Robust Power System Stabilizers Design Using Reduced Order Models

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Abstract

This paper provides the design of robust power system stabilizers using reduced order models whose state variables are torque angles and speeds. The methods are based on a modified optimal controller that place the system poles in an acceptable region in the complex plane for a given set of operating and system conditions. The output feedback gain matrix is obtained by using the strip eigenvalue assignment which it does not need the specification of weighting matrices. The effectiveness of the proposed controller is illustrated by a numeric example involving a three-machine nine-bus power system. The results show the robustness of the proposed controller and its ability to enhance system damping over several operating conditions.

Keywords: power system stabilizer, optimal control, reduced order model, strip eigenvalue assignment

I. Introduction

Power system stabilizers (PSSs) are now commonly used by utilities in modern power systems. The control signals of the PSSs are added to the excitation systems to enhance damping of the electric power system during low-frequency oscillations [1-5].

Design of conventional stabilizer is generally based on linearized fixed parameter model. This stabilizer has performed reasonable well to improve the dynamic stability of a power system. Power systems are generally non-linear and highly dynamic system. Thus, the fixed parameter conventional power system stabilizers (such as lead-lag controllers, fixed gain PI controllers, and PID controllers) designed based on linear control theory and linearized model around an operating point can not provide the desired performance over the whole range of operating conditions [6, 7]. Another approach to PSS design based on pole placement techniques has been proposed [8, 9].

Recently, modern control methods have been proposed for the PSSs and decentralized controllers have been designed on based of the optimal control theory [3, 10-14]. These methods utilize a state space representation of the power system model and calculate a gain matrix which, when applied as a multivariable feedback control will minimize a prescribed objective function. A method based on structurally constrained optimal control for the determination of stabilizer setting in multimachine power systems has been proposed [10]. Another approach used a new procedure for designing power system stabilizer under the constraint of sequential stability has been reported. Where this procedure adopted a linearized model of the power system in the state space representation. The stabilizing signal required the linear feedback of the local variables only [11]. Different approaches have been proposed to deal with PSSs design, one of which is based on reduced order models [12-14].

For practical implementation, not all of the state variables are available for measurement. In this case the optimal control low requires the design of a state observers. This increases the implementation cost and reduces the reliability of control systems. For these reasons a control scheme is favored the uses only a few desired state variables such as torque angles and speeds. The method referred to as optimal reduced order models is obtained to retain the physical meanings of the desired state variables [14]. 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.

This paper presents a new approach to design of robust power system stabilizers using reduced order models whose state variables are torque angles and speeds. The design method does not need the specification of weighting matrices. In this work, the desired positions of the eigenvalues are achieved without convergence problem. The effectiveness of the proposed controller is illustrated by a numeric example involving a three-machine nine-bus power system. The results show the robustness of the proposed controller and its ability to enhance system damping over several operating conditions.

II. System representation

The system under study consists of three-machine nine-bus power system as shown in Fig. 1. Each machine has been represented by a 3rd-order generators equipped with a static exciter [1, 16]. The PSS supplementary stabilizing signal **u** is added to the excitation system of each machine as illustrated in Fig.2. To start with, we linearise the system model around the operating point, which results in the following form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} \tag{2}$$

where **x** is the nx1 state vector, **u** is the mx1 vector of control variables and **y** is the rx1 vector of system output variables.

