A Novel Approach for Robust H_∞ PSS Design According to Various Power System Operation Conditions

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Abstract

This paper presents a novel approach to design of robust H_∞ Power System Stabilizer (HPSS) by using the feedback control approach based on multiplicative perturbation in an interconnected power system. The main objectives of this research are to reduce the oscillations and to increase the overall robust performance of the system. In the proposed HPSS design, variations of the system parameters, various operating conditions of the system loads and topology (which are called "system uncertainties") are represented by the multiplicative uncertainties model. This approach applies an independent design methodology to the so-called equivalent subsystems along with the well-known Small Gain theory and the robust stability conditions in the $M-\Delta$ setup. In this paper, the performance of the proposed HPSS is investigated in the standard benchmark four generators system in comparison with the conventional PSS. The simulation results of rotor speed deviation of generators with the proposed HPSS and the conventional PSS verify the effectiveness of the proposed HPSS.

I. INTRODUCTION

In multi-machine power system, power system stabilizer (PSS) is utilized to reduce power system oscillation and to increase the overall robust performance [1]. More frequently, the electric utilities are forced to operate power systems closer to their transient stability limits. It is expected that the power systems in the future are going to be operated under even more stressful conditions like a sudden increase in the load, loss of one generator or switching out of a transmission line, during a fault [2]. Therefore, transmission planners and operators are forced to look for ways to improve stability margins and to make more efficient use of the existing assets. One such operating challenge involves oscillatory stability performance.

Stability of power systems is one of the most important aspects in electric system operation. This arises from the fact that the power system must maintain frequency and voltage levels, under any disturbance. Although Power systems are often exhibit low-frequency electromechanical oscillations due to insufficient damping caused by adverse operating conditions, Power system stabilizer (PSS) units have long been regarded as an effective way to enhance the damping of electromechanical oscillations in power system [3]. The presence of these oscillations complicates system operation, for this reason, control strategies for damping or eliminating those must be applied.

Power System Stabilizers (PSSs) are designed to overcome the low frequency oscillations (0.2–3 Hz) in interconnected power systems. Over the past two decades, various control methods have been proposed for PSS design to improve overall system performance. Among these, conventional PSS of the lead-lag compensation type [3, 4] have been adopted by most utility companies because of their simple structure, flexibility and easy of implementation. These compensators are designed and tuned for a particular operating point of the plant. Closed-loop system stability and acceptable performance is only achieved for slight deviations from the nominal operating point of the power system. In recent years, several approaches based on modern control theories have been successfully applied to design PSSs [5-9], such as: eigenvalue assignment [10], optimal control, self-tuning and adaptive control [11], variable structure control [12, 13], rule-based and neural network based control [14–16]. The reduced order techniques [17, 18] have been applied to the PSS design problem. The first one based on the linear quadratic regulator (LQR) technique and the second one based on the iterative perturbation scheme.

Since these techniques do not take the presence of system uncertainties e.g. system nonlinear characteristics, variations of system configuration due to unpredictable disturbances, loading conditions etc, the major drawback of these works is the lack of robustness of PSSs against system uncertainties. To attack this problem, the robust control theory is one of the sophisticated countermeasures. Recently, to overcome these problems, H_∞ control has been applied to design of robust PSS [19, 20]. In these works, the designed H_∞ PSS via mixed sensitivity approach have confirmed the significant performance and high robustness. In this approach, however, due to the trade-off relation between sensitivity function and complementary sensitivity function, the selection of weighting function in H_∞ control design can not be explained easily. In this paper, a novel approach to the design of a H_∞ PSS for a multi-machine power system is presented; it is based upon a transfer function obtained from the whole range of operating conditions of a power system. The robust H_∞ PSS is designed by using the feedback control approach according to [21]. The resulting robust PSS guarantees fulfilment of performance requirements imposed on the full system. Any procedure suitable to design a PSS for a one machine linear system is applicable on the subsystem level.

The remainder of this paper is organized as follows. A detailed description of the proposed design procedure and the procedure adopted in this work are presented in Section II. The studied power system is given in Section III. Simulation results are presented in Section IV to demonstrate the effectiveness of the proposed method. Finally, the conclusions are given in Section V.

