order model derived in Ref.13 to retain the physical meanings of the output states which are also the entries in the strip eigenvalues assignment we are interested in. By using the reduced order model, the system in eqn.(1) can be reduced to the following form :

$$\dot{x}_r = A_r x_r + B_r u \tag{32}$$

where

$x_r \in R^{m\times1}$: state vector to be retained consisting of torque angles and speeds in electric power system.

A_r , B_r : constant matrices of reduced order model with appropriate dimensions.

The control law can be written to the following form :

$$u^* = -\rho K_r x_r \tag{33}$$

with the feedback gain $K_r = R^{-1} B_r^T \tilde{P}$. The matrix $\tilde{P}$ is solution of the following modified Riccati equation

$$\tilde{A}_r^T \tilde{P} + \tilde{P} \tilde{A}_r - \tilde{P} B_r R^{-1} B_r^T \tilde{P} = 0 \tag{34}$$

where $\tilde{A}_r = A_r + h_1 I$. The gain ρ is selected by using the expressions given in section 2.

Fig.2 illustrates how the theory of the above regulator can be implemented by a PI controller.

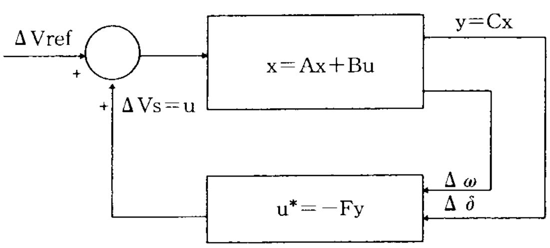


Fig.2 PI Stabilizer Design Formulated as an Output Feedback Regulator Problem

5. Simulation Results

5.1 One Machine Infinite Bus System

To demonstrate correctness and effectiveness of the proposed optimization technique, one machine system in [22] is studied on a linearized model of generator unit including a voltage regulator and exciter.

The state vector and output vector are chosen to be

$$x = [\Delta E_q \, \Delta E_{FD} \, \Delta V_A \, \Delta V_F \, \Delta\delta \, \Delta\omega]^T \tag{35}$$

$$y = [\Delta\delta \, \Delta\omega]^T \tag{36}$$

A power system stabilizer (PSS) is designed to increase the oscillation damping. An additional damping signal is given to input circuit of the voltage regulator. The system matrices are

$$A = \begin{bmatrix} -0.5517 & 0.1695 & 0 & 0 & -0.306 & 0 \\ 0 & 0.1789 & 1.0526 & 0 & 0 & 0 \\ -4205.5 & 0 & -20 & -8000 & -235.2 & 0 \\ 0 & 0.0045 & 0.0263 & -1.0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 377 \\ -0.2779 & 0 & 0 & 0 & -0.3055 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 8000 & 0 & 0 & 0 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The eigenvalues of the system using control schemes are computed and given in Table 1.

Table 1 System Eigenvalues

Open-Loop	State Feedback Control	Output Feedback Control
−0.2349±j10.7928	−1.5000±j10.8083	−1.5279±j11.2671
−8.1295±j8.9752	−8.1295±j8.9752	−7.5890±j7.7019
−3.0952	−3.0952	−1.5695±j1.0141
−1.5487	−1.5487	

The first two eigenvalues in Table 1 (the first column) are called the electrome-chanical mode. The damping ratio of this mode is 0.0217. It is desired to have a damping ratio ranging from 0.1 to 0.5 [1−2], such that the system damping is enough. It is expected to improve the damping of this mode by output feedback. The results are as follows :

give $-h_2 = -2.0$; $-h_1 = -1.0$

then $\rho = 0.8268$

with state feedback control, the damping ratio of the electromechanical is improved to be 0.1375.

Whereas, using output feedback control, the damping ratio of the electromechanical mode is improved to be 0.1344. The state feedback and output feedback gain are also given in Table 2.

Table 2 Feedback Gains

	State Feedback	Output Feedback
$\Delta\delta$	0.1949	0.1949
$\Delta\omega$	10.3110	10.3110
$\Delta E_q'$	0.1782	–
ΔE_{FD}	0.0062	–
ΔV_A	0.0003	–
ΔV_F	0.0001	–

From simulation results are shown (in Table 1) that the previous eigenvalues with real part greater than −1 have been shifted into the vertical strip of [−2, −1] by output feedback controller and the damping ratio is inside the acceptable range [1−2].

The transient response of angular frequency deviation following a 5 % change in the mechanical torque of machine is shown in Fig. 3.