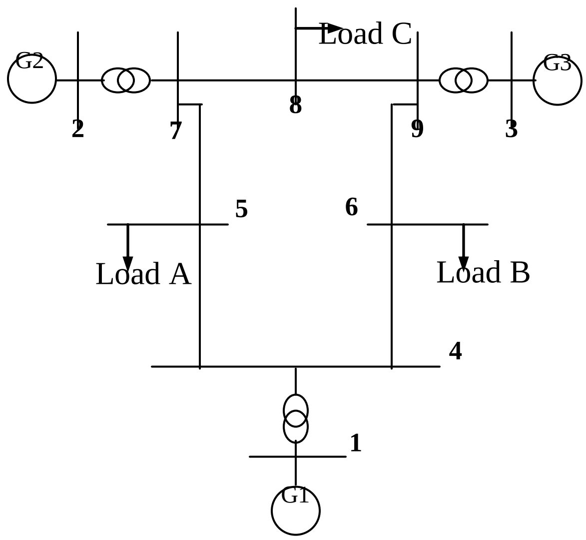


Fig. 1 Three-machine nine-bus system

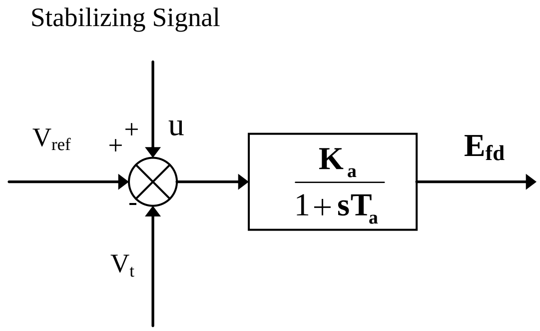


Fig. 2 IEEE Type-ST1 excitation system

An *N*-machine power system is considered to be composed of N subsystems, one for each system machine. The state variables are arranged by subsystem, so that the state vector is partitioned as

$$\mathbf{x} = [\mathbf{x}_1^{\mathbf{T}}, \mathbf{x}_2^{\mathbf{T}}, \ldots, \mathbf{x}_N^{\mathbf{T}}]^{\mathbf{T}}$$

where

$$\mathbf{x_i} = [\Delta\boldsymbol{\omega}_\mathbf{i}, \Delta\boldsymbol{\delta}_\mathbf{i}, \Delta\mathbf{E}'_{\mathbf{qi}}, \Delta\mathbf{E}_{\mathbf{fdi}}]^{\mathbf{T}} \qquad i = 1, 2, \ldots, N$$

For the *i*th machine, $\Delta\boldsymbol{\omega}_{\mathbf{i}}$ is the deviation in the rotor speed, $\Delta\boldsymbol{\delta}_{\mathbf{i}}$ is the deviation in rotor angle, $\Delta\mathbf{E}'_{\mathbf{qi}}$ is the deviation in the voltage proportional to the direct-axis flux linkage, and $\Delta\mathbf{E}_{\mathbf{fdi}}$ is the deviation in the output of the excitation system. The control vector is partitioned as

$$\mathbf{u} = [\mathbf{u}_1^{\mathbf{T}}, \mathbf{u}_2^{\mathbf{T}}, \ldots, \mathbf{u}_N^{\mathbf{T}}]^{\mathbf{T}}$$

where **u** is the reference for the voltage regulator of the *i*th machine. The system output vector is partitioned as

$$\mathbf{y} = [\mathbf{y}_1^{\mathbf{T}}, \mathbf{y}_2^{\mathbf{T}}, \ldots, \mathbf{y}_N^{\mathbf{T}}]^{\mathbf{T}}$$

where

$$\mathbf{y}_{\mathbf{i}} = [\Delta\boldsymbol{\omega}_{\mathbf{i}}, \Delta\boldsymbol{\delta}_{\mathbf{i}}]^{\mathbf{T}}$$

With the above partitions of vector **x** and **u**, matrix **B** will exhibit a block diagonal structure

$$\mathbf{B} = \text{block diag}\,\{\mathbf{B}_1, \ldots, \mathbf{B}_N\}$$

where

$$\mathbf{B}_{\mathbf{i}} = [0\ \ 0\ \ 0\ \ \mathbf{K}_{\mathbf{ai}}/\mathbf{T}_{\mathbf{ai}}]^{\mathbf{T}}$$

A, **B**, and **C** are the real constant matrices. Assuming zero interactions between subsystems, equations (1) and (2) can be written as:

$$\dot{\mathbf{x}}_{\mathbf{i}} = \mathbf{A}_{\mathbf{i}}\mathbf{x}_{\mathbf{i}} + \mathbf{B}_{\mathbf{i}}\mathbf{u}_{\mathbf{i}} \tag{3}$$

$$\mathbf{y}_{\mathbf{i}} = \mathbf{C}_{\mathbf{i}}\mathbf{x}_{\mathbf{i}} \tag{4}$$

III. Robust power system stabilizers design

In this section, a power system stabilizer is designed using reduced order models. The method is based on a modified optimal control that place the system poles in vertical strip in the complex plane. Without loss of generality, it is assumed that, in an n-machine power system, a PSS is to be installed on each machine.

We assume that the system expressed by (3) and (4) be controllable and observable. By using reduced order model, the system can be reduced to the following form [14]:

$$\dot{\mathbf{z}}_{\mathbf{i}} = \mathbf{F}_{\mathbf{i}}\mathbf{z}_{\mathbf{i}} + \mathbf{G}_{\mathbf{i}}\mathbf{u}_{\mathbf{i}} \tag{5}$$

where

$\mathbf{z}_{\mathbf{i}} \in \mathbf{R}^{\mathbf{mxl}}$: State vector to be retained consisting of torque angles and speeds.