II. PROBLEM STATEMENT

When performing control designs different aspects, such as robustness, performance and etc, have to be considered. Performance specifications describe how the system behaves in the closed-loop. Several criteria might be of interest such as stability, damping or controller effort. Robust performance specifications describe how the closed-loop system would behave if some parts of the system were changed or perturbed. In this section, the design procedure of proposed controller (PSS) is explained.

A. Representing uncertainty

Consider a single-input single-output (SISO) system $G_P(s)$ and the controller $K(s)$ (in fact the PSS) in the standard feedback configuration depicted in Fig. 1, where *r, u, y, e* are the reference, control signal, output variable and error signal respectively, of compatible dimensions. The nominal plant transfer function $G_n(s)$ is used to define the perturbed plant transfer function as:

$$G_P(s) = G_n(s)[1 + \Delta(s)W_i(s)] \tag{1}$$

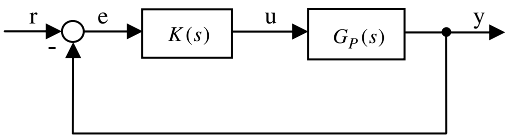

Fig. 1. Standard feedback configuration

Here $W_i(s)$ is a fixed stable transfer function or the uncertainty weight, and $\Delta(s)$ is a variable stable transfer function satisfying $\|\Delta\|_\infty < 1$. Furthermore, it is assumed that no unstable poles of G_n are canceled in forming G_P. Such a perturbation Δ is said to be allowable. The idea behind this uncertainty model is that ΔW_i is the normalized plant perturbation away from 1:

$$(G_P - G_n)/G_n = \Delta W_i \tag{2}$$

Hence if $\|\Delta\|_\infty \le 1$, then:

$$|(G_P - G_n)/G_n| \le |W_i(j\omega)|, \ \ \forall\omega \tag{3}$$

So $|W_i(j\omega)|$ provides the uncertainty profile. Standard feedback configuration of an uncertain system with the multiplicative uncertainty is depicted in Fig. 2.

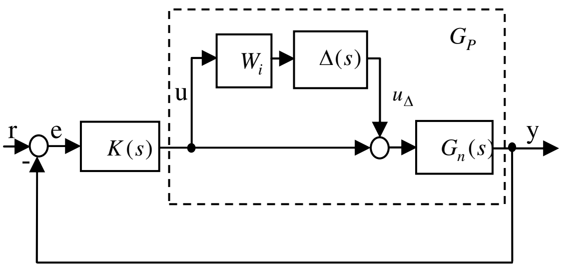

Fig. 2. Feedback system with input multiplicative uncertainty

B. Robust stability of the $M-\Delta$ structure

In this part, we derive some conditions which will ensure that the system remains stable for all perturbations in the uncertainty set. We want to determine the stability of the uncertain feedback system in Fig. 2 when there is input multiplicative uncertainty with the magnitude $W_i(j\omega)$. First, draw the block diagram of the perturbed feedback system, but ignoring the inputs (Fig. 3).

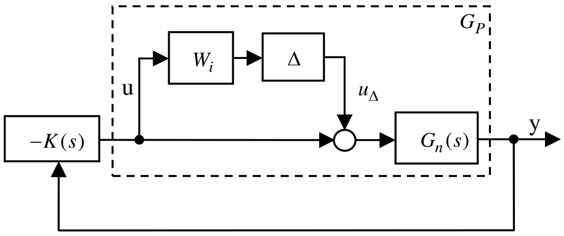

Fig. 3. Perturbed feedback system

The transfer function from the output of Δ around to the input of Δ equals $M(s)$, so the block diagram collapses to the configuration shown in Fig. 4.

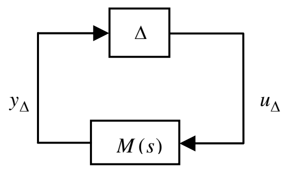

Fig. 4. $M-\Delta$ structure

If the nominal ($\Delta = 0$) feedback system is stable then the stability of the system in Fig. 2 is equivalent to stability of the system in Fig. 4, and:

$$M = -W_i \frac{G_n K}{1 + G_n K} = -W_i T \tag{4}$$

Where:

$$T = 1 - S = \frac{G_n K}{1 + G_n K} \tag{5}$$

M is the transfer function from the output of Δ to the input of Δ and T is complementary sensitivity function and S is sensitivity function. We now apply the Nyquist stability condition to the system in Fig. 4. We assume that Δ and $M = -W_i T$ are stable; the former implies that G_n and

