Paper

LMI-Based Robust H_2 Controller Design for Damping Oscillations in Power Systems

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Recent results have shown that several H_2 and H_2-related problems can be formulated as a convex optimization problem involving linear matrix inequalities (LMIs) with a finite number of variables. This paper presents an LMI-based robust H_2 controller design for damping oscillations in power systems. The proposed controller uses full state feedback. The feedback gain matrix is obtained as the solution of a linear matrix inequality. The technique is illustrated with applications to the design of stabilizer for a typical single-machine infinite-bus (SMIB) and a multimachine power system. The LMI based control ensures adequate damping for widely varying system operating conditions and is compared with conventional power system stabilizer (CPSS).

Keywords: H_2 controller, linear matrix inequality, multimachine systems, power system stabilizer, single-machine infinite-bus systems

1. Introduction

Power systems are usually large nonlinear systems, which are often subject to low frequency oscillations when working under some adverse loading conditions. The oscillation may sustain and grow to cause system separation if no adequate damping is available. To enhance system damping, the generators are equipped with power system stabilizers (PSSs) that provide supplementary feedback stabilizing signals in the excitation systems. PSSs enhance the power system stability limit by enhancing the system damping of low frequency oscillations associated with the electromechanical modes (1). Many approaches are available for PSS design, most of which are based either on classical control methods (1)~(3) or on intelligent control strategies (4)~(6).

Power systems continually undergo changes in the operating condition due to changes in the loads, generation and the transmission network resulting in accompanying changes in the system dynamics. A well-designed stabilizer has to perform satisfactorily in the presence of such variations in the system. In other words, the stabilizer should be robust to changes in the system over its entire operating range.

The nonlinear differential equations governing the behavior of a power system can be linearized at a particular operating point to obtain a linear model which represents the small signal oscillatory response of the power system. Variations in the operating condition of the system result in corresponding variations in the parameters of the small signal model. A given range of variations in the operating conditions of a particular system thus generates a set of a linear models each corresponding to one particular operating condition. Since, any given instant, the actual plant could correspond to any model in this set, a robust controller would have to impart adequate damping to each one of this entire set of linear models.

Robust control technique has been applied to power system controller design since late 1980s. The main advantage of this technique is that it presents a natural tool for successfully modeling plant uncertainties. Some of those efforts have been contributed to design robust controllers for PSS and/or FACTS devices using H_∞ concept such as mixed-sensitivity (7); μ-synthesis (8) and H_2 concept such as LQG (9). In these studies, many classical control objectives such as disturbance attenuation, robust stabilization of uncertain systems are expressed in terms of H_∞ performance and tackled by H_∞ synthesis techniques. All these efforts produce a controller, which is "robust" in the sense that these controllers provide added damping to the system under a wide range of load variations.

Design method based on the H_∞ norm of the closed-loop transfer function have gained popularity, because unlike H_2 methods (best known as LQG), they offer a single framework in which to deal both with performance and robustness. On the other hand, since an H_2 cost function offers a more natural way of representing certain aspects of the system performance, improving the robustness of H_2-based design methods against perturbations of the nominal plant is a problem of considerable importance for practical applications (10). In the robust H_2 approach, the controller is designed to minimize an upper bound on the worst case H_2 norm for a range of

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admissible plant perturbations. One of the advantages of linear matrix inequality (LMI) is mixing the time and frequency domain objectives. This paper proposes a robust H_2 controller design for damping oscillations in power systems base on linear matrix inequality. The efficiency of an LMI-based design approach as a practical design tool is illustrated with applications to the design of stabilizer for case studies, including a typical single-machine infinite-bus (SMIB) power system and a 3-machine 9-bus power system.

The paper is organized as follows. A detailed description of the proposed design procedure is given in Section 2. In Section 3, simulation results are given for a typical single-machine infinite-bus (SMIB) power system and a multimachine power system to demonstrate the effectiveness of the proposed method. Conclusions are drawn in Section 4.

2. LMI-based H_2 Controller Design

Stability is a minimum requirement for control system. However, in most practical situations, a good controller should also deliver sufficiently fast and well-damped time responses. A customary way to guarantee satisfactory transients (or dynamics) is to place the closed-loop poles in a suitable region of the complex s-plane.