$\mathbf{F}_{\mathbf{i}}, \mathbf{G}_{\mathbf{i}}$: Constant matrices of reduced order model with appropriate dimensions.

Let $(\mathbf{A}_{\mathbf{i}}, \mathbf{B}_{\mathbf{i}})$ be the pair of the open-loop system matrices in (3) and h ≧ 0 represent the prescribed degree of relative stability. Then the closed-loop matrix $\mathbf{A}_{\mathbf{ci}} = \mathbf{A}_{\mathbf{i}} - \mathbf{B}_{\mathbf{i}}\mathbf{R}_{\mathbf{i}}^{-1}\mathbf{B}_{\mathbf{i}}^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}}$ has all its eigenvalues lying on the left side of the -h vertical line as shown in Fig. 3a, where the matrix $\overline{\mathbf{P}}_{\mathbf{i}}$ is the solution of the following Riccati equation:

$$(\mathbf{A}_{\mathbf{i}} + \mathbf{h}\mathbf{I}_{\mathbf{n}})^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}} + \overline{\mathbf{P}}_{\mathbf{i}}(\mathbf{A}_{\mathbf{i}} + \mathbf{h}\mathbf{I}_{\mathbf{n}}) - \overline{\mathbf{P}}_{\mathbf{i}}\mathbf{B}_{\mathbf{i}}\mathbf{R}^{-1}\mathbf{B}_{\mathbf{i}}^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}} + \mathbf{Q}_{\mathbf{i}} = 0_n \tag{6}$$

Note that in (6) with $\mathbf{Q} = \mathbf{0}_{\mathbf{n}}$, the unstable eigenvalues of $(\mathbf{A}_{\mathbf{i}} + \mathbf{h}\mathbf{I}_{\mathbf{n}})$ are shifted to their mirror image positions with respect to the -h vertical line, which are the eigenvalues of the closed-loop system matrix $\mathbf{A}_{\mathbf{ci}}$.

For the reduced order models, we 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. 3b and give an mxm matrix $\overline{\mathbf{F}}_{\mathbf{i}} = \mathbf{F}_{\mathbf{i}} + \mathbf{h}_1\mathbf{I}_{\mathbf{m}}$

The control law changed to be

$$\mathbf{u}(\mathbf{t}) = -\rho_{\mathbf{i}}\overline{\mathbf{K}}_{\mathbf{i}}\mathbf{z}_{\mathbf{i}} \tag{7}$$

with the feedback gain $\overline{\mathbf{K}}_{\mathbf{i}} = \mathbf{R}^{-1}\mathbf{G}_{\mathbf{i}}^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}}$. The matrix $\overline{\mathbf{P}}_{\mathbf{i}}$ is the solution of the following modified Riccati equation:

$$\overline{\mathbf{F}}_{\mathbf{i}}^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}} + \overline{\mathbf{P}}_{\mathbf{i}}\overline{\mathbf{F}}_{\mathbf{i}} - \overline{\mathbf{P}}_{\mathbf{i}}\mathbf{G}_{\mathbf{i}}\mathbf{R}^{-1}\mathbf{G}_{\mathbf{i}}^{\mathbf{T}}\overline{\mathbf{P}}_{\mathbf{i}} = 0_{\mathbf{m}} \tag{8}$$

The constant gain ρ_i is selected by

$$\rho_i = \frac{1}{2} + \frac{h_2 - h_1}{tr(G_i \bar{K}_i)} \tag{9}$$

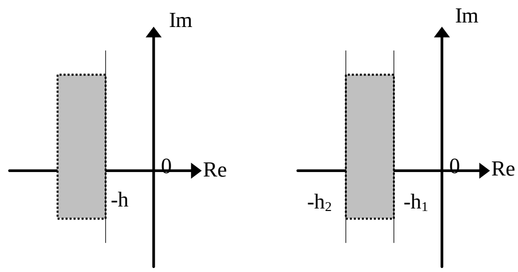
The optimal closed-loop system can be written as follows:

$$\dot{x} = (A - B\hat{K}C)x \tag{10}$$

where

$$B = C^T G$$
$$G = \text{block diag}\ \{G_1, \cdots, G_N\}$$
$$\hat{K} = \text{block diag}\ \{[\alpha_1 \quad \beta_1], \cdots, [\alpha_N \quad \beta_N]\}$$
$$\alpha_i = \rho_i \bar{K}_{i1}$$
$$\beta_i = \rho_i \bar{K}_{i2}$$

Equation (10) consists of a set of eigenvalues which lie inside the vertical strip of the [$-h_2$, $-h_1$] as shown in Fig. 3b. The implementation details of the proposed controller are shown in Fig. 4.



