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Robust H_2 Controller Design for Damping Power System Oscillations

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Abstract: *This paper presents robust H_2 controller design for damping power system oscillations. The proposed controller uses full state feedback. The feedback gain matrix is obtained as the solution of a linear matrix inequality (LMI). The technique is illustrated with applications to the design of stabilizer for a multi-machine 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, power system stabilizer, multi-machine power system*

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I. INTRODUCTION

Modern 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 extend 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 performs 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 about 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 methods 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 a 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 admissible plant perturbations. One of the advantages of linear matrix inequality (LMI) is mixing the time and frequency domain objectives [11-13]. This paper proposes a robust H_2 controller design with regional pole constraints for damping power system oscillations base on linear matrix inequality. The efficiency of an LMI-based design approach as a practical design tool is illustrated with case studies, including a 3-machine 9-bus power system.

II. PROBLEM FORMULATION

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. LMI formulation for H_2 performance

Let us consider the following linear system:

$$\begin{aligned} \dot{x} &= Ax + Bw \\ z &= Cx \end{aligned} \tag{1}$$

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

$$\|H_{wz}(s)\|_2^2 = \frac{1}{\pi}\int_0^{\infty} trace(H_{wz}^*(j\omega)H_{wz}(j\omega))d\omega \tag{2}$$

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

$$\min \; trace(CPC^{\mathrm{T}})$$

$$\begin{aligned} AP + PA^{\mathrm{T}} + BB^{\mathrm{T}} &\le 0 \\ P = P^T &> 0 \end{aligned} \tag{3}$$

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

$$AP + PA^T + Q = 0 \tag{4}$$

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 Figure 1. The generalized plant P has a state space representation

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{12} u \end{aligned} \tag{5}$$

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,

$$\min \; trace[(C_1 + D_{12}K)P(C_1 + D_{12}K)^{\mathrm{T}}] \tag{6}$$

$$\begin{aligned} (A + B_2K)P + P(A + B_2K)^{\mathrm{T}} + B_1B_1^T &\le 0 \\ P = P^T &> 0 \end{aligned} \tag{7}$$

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

$$\min \; trace(W) \tag{8}$$

$$AY + YA^T + B_2L + L^TB_2^T + B_1B_1^T \le 0 \tag{9}$$

$$\begin{bmatrix} Y & YC_1^T + L^TD_{12}^T \\ C_1Y + D_{12}L & W \end{bmatrix} \ge 0 \tag{10}$$

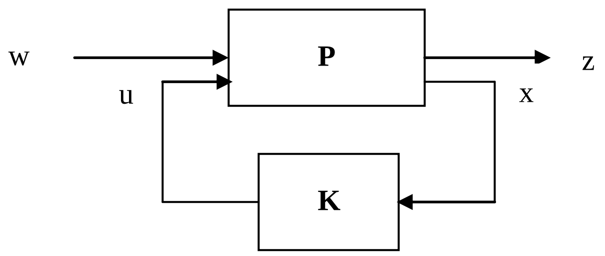


Figure1 Generalized plan

2.2. LMI formulation for regional pole constraints

In the synthesis of control systems, meeting some desired transient performance objectives (to ensure fast and well-damped transient response, reasonable feedback gain, etc.) should be considered. Generally, H_2 norm design does not directly deal with the transient response of the closed-loop system. In contrast, a satisfactory transient response can be guaranteed by confining its poles in a prescribe region. For many practical problems, exact pole assignment may not be necessary; it suffices to locate the closed-loop poles in a prescribe sub-region in the complex left half plane.

Definition 1: LMI stability region [14]. A subset *D* of the complex plane is called an LMI region if there exist a symmetric matrix $\alpha = [\alpha_{kl}] \in R^{m \times m}$ and a matrix $\beta = [\beta_{kl}] \in R^{m \times m}$ such that

$$D = \{z \in C : f_D(z) < 0\} \tag{11}$$

where the characteristic function $f_D(z)$ is given by $f_D(z) = [\alpha_{kl} + \beta_{kl} z + \beta_{kl} \bar{z}]_{1 \le k,l \le m}$ (f_D is valued in the space of *m x m* Hermitian matrices).