2.1 Introduction of Linear Matrix Inequality A wide variety of problems in control theory and system can be reduced to a handful of standard convex and quasi-convex optimization problems that involve linear matrix inequalities (LMIs), that is constraints of the form [11]:

$$F(x) \triangleq F_0 + \sum_{i=1}^{m} x_i F_i > 0 \quad \cdots\cdots (1)$$

where $x = [x_1, x_2, \cdots, x_m] \in R^m$ is the variable, and the symmetric matrices $F_i = F_i^T \in R^{n\times n}, i = 0, \cdots, m$, are given. The set $\{x | F(x) > 0\}$ is convex, and need not have smooth boundary.

When the matrices F_i are diagonal, the LMI $F(x) > 0$ is just a set of linear inequalities. Nonlinear (convex) inequalities are converted to LMI form using Schur complements. The basic idea is as follows:

$$\begin{bmatrix} Q(x) & S(x) \\ S(x)^T & R(x) \end{bmatrix} > 0 \quad \cdots\cdots (2)$$

where $Q(x) = Q(x)^T$, $R(x) = R(x)^T$, and $S(x)$ depend affinely on x, is equivalent to

$$R(x) > 0, Q(x) - S(x)R(x)^{-1}S(x)^T > 0 \quad \cdots\cdots (3)$$

In other words, the set of nonlinear inequalities Eq. (3) can be represented as the LMI Eq. (2).

Two standard LMI optimization problems are of interest:

(1) LMI feasibility problem. Given an LMI $F(x) > 0$, the corresponding LMI feasibility problem is to find x^{feas} such that $F(x^{feas}) > 0$ or determine that the LMI is infeasible.

(2) Semi-Definite Programming problem (SDP). An SDP requires the minimization of a linear objective subject to LMI constraints:

$$\left.\begin{array}{l} \text{Minimize } c^T x \\ \text{Subject to } F(x) > 0 \end{array}\right\} \quad \cdots\cdots (4)$$

where c is a real vector, and F is a symmetric matrix that depends affinely on the optimization variable x. This is *a convex optimization problem.*

Both these problems can be numerically solved vary efficiently, using currently available software [12] [13].

2.2 Proposed H_2 Controller Design Let us consider the following linear system:

$$\left.\begin{array}{l} \dot{x} = Ax + Bw \\ z = Cx \end{array}\right\} \quad \cdots\cdots (5)$$

where A is stable, x is the state, w is the input and z is the exit, the H_2 norm of the transfer function from w to z, $H_{zw}(s)$, is

$$\|H_{zw}(s)\|_2^2 = \frac{1}{\pi}\int_0^{\infty} \text{trace}(H_{zw}^*(j\omega)H_{zw}(j\omega))d\omega \quad \cdots\cdots (6)$$

where * denotes the transpose conjugate operator. One way of calculating this norm, among many others, is through the following semidefinite program:

$$\left.\begin{array}{ll} \min & \text{trace}(CPC^T) \\ \text{s.t.} & AP + PA^T + BB^T \le 0 \\ & P = P^T > 0 \end{array}\right\} \quad \cdots\cdots (7)$$

The constraints above define a nonempty set if and only if A is a stable matrix. In fact, it is easy to see that if the last problem is feasible for some matrix P then there exists a matrix $Q = Q^T > 0$ such that the Lyapunov equation

$$AP + PA^T + Q = 0 \quad \cdots\cdots (8)$$

is satisfied, thus A is stable. This fact can be explored in several ways in control design and many of the resulting problems reduce to semidefinite programs.

The design problem treated in this paper consists of finding an internally stabilizing controller that minimizes a worst-case H_2 norm constraint. Consider the control system shown in Fig. 1. The generalized plant P has a state space representation

$$\left.\begin{array}{l} \dot{x} = Ax + B_1 w + B_2 u \\ z = C_1 x + D_{12} u \end{array}\right\} \quad \cdots\cdots (9)$$

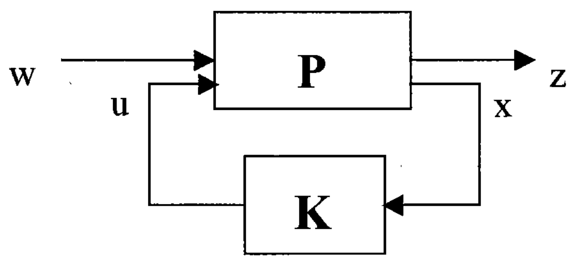

Fig. 1. Generalized plant

where $D_{12}^T D_{12} > 0$, $x \in R^n$, $w \in R^q$, $z \in R^p$ and $u \in R^m$, the H_2 state feedback design problem can be stated as "find a gain K such that the input $u = Kx$ stabilizes the system above and minimizes the H_2 norm of the transfer function $H_{zw}(s)$". The substitution of this input in the norm calculation problem given before provides

$$\left.\begin{array}{ll} \min & \mathrm{trace}[(C_1 + D_{12}K)P(C_1 + D_{12}K)^T] \\ \mathrm{s.t.} & (A + B_2K)P + P(A + B_2K)^T + B_1B_1^T \leq 0 \\ & P = P^T > 0 \end{array}\right\} \quad \cdots\cdots (10)$$