G_P must have the same unstable poles, the latter is equivalent to assuming nominal stability of the closed-loop system. The Nyquist stability condition then determines RS (Robust Stability) if and only if the "loop transfer function" $M\Delta$ does not encircle -1 for all Δ. Thus:

$$\begin{aligned} RS \;&\Leftrightarrow\; |M(jw)|<1\,,\ \forall\omega \\ &\Leftrightarrow\; \|M\|_\infty<1 \end{aligned} \qquad (6)$$

C. Robust performance and H_∞ loop-shaping design

In several application, designer have acquired through experience desired shapes for the Bode magnitude plot of S. In particular, suppose that good performance is known to be achieved if the plot of $|S(j\omega)|$ lies under curve. We could rewrite this as:

$$|S(j\omega)|<|W_p(j\omega)|^{-1},\ \forall\omega \qquad (7)$$

Or in other words:

$$\|W_pS\|_\infty<1 \qquad (8)$$

Here $W_p(s)$ is a fixed stable transfer function or the performance weight. Other performance problems could be posed by focusing on the response to the other exogenous input, d. Note that the transfer function from d to e, u in Fig. 5 with ignoring uncertainty and reference, are given by:

$$\begin{bmatrix} e \\ u \end{bmatrix} = -\begin{bmatrix} S \\ KS \end{bmatrix} d \qquad (9)$$

Various performance specification could be made using weighted versions of the transfer functions above.

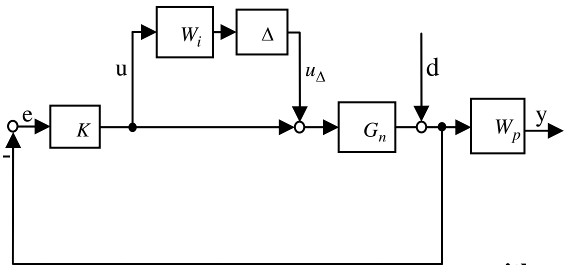

Fig. 5. Diagram for robust performance with multiplicative uncertainty

Consider performance in terms of the weighted sensitivity function as discussed in above. The condition for nominal performance (NP) from d to y is then:

$$\begin{aligned} NP \;&\Leftrightarrow\; |W_pS|<1\,,\ \forall\omega \\ &\Leftrightarrow\; |W_p|<|1+L|\,,\ \forall\omega \end{aligned} \qquad (10)$$

and the loop transfer functions is:

$$L=G_nK \qquad (11)$$

Now $|1+L|$ represents at each frequency the distance of $L(j\omega)$ from the point -1 in the Nyquist plot, so $L(j\omega)$ must be at least a distance of $|W_p(j\omega)|$ from -1.

For robust performance we require the performance condition (10) to be satisfied for all possible plants, that is, including the worst-case uncertainty:

$$\begin{aligned} RP \;&\Leftrightarrow\; |W_pS_P|<1\,,\ \forall S_P,\forall\omega \\ &\Leftrightarrow\; |W_p|<|1+L_P|\,,\ \forall L_P,\forall\omega \end{aligned} \qquad (12)$$

This corresponds to requiring $|\hat{y}/d|<1$, $\forall\Delta$ in Fig. 5, where we consider Input multiplicative uncertainty, and the set of possible loop transfer functions is:

$$\begin{aligned} L_P = G_PK &= G_n(s)[1+\Delta(s)W_i(s)]K \\ &= L[1+W_i\Delta] \end{aligned} \qquad (13)$$

From the definition in (12) we have that RP is satisfied if the worst-case (maximum) weighted sensitivity at each frequency is less than 1. The perturbed sensitivity is:

$$S_P=(1+L_P)^{-1}=1/(1+L[1+W_i\Delta]) \qquad (14)$$

And the worst-case (maximum) is obtained at each frequency by selecting $|\Delta|=1$ such that the terms ($1+L$) and $W_iL\Delta$ (which are complex numbers) point in opposite directions. We get:

$$\max_{S_P}|W_pS_P| = \frac{|W_p|}{|1+L|-|W_iL|} = \frac{|W_pS|}{1-|W_iT|} \qquad (15)$$

The RP-condition becomes:

$$RP \quad \Leftrightarrow \quad \max_{\omega}(|W_p S| + |W_i T|) < 1 \qquad (16)$$

A necessary and sufficient condition for robust performance according to [21] is:

$$\big\| |W_p S| + |W_i T| \big\|_\infty < 1 \qquad (17)$$

The RP-condition (16) for this problem is closely approximated by the following mixed sensitivity H_∞ condition:

$$\left\| \begin{matrix} W_p S \\ W_i T \end{matrix} \right\|_\infty = \max_{\omega} \sqrt{|W_p S|^2 + |W_i T|^2} < 1 \qquad (18)$$

To be more precise, condition (18) is within a factor of at most $\sqrt{2}$ to condition (16). This means that for SISO systems we can closely approximate the RP-condition in terms of an H_∞ problem.