(a) Vertical line (b) Vertical strip

Fig. 3 Complex s-plane

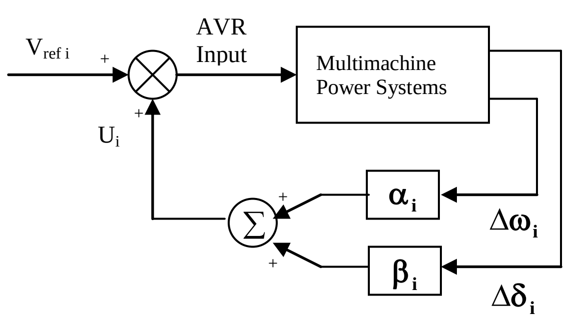


Fig. 4 Proposed controller

IV. Simulation results

To evaluate the performance of the proposed controller, tests have been carried out on the three-machine nine-bus power system as shown in Fig. 1. The system data is given in appendix.

The variation of loading conditions and open loop eigenvalues of the study system are given in Table 1 and Table 2, respectively. Table 2 shows, each pair of conjugate eigenvalues corresponds to an oscillation mode, there are six modes in this study system. Mode 1, 2, and 3 are the electromechanical modes. Mode 4, 5, and 6 are oscillation modes determined by excitation system of the machine. It can be seen that the damping of the electromechanical modes for all the operating condition are poor (damping ratio: ζ < 10%). Only the electromechanical modes are to be shifted. In this work, we choose h_1 = 2 and h_2 = 3 for all operation conditions. Consequently, the electromechanical modes with absolute real part less then $h_1 = 2$, will be shifted to the vertical strip of $[-h_2, -h_1] = [-3, -2]$. The closed loop eigenvalues of the study system for three operating conditions are given in Table 3. It can be seen that the electromechanical modes have been shifted into the acceptable region. The system response of the angular frequency to a 5% step disturbance input at the AVR voltage reference of machine 1 for all operating conditions are shown in Fig. 5, 6, and 7, respectively. For comparison purposes, the open loop responses (without controller) are also included. The system oscillations of the rotor speed deviation for all the 3 machines are seen to very well damped with the controller.

Table 1

Loading condition (in p.u)

	Heavy		Nominal		Light	
Generator						
	P	Q	P	Q	P	Q
G1	1.330	0.630	0.716	0.270	0.465	-0.092
G2	1.900	0.361	1.630	0.066	1.100	-0.225
G3	1.200	0.120	0.850	- 0.109	0.300	-0.319
Load						
A	1.750	0.700	1.250	0.500	0.750	0.300
B	1.200	0.400	0.900	0.300	0.500	0.150
C	1.400	0.500	1.000	0.350	0.600	0.200

Table 2

Open loop eigenvalues of the study system

Modes	Heavy	Nominal	Light
1	-0.0306±j10.772	- 0.0321±j12.3592	- 0.0167±j13.9497
2	-0.0064±j 6.4621	- 0.0118±j 7.0773	- 0.0058±j 7.7369
3	-0.0174±j 2.7842	- 0.0114±j 3.1716	- 0.0040±j 3.6173
4	-5.0406±j 1.0785	- 5.0464±j 0.9527	- 5.0549±j 0.7693
5	-5.3522±j 5.5831	- 5.3517±j 5.5244	- 5.3618±j 5.4070
6	-5.2085±j 4.2952	- 5.1883±j 4.1740	- 5.1861±j 3.9965

Table 3

Closed loop eigenvalues of the study system

Modes	Heavy	Nominal	Light
1	-2.5185±j10.961	-2.5047±j12.5259	- 2.4938±j14.0930
2	-2.4926±j 6.7505	-2.4915±j 7.3475	- 2.4864±j 7.9825
3	-2.4966±j 3.4215	-2.4937±j 3.7415	- 2.4945±j 4.1173
4	-5.0233±j 1.0150	-5.0354±j 0.9027	- 5.0500±j 0.7411
5	-5.3531±j 5.5621	-5.3604±j 5.5015	- 5.3746±j 5.3900
6	-5.2083±j 4.2945	-5.1869±j 4.1667	- 5.1873±j 3.9913