So, defining the new variables $Y = Y^T = P$, $L = KP$, $W = W^T$, and using Schur's complement it is possible to rewrite the problem above as the LMI problem

$$\left.\begin{array}{ll} \min & \mathrm{trace}(W) \\ \mathrm{s.t.} & AY + YA^T + B_2L + L^TB_2^T + B_1B_1^T \leq 0 \\ & \begin{bmatrix} Y & YC_1^T + L^TD_{12}^T \\ C_1Y + D_{12}L & W \end{bmatrix} \geq 0 \end{array}\right\} \quad \cdots\cdots (11)$$

The above expression is a matrix inequality, linear in the variables Y and L, and can be solved using standard optimization techniques. Once a feasible solution (Y, L) satisfying Eq. (11) is found, the required state feedback gain matrix can be computed as $K = LY^{-1}$.

3. Simulation Results

To test the performance of the proposed stabilizer, simulation studies were performed on the two systems: a single-machine infinite-bus (SMIB) system and a 3-machine 9-bus system.

3.1 A Single-machine Infinite-bus System A typical single-machine infinite-bus (SMIB) power system [14] is chosen for analysis of the proposed controller as shown in Fig. 2. The static fast exciter is shown in Fig. 3. The overall system is of fourth order, with the synchronous machine represented by third order model and exciter-voltage regulator system represented by first order dynamics. The state variables of this model are $\Delta\omega$, $\Delta\delta$, $\Delta E'_q$, ΔE_{fd}, respectively, angular speed, rotor angle, voltage behind transient, and excitation voltage. The power input to the generator shaft is assumed constant, the network is represented by a set of algebraic equations and the loads are modeled by constant impedances. The machine data, exciter data, block diagram of CPSS, and CPSS constants are given in the Appendix.

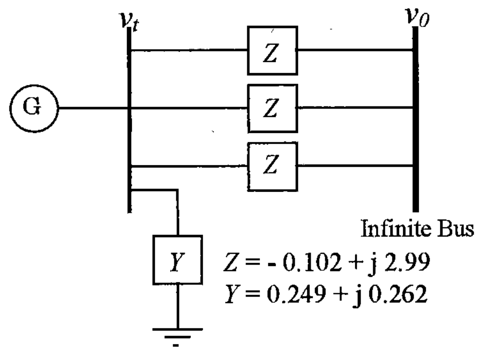

Fig. 2. A SMIB power system

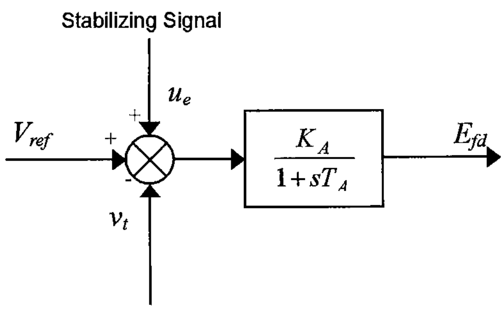

Fig. 3. Static fast exciter model

The operating condition: $P_e = 1.0$ pu, $Q_e = 0.015$ pu and $v_t = 1.05$ pu are chosen as the nominal operating condition and other operating points are regarded as perturbations of the nominal system. The eigenvalues of the nominal system are $0.295 \pm j4.96$ and $-10.4 \pm j3.28$. It is observed that the electromechanical mode (characterized by the pair of eigenvalues $0.295 \pm j4.96$) is negatively damped and the eigenvalues for this mode should be shifted leftward to more desirable locations into the left half s-plane.

As explained in Section 2, the feasibility problem was solved for (Y, L) and the required state feedback matrix was obtained as $K = LY^{-1}$, where Y is a symmetric, positive definite matrix and L is the matrix introduced to obtain linearity.