III. CASE STUDY

To show the effect of proposed controller as a PSS on damping the inter-area electromechanical mode power oscillation, the proposed method was tested on the test power system shown in Fig. 6. This two-area power system, introduced in [22] as a benchmark system, consists of two generators in each area, connected via a 220 km tie line. All generators are equipped with simple exciters and modeled with subtransient models.

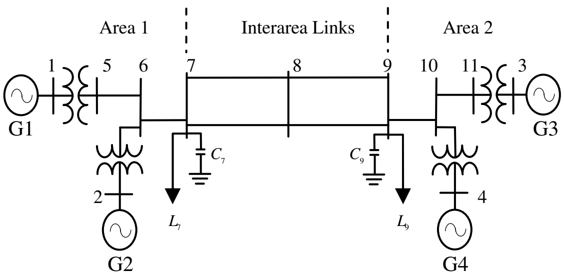

Fig. 6. The Two-Area four-generator test power system

The two-area power system was linearized in the operating condition described with the nominal power flow of 400 MW from Area 1 to Area 2.

The main objectives of this research are to reduce the oscillation in the system and to increase the overall robust performance. The generator with greatest participation in inter-area mode is generator 3, which makes it the most suitable generator to install a PSS.

The transfer function from the input of V_{ref} (the reference signal of AVR) around to the output of $\Delta\omega$ without controller equals $G_P(s)$ with order 48. To obtain the nominal plant transfer function $G_P(s)$ is reduced to order 8 and equals $G_n(s)$. The actual system and nominal low order model exhibit similar characteristics in the frequency domain. This is verified in Fig. 7 which compares the magnitude and phase plots of the transfer functions of the actual and nominal system. A very good match in the 0.1-50 Hz frequency range is obtained.

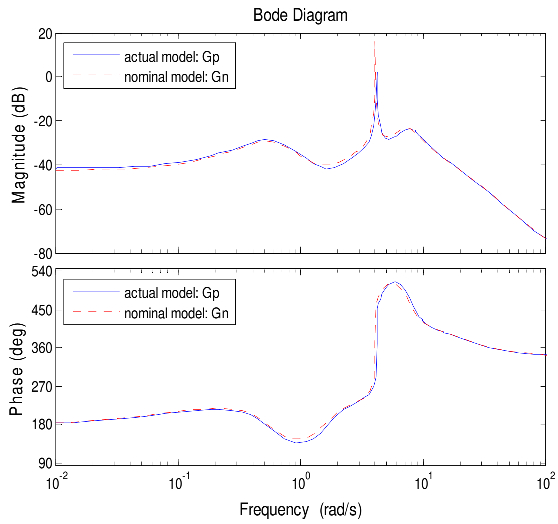

Fig. 7. Comparing Bode plots of nominal and actual Systems

A 34-order controller is designed following the procedure described in previous section. Then it can be reduced to order 4 via an order reduction technique. Bode diagram of the reduced order controller (HPSS) and the 34-order is depicted in Fig. 8.

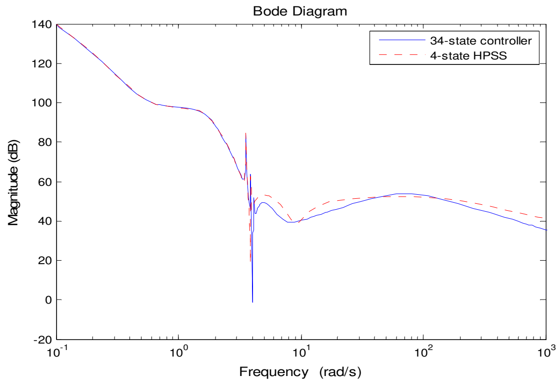

Fig. 8. Comparing Bode plots of HPSS and controller with order 34

IV. SIMULATION RESULTS

To show the effect of the proposed PSS (HPSS) on damping of the oscillations and the settling time, in this section ,six contingencies of the operation conditions are considered and compared with a conventional PSS (CPSS) and without any PSS (NO PSS).