The location of the closed-loop poles of $(A + B_2 K)$ in (7) concern with the performance of the closed-loop system, i.e., the stability, the decay rate, the maximum overshoot, the rise time and settling time. Therefore, it is interesting work for control engineers to design the control gain *K* such that the closed-loop poles of $(A + B_2 K)$ lie in a suitable sub-region of the left half plane. The interesting region for control purposes is the set $S(\alpha, r, \theta)$ of complex number $x + jy$ such that

$$x < -\alpha < 0, \ |x + jy| < r, \text{ and } \tan(\theta)x < -|y| \tag{12}$$

as shown in Figure 2. Confining the closed-loop poles to this region ensures a minimum decay rates α, a minimum damping ratio $\zeta = \cos\theta$, and a maximum undamped natural frequency $\omega_d = r \sin\theta$ (θ in radian).

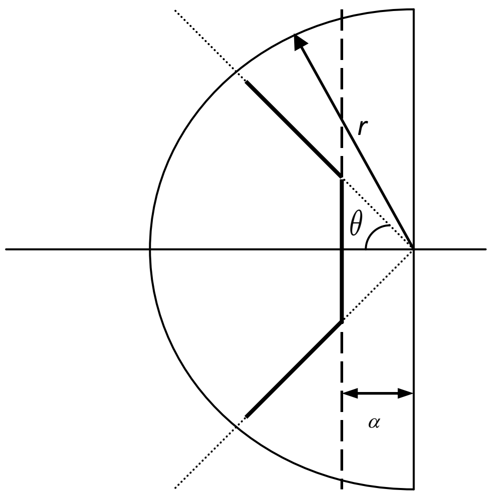


Figure 2 Region $S(\alpha, r, \theta)$

The LMI formulations for the poles of $(A + B_2 K)$ lie in the region $S(\alpha, r, \theta)$ are characterized as the following LMIs [14], [15]: if there exists symmetric $P > 0$ such that

$$(A + B_2 K)P + P(A + B_2 K)^T + 2\alpha P < 0 \tag{13}$$

$$\begin{bmatrix} -rP & (A+B_2K)P \\ P(A+B_2K)^T & -rP \end{bmatrix} < 0 \tag{14}$$

and

$$\begin{bmatrix} \sin(\theta)((A+B_2K)P+P(A+B_2K)^T) & \cos(\theta)((A+B_2K)P-P(A+B_2K)^T) \\ \cos(\theta)(P(A+B_2K)^T-(A+B_2K)P) & \sin(\theta)((A+B_2K)P+P(A+B_2K)^T) \end{bmatrix} < 0 \tag{15}$$

with $L=KP$, $Y=P$, the above LMIs are equivalent to

$$AY+YA^T+B_2L+(B_2L)^T+2\alpha Y<0 \tag{16}$$

$$\begin{bmatrix} -rY & AY+B_2L \\ YA^T+(B_2L)^T & -rY \end{bmatrix} < 0 \tag{17}$$

$$\begin{bmatrix} \sin(\theta)(AY+B_2L+YA^T+(B_2L)^T) & \cos(\theta)(AY+B_2L-YA^T-(B_2L)^T) \\ \cos(\theta)(YA^T+(B_2L)^T-AY-B_2L) & \sin(\theta)(AY+B_2L+YA^T+(B_2L)^T) \end{bmatrix} < 0 \tag{18}$$

From the analysis above, if there exists Y and L for (16)-(18), then the poles of $(A+B_2K)$ lie in the region $S(\alpha,r,\theta)$.

2.3. H_2 control with regional pole constraints

The combination objectives of robust H_2 control with regional pole constraints can be characterized as follows:

$$\min_{\{Y,L\}} \; trace(W)$$

s.t. (9), (10) and (16)-(18) (19)

From analysis above, the most important task in this paper is to find the variable Y and L, and can be solved using standard optimization techniques. Once a feasible solution (Y, L) satisfying (19) is found, the required state feedback gain matrix can be computed as $K=LY^{-1}$.

III. SIMULATION RESULTS AND DISCUSSION

3.1. Dynamic model of the power system

Neglecting the effect of damper winding, stator transient and resistance, the synchronous machine together with its excitation system is modeled using the following 4th order non-linear dynamic equations [16]:

$$\dot{\omega}=\frac{1}{M}(T_m-T_e+D(\omega-1)) \tag{20}$$

$$\dot{\delta}=\omega_b(\omega-1) \tag{21}$$

$$\dot{E}_q^{'}=\frac{1}{T_{d0}^{'}}\left\{E_{fd}-(x_d-x_d^{'})i_d-E_q^{'}\right\} \tag{22}$$

$$\dot{E}_{fd}=\frac{1}{T_A}\left\{K_A(v_{ref}-v_t+u_e)-E_{fd}\right\} \tag{23}$$

It can be seen that this model is non-linear. To permit analysis and control of the power system, the model is linearised around the operating point. The state variables of this model are $\Delta\omega,\Delta\delta,\Delta E_q^{'},\Delta E_{fd}$, respectively, angular speed, rotor angle, voltage behind transient, and excitation voltage. In this study, we assumed that all state variables are available used for feedback.