For evaluation purposes, the performance of the system with the proposed controller was compared to the CPSS. Simulation was carried out for the following disturbances:

[Case 1] Operation at the nominal operation condition

In this simulation, the studied power system is operated at the nominal condition. A system performance with a 10% step increase in the reference voltage is shown in Fig. 4. The following results show that the

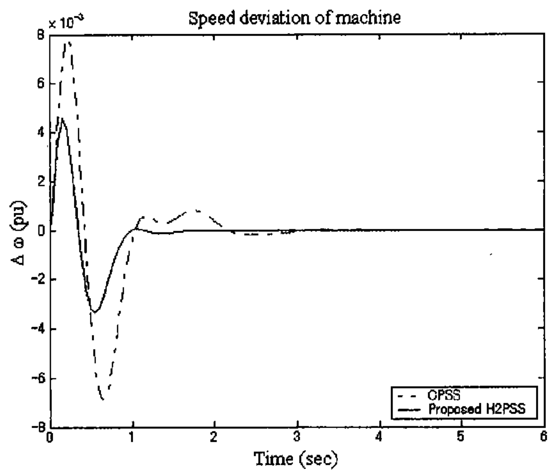

Fig. 4. Response with 10% step in V_{ref} for case 1

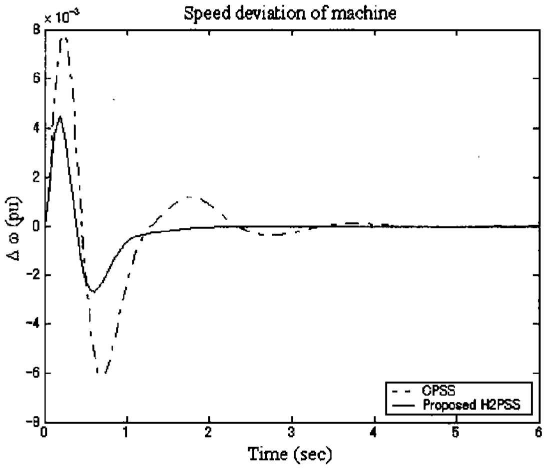

Fig. 5. Response with 10% step in V_{ref} for case 2

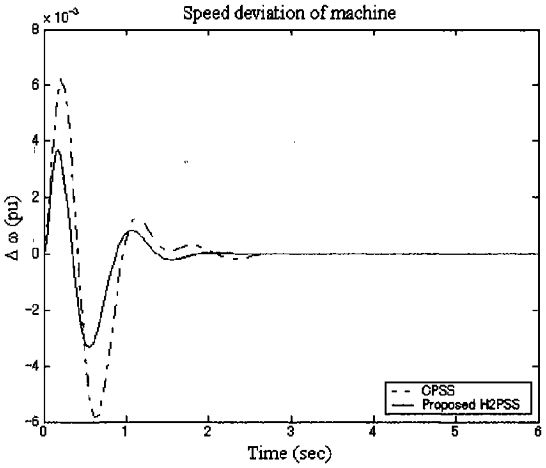

Fig. 6. Response with 10% step in V_{ref} for case 3

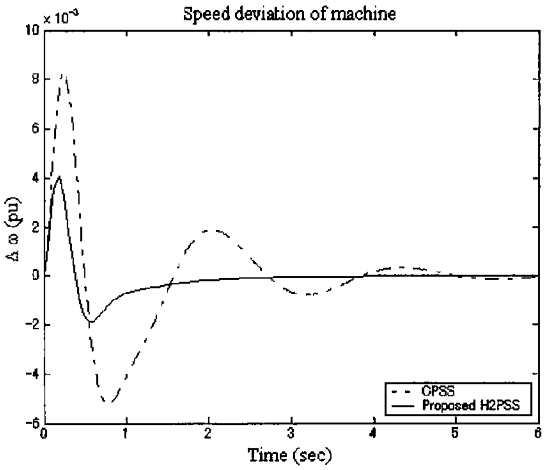

Fig. 7. Response with fault disturbance for case 4

oscillation with proposed H2PSS is damped out much faster than CPSS.

[Case 2] Operation in changed loading condition

In this simulation, the loading condition is changed. The reactive power is increased from 0.015 to 0.2 pu.

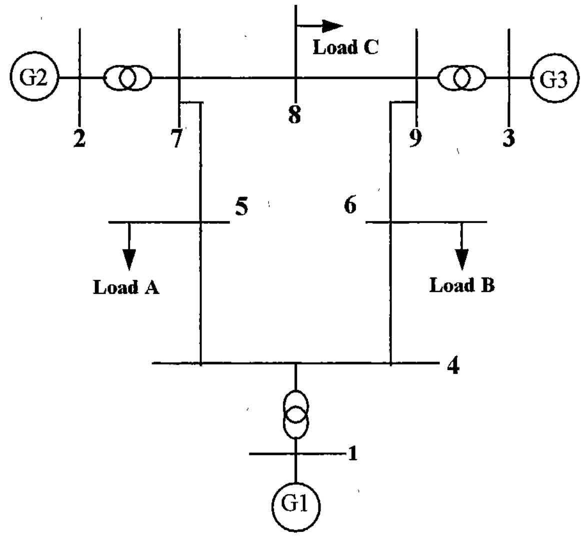

Fig. 8. Three-machine nine-bus power system

A system performance with a 10% step increase in the reference voltage is shown in Fig. 5. The dynamic performance is enhanced by the proposed H2PSS with a lower peak value of oscillation in frequency speed deviation than by the CPSS.