1) A line outage after three-phase short-circuit fault at Bus 9. In this case, a three-phase fault is occurs at the end of line 8-9 at t=0.3 sec. The faulty circuit is disconnected by appropriate circuit breaker at t=0.4 sec. The system operates with one tie circuit connecting buses 8 and 9. The speed deviation of generator 3 with the proposed controller is investigated in comparison with the responses of the generator with conventional PSS [3,4] and NO PSS. As seen in Fig. 9, it is clearly shown that the oscillations damping and the settling time of the proposed controller (HPSS) is better than those of the CPSS and NO PSS.

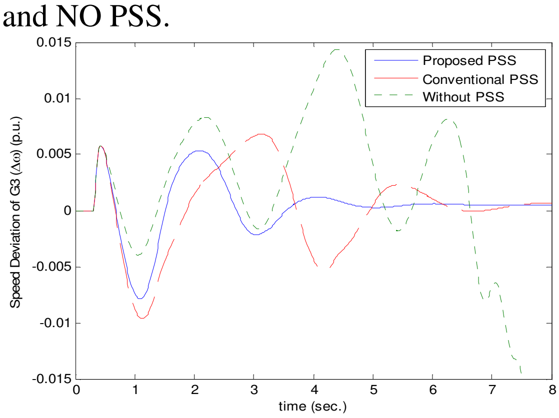

Fig. 9. speed deviation of generator 3 for the contingency 1

2) A three-phase short-circuit fault at Bus 9 without line outage. In this case, a three-phase fault disturbance occurs at the end of line 8-9 at t=0.3 sec and it is cleared at 0.5 second without line outage. The response of speed deviation of generator 3 is investigated in comparison with the responses of the generator with CPSS and NO PSS. As seen in Fig. 10, it is clearly shown that the proposed PSS improves the response and reduce the steady state error in comparison with the CPSS and NO PSS.

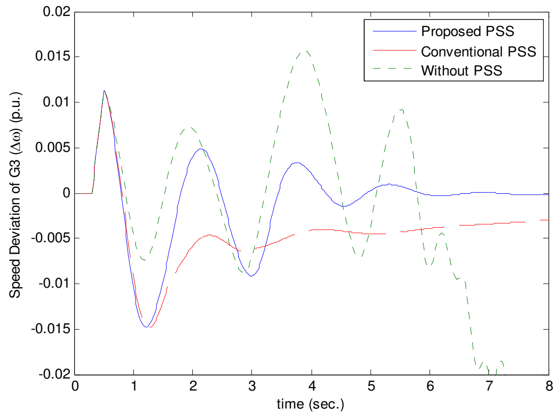

Fig. 10. speed deviation of generator 3 for the contingency 2

3) The load of bus 7 decreases by 15%. The speed deviation of generator 3 to decreasing of the load of bus 7 is investigated in comparison with the responses of the generator with CPSS and NO PSS. As seen in Fig. 11, it is clearly shown that the oscillations and the settling time of the proposed PSS is better than those of the CPSS and NO PSS.

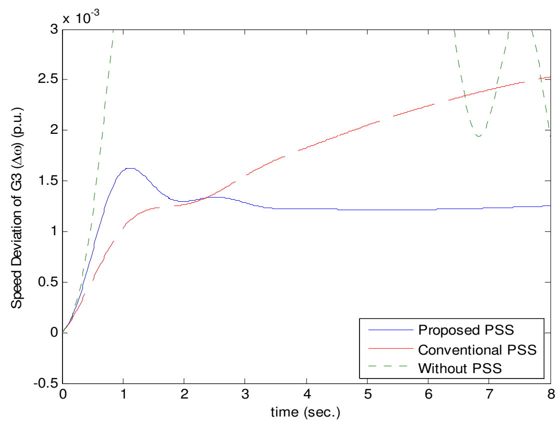

Fig. 11. speed deviation of generator 3 for the contingency 3

4) The load of bus 9 increases by 15%. The speed deviation of generator 3 to load increase at bus 9 are investigated in comparison with the responses from the CPSS and NO PSS. As seen in Fig. 12, it is clearly shown that the damping of oscillations and the settling time of the generator 3 with proposed PSS is better than those with the CPSS and NO PSS.