3.2. A 3-machine 9-bus system

In this part of the study, the 3-machine 9-bus power system shown in Figure 3 is considered. Details of the system data are given in [17]. Each machine has been represented by 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 PSS to improve the dynamic performance.

To identify the optimum locations of PSSs, the participation factor method [18] was used. The results of the method indicate that 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 pair of conjugate eigenvalues corresponds to an oscillation mode, there are two modes in this study system. Mode 1 and 2 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 system, a damping ratio, ζ of at least 10% and the real part of eigenvalue not greater than –0.5 for the troublesome low frequency electromechanical mode.

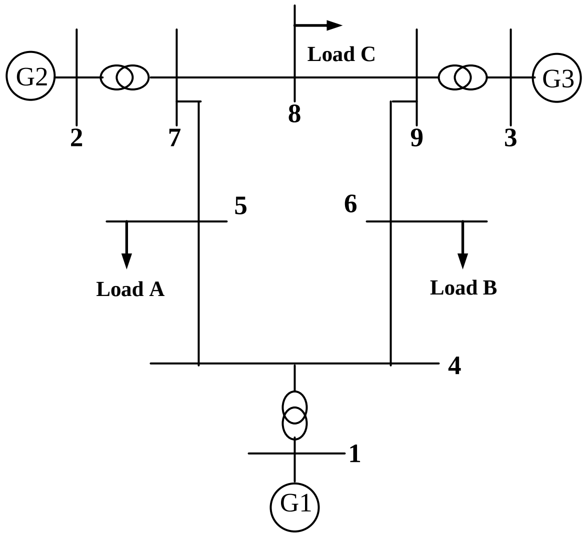


Figure 3 Three-machine nine-bus power system [17]

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	0.362	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 loopeigenvalues of the study system

Modes	Heavy	Nominal	Light
1	-0.187±j 7.68	-0.241±j 7.71	-0.399±j7.71
2	-0.970±j 14.10	-0.842±j 14.10	-0.585±j 14.10

In order to improve the damping of electromechanical modes, a decentralized controller was designed for present system at the nominal loading conditions based on the proposed design technique in Section 2. In this objective, 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 are block diagonal. The locally measured states: $\Delta\omega, \Delta\delta, \Delta E_q^{'}, \Delta E_{fd}$ is feedback at the AVR reference input of each machine after multiplication by suitable feedback gains. The LMI problem was constructed by writing LMI (19). The feasibility problem was solved for (Y,L) and the required state feedback matrix was obtained as $K = LY^{-1}$. If the matrix 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.

In order to facilitate comparison with CPSS, the design and tuning of CPSS for this multi-machine system were used method in [19]. In this paper, a CPSS with transfer function,

$$G(s) = K_c \frac{sT_w}{1+sT_w} \frac{(1+sT_1)^2}{(1+sT_2)^2} \tag{24}$$

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 multi-machine system is given in Table 3. The output of all CPSS is limited to ± 0.1 p.u.

Table 3 CPSS parameters

Gen#	K_c	T_w	T_1	T_2
2	83.24	8.0	0.329	0.140
3	33.01	8.0	0.169	0.072

By the similar above procedure, we can solve the eigenvalue problem in (19) with pole constraints in the region of *S*(1.6, 25, 1.369). 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 region *S* with the proposed H2PSS. This demonstrates that the system damping with the proposed H2PSS is greatly enhanced.