[Case 3] Operation in the leading power factor

It is very important to test the PSS under the leading power factor operating condition. A 10% step increase in the reference voltage was applied. The simulation result is shown in Fig. 6. It can be concluded that the performance of the proposed H2PSS is much better and the oscillation is damped out much faster than CPSS.

[Case 4] Operation in the one-line fault condition

A line fault is assumed; one of the transmission lines met a line-fault and the circuit breaker operated. The simulation result as shown in Fig. 7. As in the cases considered previously, it can be shown that the proposed H2PSS is superior to the CPSS with fixed parameters in its robustness.

3.2 A 3-machine 9-bus System In this part of the study, the 3-machine 9-bus power system shown in Fig. 8 is considered. Details of the system data are given in Ref. (15).

Each machine has been represented by a 3rd-order generators equipped with a static exciter. Without power system stabilizers, the system damping is poor and the system exhibits highly oscillatory response. It is therefore necessary to install one or more PSSs to improve the dynamic performance. To identify the optimum locations of PSSs, the participation factor method [16] was used. The results of the method indicate that all generators (G1, G2 and G3) are the optimum locations for installing PSSs to damp out the electromechanical modes of oscillations.

To design the proposed controller, three operation conditions, i.e. a heavy loading condition, a nominal loading condition, and a light loading condition, are considered as shown in Table 1. The open loop eigenvalues (dominant eigenvalues) of the study system for three operating conditions are given in Table 2. As each

Table 1. Loading condition (in pu)

	Heavy		Nominal		Light	
Generator	P	Q	P	Q	P	Q
G1	1.330	0.630	0.716	0.270	0.362	0.162
G2	1.900	0.361	1.630	0.066	0.800	-0.109
G3	1.200	0.120	0.850	- 0.109	0.450	-0.204
Load						
A	1.750	0.700	1.250	0.500	0.650	0.550
B	1.200	0.400	0.900	0.300	0.450	0.350
C	1.400	0.500	1.000	0.350	0.500	0.250

Table 2. Open loop eigenvalues of the study system

Modes	Heavy	Nominal	Light
1	-0.379±j 3.34	-0.401±j 3.46	-0.468±j 3.53
2	-0.158±j 7.60	-0.159±j 7.63	-0.377±j 7.44
3	-0.924±j 13.2	-0.759±j13.30	-0.983±j13.40

pair of conjugate eigenvalues corresponds to an oscillation mode, there are three modes in this study system. Mode 1, 2 and 3 are the rotor oscillation modes (the electromechanical modes). It can be seen that the damping of the rotor oscillation modes for all the operating conditions are poor. In the power systems, a damping ratio (ζ) of at least 10% and the real part of eigenvalue (σ) not greater than -0.5 for the troublesome low frequency electromechanical mode, guarantees that the low frequency oscillations, when excited, will die down in a reasonably short time.

In order to improve the damping of electromechanical modes, a decentralized controller was designed for all generators at the nominal loading conditions based on the proposed design technique in Section 2. In this scheme, each of the generators is fitted with a partial state feedback controller so that only locally available states are feedback at each generator. This implies that the state feedback matrix K of the overall system is block diagonal. This is schematically shown in Fig. 9, where the submatrices K_1, K_2, and K_3 are the feedback gain of each of the three generators. The locally measured states: $\Delta\omega$, $\Delta\delta$, $\Delta E_q'$, and, ΔE_{fd} are feedback at the AVR reference input of each machine after multiplication by suitable feedback gains. The LMI problem was constructed by writing LMI Eq. (11). The feasibility problem was solved for (Y, L) and the required state feedback matrix was obtained as $K = LY^{-1}$. If the matrices L and Y used in LMI formulation are restricted to be block diagonal then the product LY^{-1} will also have a block diagonal structure. Such a requirement on the L and Y matrices merely means restricting certain off diagonal elements to be zero which is an easily implemented additional constraint in the optimization problem.