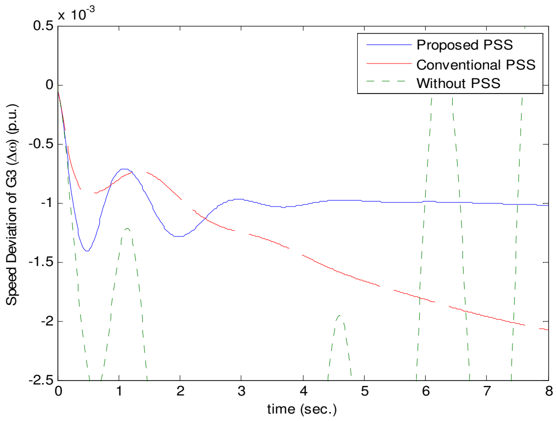

Fig. 12. speed deviation of generator 3 for the contingency 4

5) A line outage after three-phase short-circuit fault at Bus 8. In this case, a three-phase fault is occurs at the end of line 7-8 at 0.3 sec. The fault is removed at 0.45 sec. The system operated with one tie circuit connecting buses 8 and 9. The speed deviation of generator 3 with the proposed controller is investigated in Fig.13 in comparison with the responses of the generator the CPSS and NO PSS.

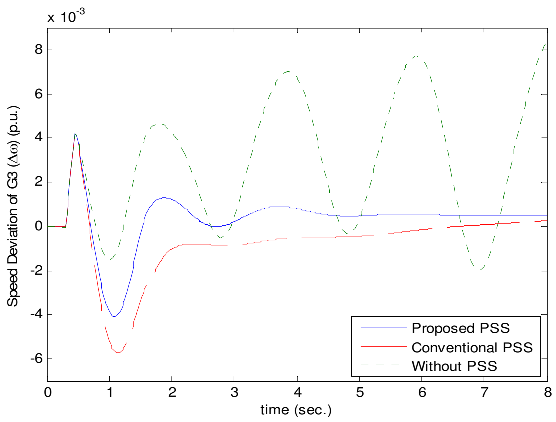

Fig. 13. speed deviation of generator 3 for the contingency 5

The oscillations damping and the settling time of the CPSS is better than those of the proposed PSS, because the conventional PSS is designed and tuned for this particular operating point of the plant.

6) A three-phase fault at Bus 8 without line outage. A three-phase fault disturbance occured at the end of line 7-8 at 0.3sec and is cleared at 0.5 second without line outage. The speed deviation of generator 3 is investigated in comparison with the responses of the generator with the CPSS and NO PSS. As seen in Fig. 14, it is clearly shown that the oscillations and the settling time of the proposed PSS is better than those of the CPSS and NO PSS.

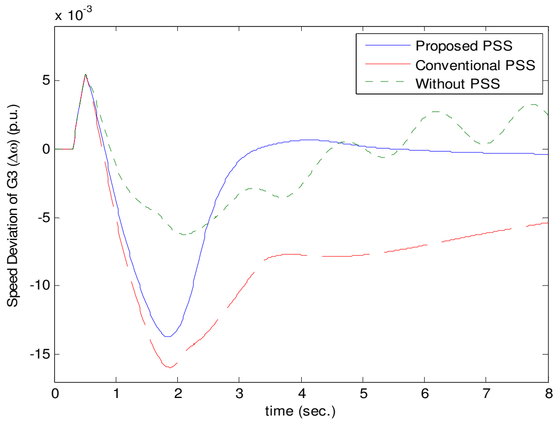

Fig. 14. speed deviation of generator 3 for the contingency 6

V. CONCLUSIONS

In a multi-machine environment, the conventional PSS (CPSS) does not guarantee the robustness of the PSS with variable operating condition, location, and severity of the faults. Therefore, in this paper a new robust H_∞ Power System Stabilizer (HPSS) based on the feedback control approach and using input multiplicative uncertainty model has been proposed for an interconnected power system. The designed robust controller has some advantages in the low order configuration. Moreover, it uses only the speed deviation of generator as the feedback signal input. Therefore, it is easy to realize in practical power system. The effectiveness and performance of the proposed method is tested on a four generators power system under various operating conditions. The simulation results show that the proposed HPSS causes a desirable robust oscillation damping effectively over various conditions and is superior to the conventional PSS.

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