Table 4 Closed-loopeigenvalues of the study system

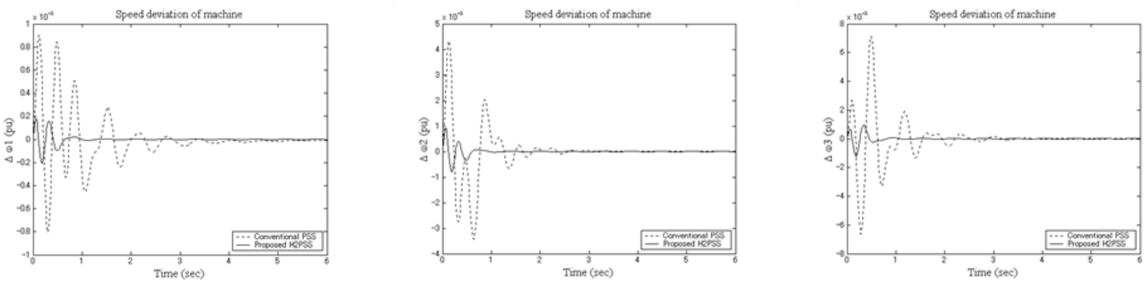
Modes	Heavy	Nominal	Light
1	-4.420±j 8.26	-4.880±j 7.86	-3.360±j 7.40
2	-2.510±j 9.82	-3.584±j 10.25	-4.720±j 12.52

To demonstrate the capability of the proposed H2PSS 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.

a) Nominal loading condition: The dynamic response of the system is shown in Figure 4. It is obvious that the system performance with the proposed H2PSS is better than CPSS.

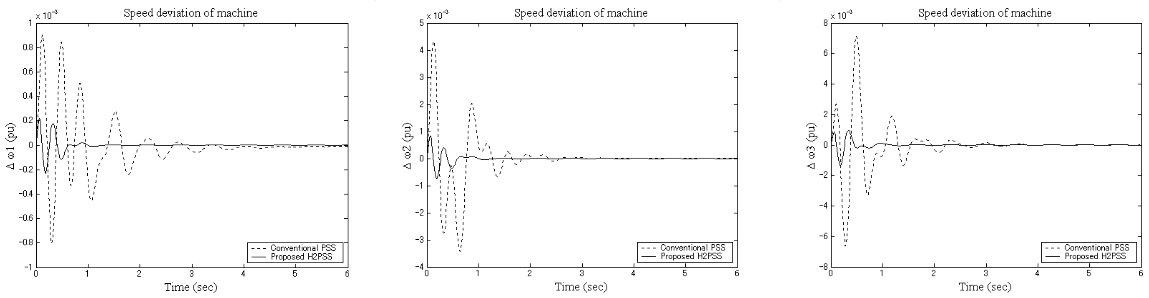
b) Heavy loading condition: The simulation results are shown in Figure 5. The results here show the superiority of the proposed H2PSS to the CPSS. It can be concluded that the proposed H2PSS provides very good damping over a wide range of operating conditions.

c) Light loading condition: The simulation results are shown in Figure 6. It is clear that the proposed H2PSS provide good damping characteristics to low-frequency oscillations and greatly enhance the dynamic stability of power system.



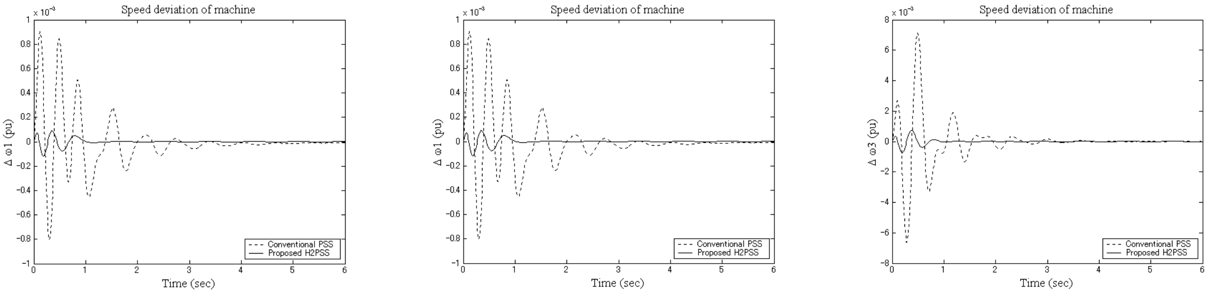
(a) (b) (c)

Figure 4 Generator responses under nominal loading condition



(a) (b) (c)

Figure 5 Generator responses under heavy loading condition



(a) (b) (c)

Figure 6 Generator responses under light loading condition

IV. Conclusion

The design of robust H_2 control with regional pole constraints for damping power systems oscillations based on linear matrix inequalities was presented in this paper. The performance evaluation of the proposed stabilizer on multi-machine power systems shows that this increased robustness could be achieved with reasonable feedback gain magnitudes. Further, in the multi-machine 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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