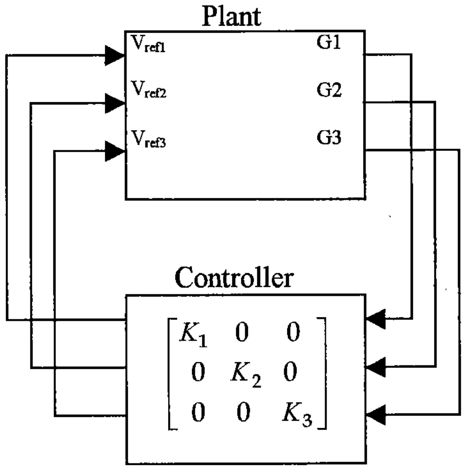

Fig. 9. Schematic of decentralized state feedback controller

Table 3. CPSS parameters

Gen#	K_c	T_w	T_1	T_2
1	83.24	8.0	0.329	0.140
2	33.01	8.0	0.169	0.072
3	78.18	8.0	0.124	0.053

Table 4. Closed-loop eigenvalues of the study system

Modes	Heavy	Nominal	Light
1	-4.160±j 5.41	-5.010±j 3.21	-6.080±j 7.84
2	-1.040±j 8.52	-3.830±j 7.77	-3.310±j 6.60
3	-5.40, -13.1	-7.870±j 6.61	-1.47, -4.89

In order to facilitate comparison with CPSS, the design and tuning of CPSS for this multi-machine system were used method in Ref. (17). In this paper, a CPSS with transfer function

$$G(s) = K_c \frac{sT_w}{1 + sT_w} \frac{(1 + sT_1)^2}{(1 + sT_2)^2} \qquad (12)$$

was used and the parameters of stabilizer have been tuned to provide an adequate amount of damping for mode of oscillation. The CPSS data for a three-machine system is given in Table 3. The output of all CPSS is limited to ±0.1 pu.

With the proposed H2PSS, the closed-loop eigenvalues are given in Table 4. It is quite clear that the system eigenvalues associated with the electromechanical modes have been successfully shifted to the left of $s = -0.5$ line with the proposed H2PSS. This demonstrates that the system damping with the proposed H2PSS is greatly enhanced.

To demonstrate the capability of the proposed HPSS to enhance system damping over a wide range of operating conditions, three different loading conditions were considered. A 10% step change in the reference voltage was applied at machine 2 (G2) as follows.

