SYNTHESIS OF TWO-INPUT PSS BASED ON THE H_∞ CONTROL THEORY

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In the standard mixed sensitivity weighting strategy for H_∞ controllers, the designer can formulate desired requirements (desired loop shape) using frequency domain weighting functions. The ‘all pass’ property of the optimal H_∞ control laws ensures that the singular value Bode plots will precisely conform to those specified by the weighting functions. However, there is a serious drawback to this property; namely, the resulting standard H_∞ -PSS always cancels the stable poles of the plant (pole-zero cancellation). It is known that the cancellation of lightly damped poles can lead to poor robust stability and performance. In the case of multi-input H_∞ controller, it becomes much more difficult to achieve good robust stability and performance.

In this paper, a design of H_∞ -PSS is proposed to prevent the pole zero cancellation phenomenon and increase the damping of weakly damped modes. The design method consists of applying the bilinear transform to a stable poorly damped nominal plant in order to transform it into a fictitious unstable plant suitable for the standard mixed sensitivity design approach. A combination of additive and multiplicative uncertainty representation was used to achieve the robust stability for a wide range of operating conditions. The PSS designed based on the proposed approach was compared with those based on the standard H_∞ approach and the conventional method.

Simulation results show that the proposed PSS gives better performance and is more robust than the standard H_∞ -PSS and the optimally tuned conventional PSS.

Keywords: Low frequency oscillations, H_∞ -PSS, uncertainty representation, pole-zero cancellation, bilinear transform.

1. Introduction

Low frequency oscillations in power systems are undesirable because they can limit the ability of the system to transmit power. The only practical way of reducing or eliminating low frequency oscillations without resorting to costly operation restrictions or transmission reinforcements is to use power system stabilizers (PSSs). The fundamental concept of a PSS is to add supplementary damping to the excitation control by modulating the voltage regulator reference with a stabilizing signal [2]. The effectiveness of conventional PSSs in damping low frequency oscillations was first investigated by Demello and Concordia [1]. They show that these PSSs can give good performances under small disturbances if they are properly tuned [2-3]. However, during severe disturbances such as short circuit faults, or when the operating conditions change over a wide frequency range, the performance of the conventional PSSs may deteriorate.

In the last 30 years, several methods such as root locus, pole placement, linear optimal control (LOC), etc., have been proposed to improve the performance of conventional PSSs. The main disadvantage of these methods is the lack of robustness. To cope with this problem, researchers have turned to advanced control schemes such as fuzzy logic, artificial neural network, adaptive controls, etc. However, these approaches require either intensive, cumbersome computations and long processing time or are non-robust. For example, it is known that in the presence of high frequency unmodeled dynamics or unmeasurable disturbances, adaptive controls themselves may become non-robust [10].

Recently, design of PSS using the H_∞ optimal control theory has received considerable attention [4-9]. Besides the fact that many classical design objectives are included in H_∞ design, it also presents a natural tool for successfully modeling plant uncertainties. In [4], R. Q. Zhao and J. Jiang have proposed a robust controller based on the H_∞ control for a Static Var Compensator (SVC) to improve the damping of power systems. The same authors have also designed an H_∞ controller of two inputs one output to improve local modes and

excitation modes of a single machine connected to an infinite bus [5]. S. Chen and O. P. Malik [6] have proposed an H_∞ -PSS to stabilize a power system. Ashgharian [7] has proposed two inputs, two outputs H_∞ controller to enhance the overall stability of a power system. K. Ohtsuka *et al* have used a discrete state-space approach to design a state feedback H_∞ controller for a generator control system [8]. S. S. Ahmed *et al* [9] have designed sub-optimal H_∞ excitation controllers for a nine-bus three-machine benchmark network by imposing additional constraints on the standard optimal H_∞ solution.

In the above references, controllers were designed to maintain the performance and robust stability of the closed-loop system for a wide range of operating conditions in spite of the presence of uncertainties in the system. These uncertainties arise because of changes in operating conditions, approximations in modeling, parameter variations, faults, etc. Although it has been demonstrated in [5-8] that the standard H_∞ -PSS can maintain the robustness of the system, some problems still exist when dealing with systems having poorly damped oscillation modes. In such a case, good performance and robustness cannot be guaranteed. The reason is that the standard H_∞ -PSS cancels the poorly damped modes of the plant with its transmission zeros [11-17]. As a result, the damping of these modes cannot be increased by the PSS.

It should be mentioned that most of the above cited literature [5-8] have not addressed the issues concerning the pole-zero cancellation phenomenon. Only references [4,9] have proposed some methods to deal with this problem. R. Q. Zhao and J. Jiang [4] have proposed a robust SVC design method to increase the damping of the system by minimizing the H_∞ norm of the transfer function from input disturbance to plant output. S.S. Ahmed *et al* [9] have proposed a simplified version of the bilinear transform presented in [16-17] to deal with this shortcoming. A problem that may arise with the above mentioned methods is that the obtained controllers may be unstable. It was suggested in [9] that high order weighting functions be used in the design to prevent unstable controllers. However, this brings some unnecessary complications into the design.

In [11-12] and [13-14], the authors have used the bilinear

transform introduced in [16-17] and the partial pole placement technique, respectively to avoid the pole-zero cancellation problem.