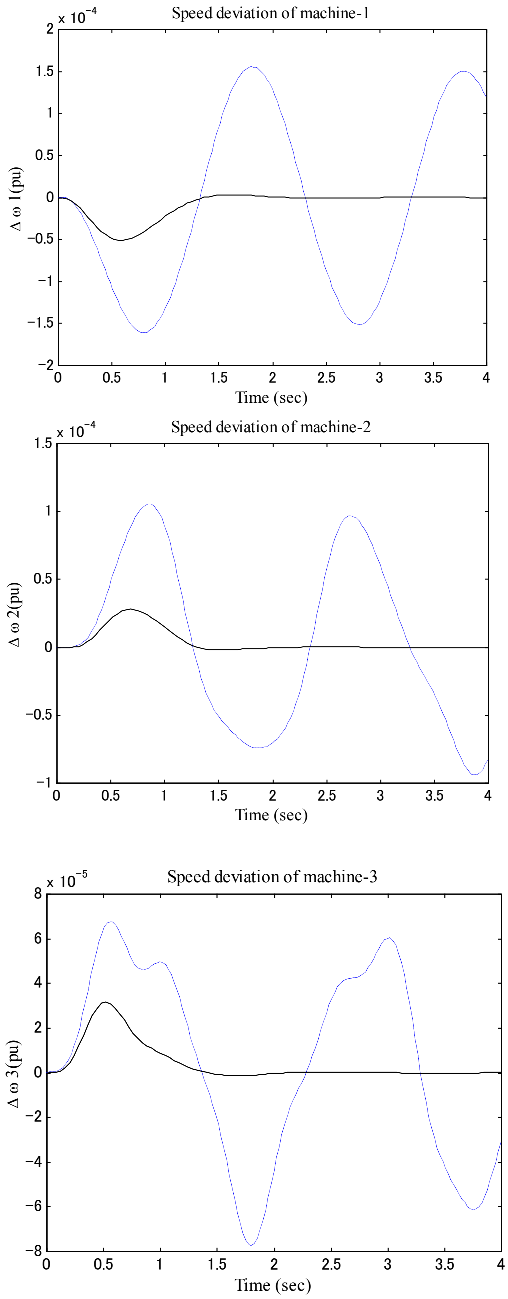


Fig. 5 System response with nominal loading condition
--- : without controller; ___ : with controller