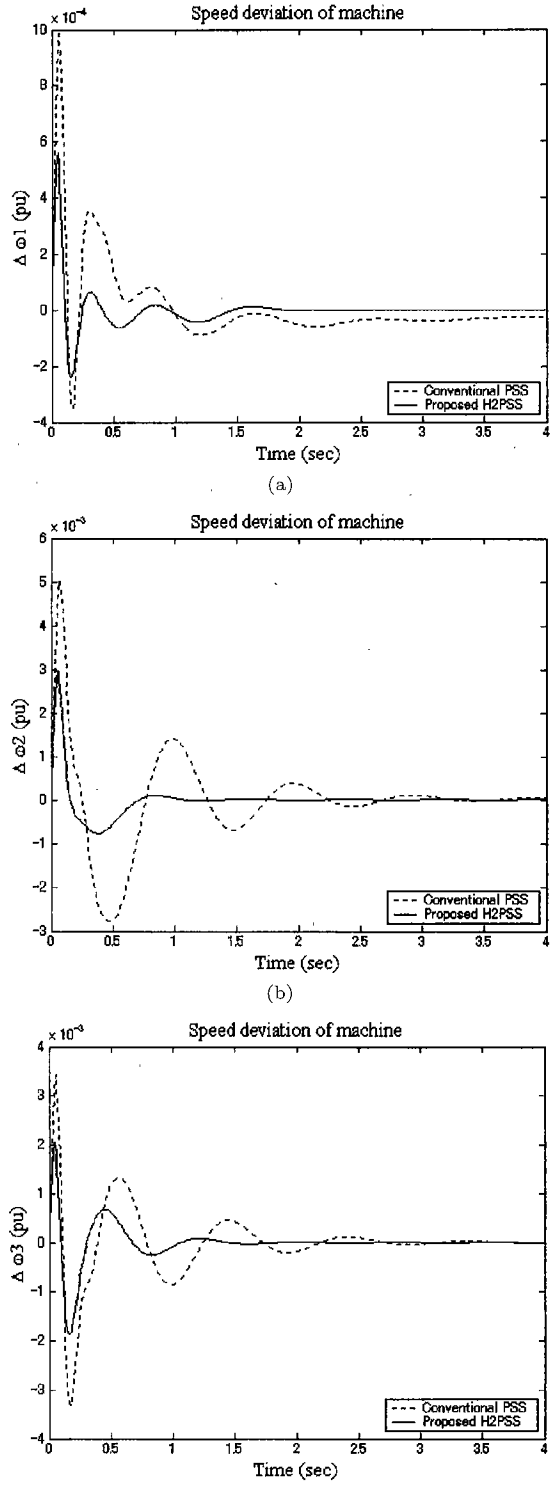

Fig. 10. Generator response under nominal loading condition

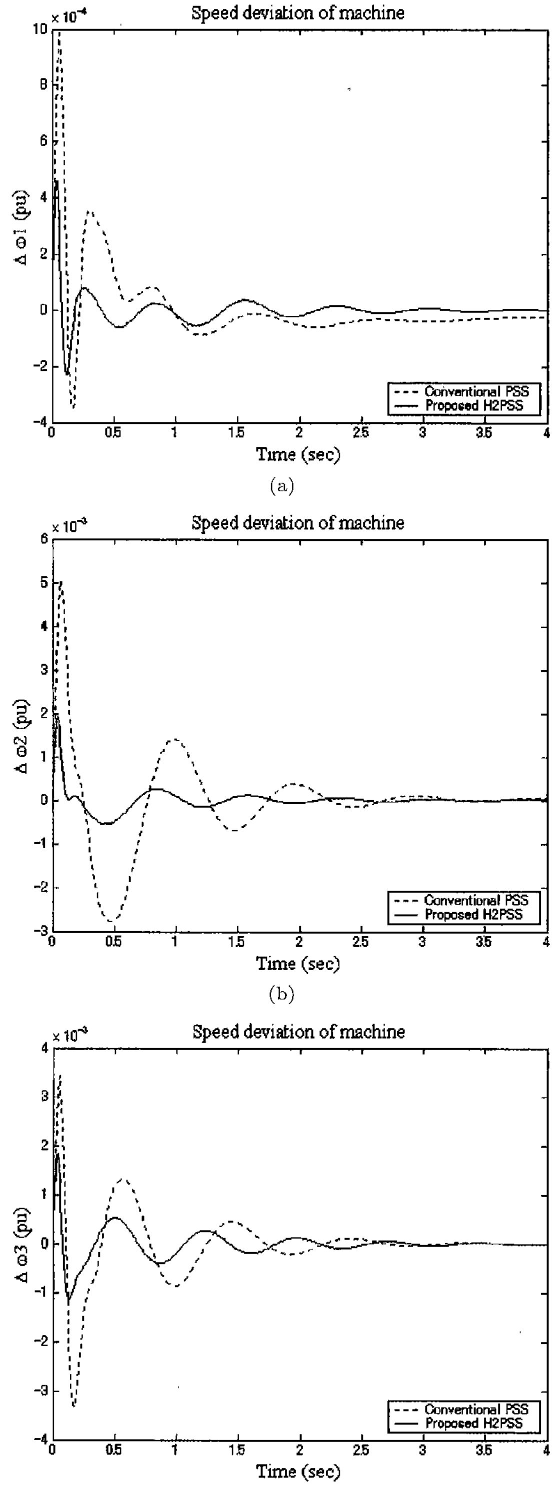

Fig. 11. Generator response under heavy loading condition

(a) Nominal loading condition: The dynamic response of the system is shown in Fig. 10. It is obvious that the system performance with the proposed H2PSS is better than CPSS.

(b) Heavy loading condition: The simulation results are shown in Fig. 11. The results here show the superiority of the proposed H2PSS to the CPSS. It can be concluded that the proposed H2PSS provides very good damping over a wide range of operating conditions.

(c) Light loading condition: The simulation results are shown in Fig. 12. It is clear that the proposed H2PSS provide good damping characteristics to low-frequency oscillations and greatly enhance the dynamic stability of power system.