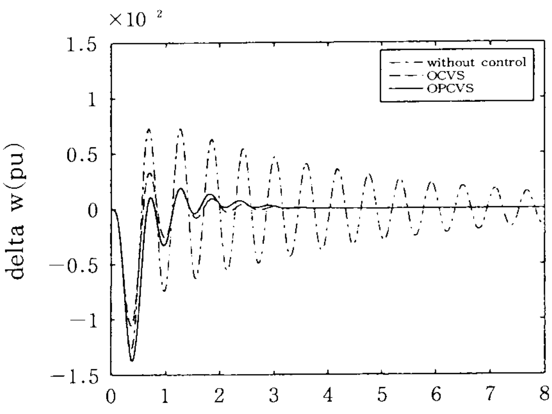


Fig.3 Transient Response of the Angular Frequ-encies to a 5 % Change in the Mechanical Torque of Machine .

5.2 Multimachine System

To assess the proposed method in the case of multimachine system . The system shown in the Fig. 4, taken from Ref.23, is studied.

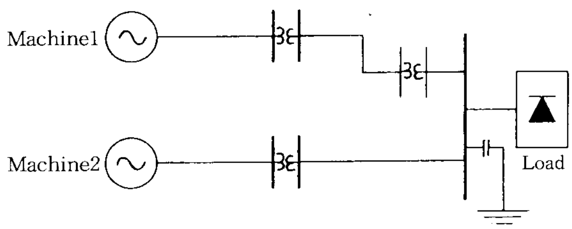


Fig.4 Multimachine System

The model given in Ref.23 is

$$\dot{x} = Ax + Bu$$
$$y = Cx \qquad (37)$$

where

$$x^T = [\Delta\omega_1\ \Delta\delta_1\ \Delta e_{q1}'\ \Delta e_{FD1}\ \Delta\omega_2\ \Delta\delta_2\ \Delta e_{q2}'\ \Delta e_{FD2}]$$

$$A = \begin{bmatrix} -0.244 & -0.9747 & -0.1431 & 0 & 0 & 0.0747 & 0.0041 & 0 \\ 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.046 & -0.455 & 0.244 & 0 & 0.046 & 0.13 & 0 \\ 0 & -398.56 & -19498.8 & -50 & 0 & 398.58 & -3967 & 0 \\ 0 & 0.178 & -0.0433 & 0 & -0.2473 & -0.178 & -0.146 & 0 \\ 0 & 0 & 0 & 0 & 376.99 & 0 & 0 & 0 \\ 0 & 0.056 & 0.1234 & 0 & 0 & -0.0565 & -0.3061 & 0.149 \\ 0 & -677.39 & -10234.22 & 0 & 0 & 677.78 & -13364.16 & -50 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 25000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 25000 \end{bmatrix}^T$$

For the system as shown in Fig. 4, the system eigenvalues without control are tabulated in the first column of Table 3. The first and the second pairs of eigenvalues are electromechanical modes. The minimal damping ratio of electromechanical modes is 0.0092, that is not good enough. To improve the system dynamic stability, those modes should be shifted toward certain desirable locations. In the eigenvalues assignment, if we choose h_1 = 3.0 and h_2 = 3.5, the electromechanical modes with absolute real parts lesser than h_1 = 3.0, will be shifted to the vertical strip of $[-h_2, -h_1]$ = [−3.5, −3.0]. The other modes will not be changed (see, subsection 5.1). Two output feedback schemes are compared : (1) reduced order model, and (2) proposed method. The minimal damping ratio of those modes is improved to be 0.2638, that is inside the acceptable range [1–2]. It is shown from Table 3, that the relative stability of the proposed method is much better than optimal reduced order model[23]. The feedback gains are given in Table 4.

Table 3 System Eigenvalues

Open-Loop	Reduced Order Model	Proposed Method
$-0.0904\pm j9.8430$	$-0.6120\pm j10.2843$	$-3.2255\pm j11.7948$
-0.0006	$-1.9248\pm j1.9185$	$-2.8460\pm j2.8559$
-0.2443	$-23.3329\pm j67.2307$	$-22.1633\pm j66.7605$
$-25.1741\pm j67.8187$	$-24.9273\pm j29.8745$	$-22.3914\pm j27.4017$
$-25.2329\pm j30.3073$		

Vertical strip in h_2 = 3.5 ; h_1 = 3.0

Table 4 Feedback Gains

	Reduced Order Model		Proposed Method	
	u_1	u_2	u_1	u_2
$\Delta\omega_1$	196.5413	32.4768	33.617	2.7059
$\Delta\delta_1$	1.2387	0.1697	0.3545	0.0803
$\Delta\omega_2$	59.4160	0.3957	5.2246	15.7479
$\Delta\delta_2$	0.1028	.3081	0.0608	0.0849

ρ = 0.5216

The transient responses of the angular frequencies to a 5 % change in the mechanical torque of machine 1 and machine 2 are shown in Fig. 5 and Fig. 6, respectively.