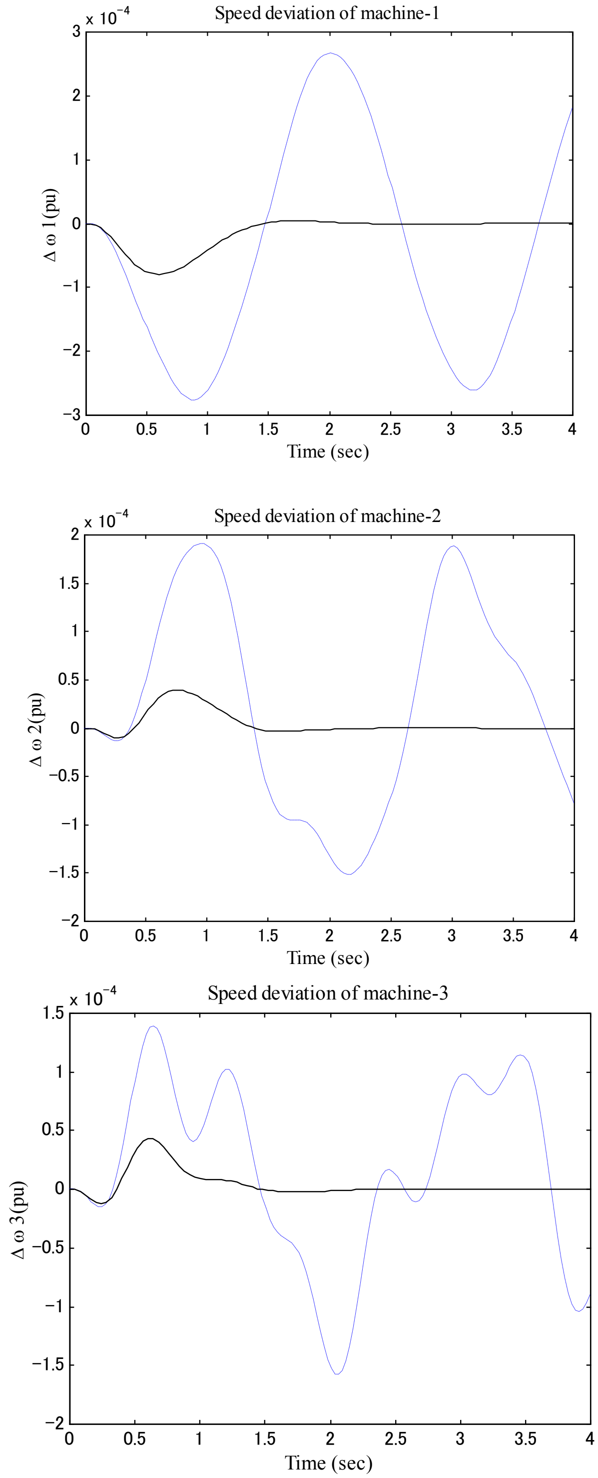


Fig. 6 System response with heavy loading condition
--- : without controller; ___ : with controller

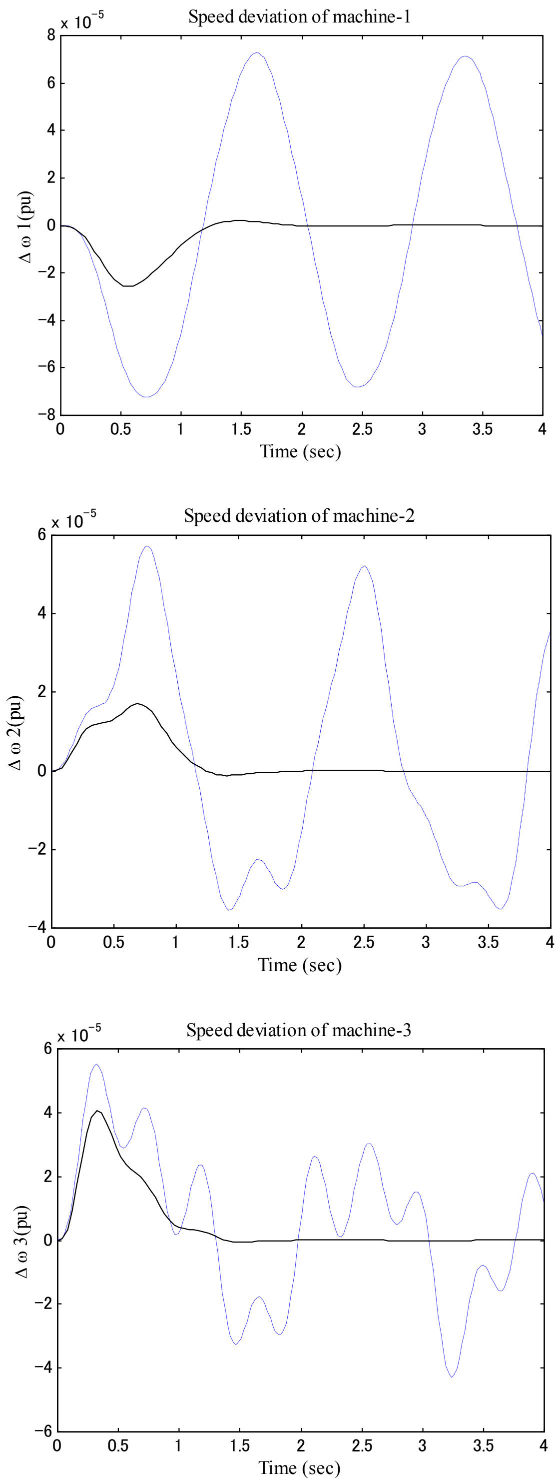


Fig. 7 System response with light loading condition
--- : without controller; ___ : with controller

V. Conclusion

In this paper, robust power system stabilizer design using reduced order model has been presented. The proposed technique is seen to provide the desired closed loop performance over the specified range of operating condition. The output feedback control gain is obtained by using the strip eigenvalue assignment which it does not need the specification of weighting matrices. The design procedure is simple and bears much potential for practical implementations. It is demonstrated by simulation results that the proposed controller can significantly increase the damping of power system oscillations over several operating conditions.

VI. References

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