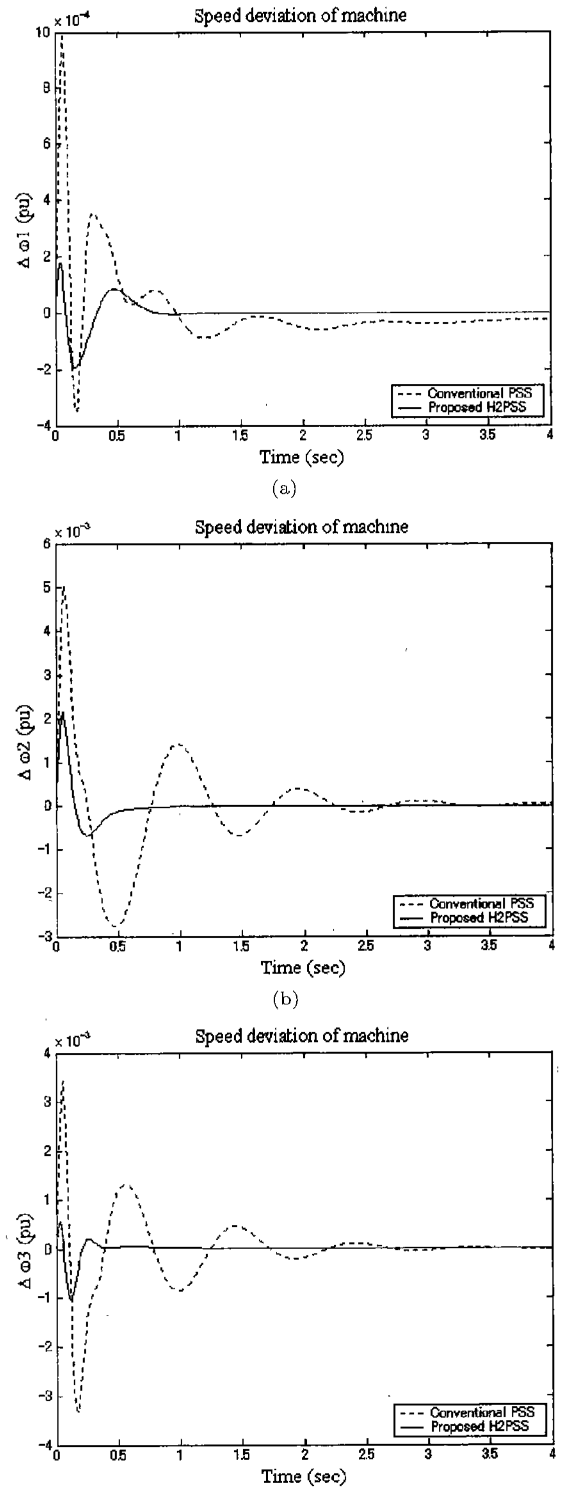

Fig. 12. Generator response under light loading condition

4. Conclusions

The design of robust H_2 controller for damping oscillations in power systems based on linear matrix inequalities was presented in this paper. The performance evaluation of the proposed stabilizer on SMIB and multimachine systems shows that this increased robustness could be achieved with reasonable feedback gain magnitudes. Further, in the multimachine case, the control is decentralized and only locally measured variables are feedback at each generator. Simulation results show that the proposed stabilizers (H2PSS) can effectively enhance the damping of low frequency oscillations and perform better than conventional stabilizers (CPSS).

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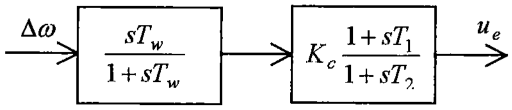
Appendix

System equations and machine parameters
Generator:

$$\dot{\omega} = \frac{1}{M}(T_m - T_e + D(\omega - 1)) \cdots\cdots\cdots\cdots \text{(A1)}$$



app. Fig. 1. Block diagram of conventional PSS used for comparison

app. Table 1. Machine data

M	T'_{d0}	D	x_d	x'_d	x_q
9.26	7.76	0	0.973	0.19	0.55

app. Table 2. Exciter data

K_A	T_A
50	0.05

app. Table 3. CPSS constants

T_w	T_1	T_2	K_c
3.0	0.685	0.1	7.09

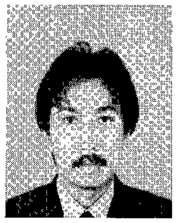
$$\dot{\delta} = \omega_b(\omega - 1) \cdots\cdots (A2)$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}\{E_{fd} - (x_d - x'_d)i_d - E'_q\} \cdots\cdots (A3)$$

$$T_e = E'_q i_q + (x_q - x'_d) i_d i_q \cdots\cdots (A4)$$

Exciter:

$$\dot{E}_{fd} = \frac{1}{T_A}\{K_A(v_{ref} - v_t + u_e) - E_{fd}\} \cdots\cdots (A5)$$



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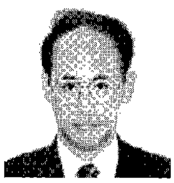

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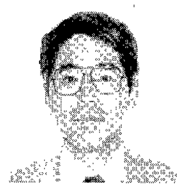

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