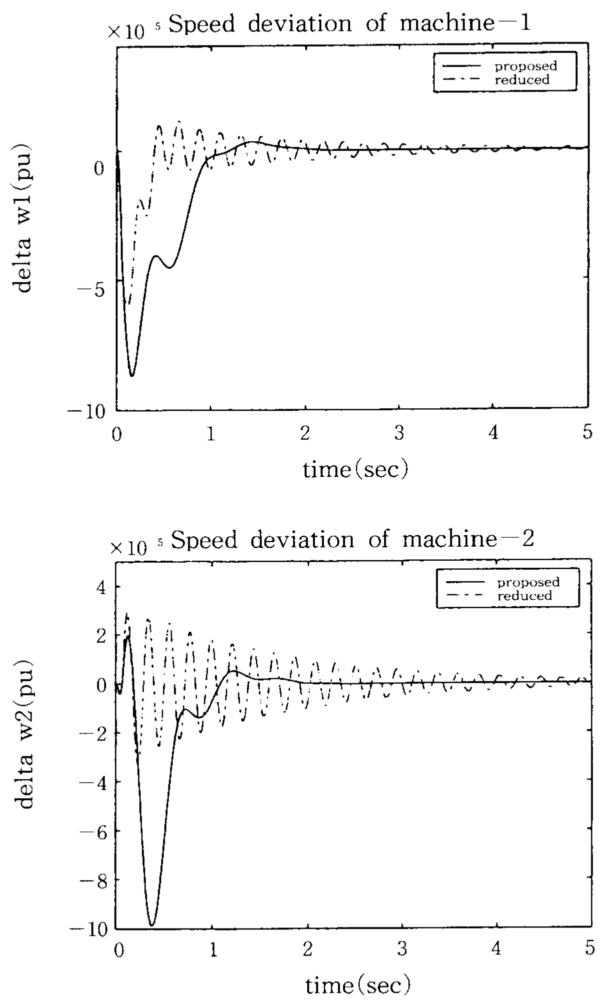


Fig.5 Transient Response of the Angular Frequencies to a 5 % Change in the Mechanical Torque of Machine 1.

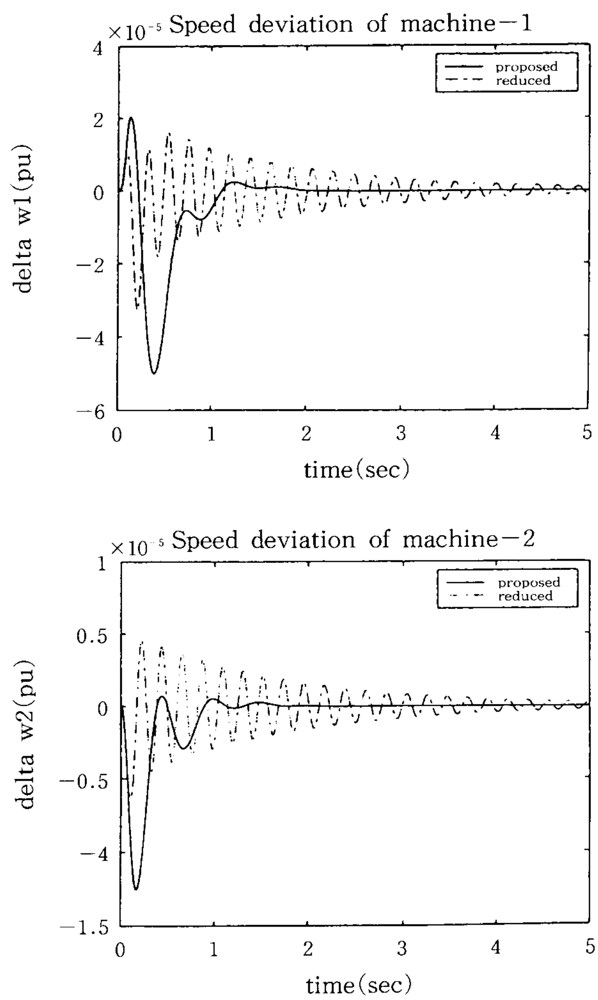


Fig.6 Transient Response of the Angular Frequencies to a 5 % Change in the Mechanical Torque of Machine 2.

6. Conclusions

An output feedback controller is designed to increase the stability of interconnected power system. The electromechanical modes can be shifted to a pre-specified vertical strip without effecting the other modes. The design method is very simple and avoid the difficulty of choosing weighting matrices.

The reduced order model retains the modes that mostly affect some desired variables which are usually the variable or measurable variables. In this analysis these variables are torque angles and angular frequencies (speeds). Starting with the optimal reduced order model approach, the algorithm for the designing output feedback excitation controller is constructed. The values of the feedback gains are calculated by using strip eigenvalue assignment method. Results from simulation show that the proposed controller can effectively damp system oscillations under disturbances.

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