In this paper, the bilinear transform proposed in [11-12] is used to design a two-input one output H_∞ -PSS. Plant uncertainties are modeled as a combination of additive and multiplicative uncertainty representation. An advantage of the bilinear transform adopted in this paper is that two parameters are used to perform the transformation instead of one parameter as proposed in [9]. For example, the parameters of the bilinear transform described in this paper can be used to prevent the controller from becoming non-minimum phase (right half-plane zeros) controller. Another advantage of this method over both the partial pole-placement [13-14] and the reformulated mixed sensitivity design method [4] is that it can remove ill-conditioning problems arising when the system matrix is close to singularity or when computational assumptions for solving the two Riccati equations are not satisfied [16]. The main difficulty with this method is that the amount of damping that can be obtained is limited by the pole-zero pattern of the system. That is, in some cases the transformation may not exist, or if it exists the system may not be stabilizable, or the controller may be unstable [9]. To deal with the above mentioned problems, the parameters of the bilinear transform have been carefully chosen to satisfy our design requirements. An issue that has required a great care in designing the proposed two-input PSS is that two weighting functions have to be chosen at a time to achieve good stability and robustness.

Another point that needs to be clarified is that by using a combination of additive and multiplicative uncertainty representation, we can specify both the control sensitivity and the complementary sensitivity functions at a time. As a result, both the performance and robustness of the system can be improved within the limitations imposed by plant capacity and measurement noise [15].

This paper is organized as follows: Section 2 describes the dynamic of the system model. Section 3 presents the H_∞ optimal control problem, including the standard H_∞ design formulation. The synthesis of the proposed PSS is presented in section 4. Simulation results are given in section 5.

2. Dynamic of the System Model

Figure 1 describes a synchronous machine connected to an infinite bus of voltage V_b through double-circuit transmission lines having an external reactance x_e . Although the machine has a standard AVR, a supplementary damping provided by the PSS is needed to improve the stability of the system. The dynamic behavior of the synchronous machine is described by nonlinear equations as given in [1-3, 12]. The nominal system is obtained after the nonlinear equations are linearized around an operating point as shown in Table 1. A simple, but widely used linearized system called the Heffron-Phillips model is used to derive the nominal system [1-3].

The linearized equations are expressed in state-space form as follows:

$$\dot{x} = A_o x + B_o u + L_o d \tag{1}$$

$$y = C_o x + D_o u \tag{2}$$

where the state variables are $x = [\Delta\omega \ \Delta\delta \ \Delta E'_q \ \Delta E'_d \ \Delta T_m]^T$, the system output is $y = [\Delta\omega \ \Delta T_e]^T$. ω denotes the shaft speed, δ is the load angle, E'_q is the internal machine voltage, E'_d is the field voltage, T_e is the electrical torque (same as the output power P_e) and T_m is the mechanical torque. The input signal u represents the system control signal and the signal d is the external disturbance. A_o , B_o , L_o , C_o and D_o are constant matrices of appropriate dimensions.

The transfer functions of the nominal system from voltage reference V_{ref} to both outputs $\Delta\omega$ ($\Delta\omega/\Delta V_{ref}$) and ΔT_e ($\Delta T_e/\Delta V_{ref}$) show

that the former has a zero on the imaginary axis ($z = 0$), while the later has its zeros very close to the imaginary axis. The dominant modes are poorly damped with natural oscillation frequency at about 10 rad/sec. It has also been found that the nominal plant has at least two more poles than zeros, which means a strictly proper plant.

From the computational viewpoint of H_∞ optimal control, plants with imaginary axis zeros/poles or strictly proper plants present some ill conditioning problems [16-17]. That is, the system equations for solving the H_∞ optimal control problem may be close to singularity or some computational assumptions may not be satisfied. A method that can be used to deal with ill conditioning problems caused by imaginary axis zeros is to modify the original direct-feedthrough term D_o by adding to this term a very small value ϵ . This technique was adopted in the design of the standard H_∞ -PSS. It should be noted however that this technique is only valid for shifting the $j\omega$ zeros, but cannot be used to shift the $j\omega$ poles. On the other hand, the bilinear transform is effective not only in preventing the ill conditioning problems caused by $j\omega$ poles and zeros but also in improving the damping of the system.

To design the proposed PSS, first, the system is considered under different operating conditions to obtain different sets (A , B , L , C , D). These sets of models include all possible representations of the real system. Secondly, the model uncertainties are derived and described as a combination of multiplicative and additive uncertainty representation. The next step is to find the upper bounds on these uncertainties using frequency domain weighting functions. Then the bilinear transform is applied to the nominal plant. Finally, stabilizing controllers satisfying the specified closed-loop objectives are obtained by minimizing the H_∞ norm of the closed-loop transfer functions.

3. H_∞ Optimal Control Problem

H_∞ optimization of control system deals with the minimization of the peak value of certain closed-loop frequency response functions. In other words, by using the H_∞ control, we wish to design a controller that offers the best protection against the worst disturbance, i.e., a controller that can take into account both model uncertainty and performance specifications.

Table 1. Possible Operating Conditions (1000 MVA base)

System parameters	Maximum value	Nominal value	Minimum value
P_e	1.133	0.900	-0.967
Q_e	0.437	0.437	-0.437
X_e	1.800	0.350	0.120
K_a	100.0	20.00	0
D	---	0.220	-5.000

K_a : exciter gain, D : Damping coefficient

Fig. 1 Power System Configuration

Let consider the general feedback configuration as shown in Fig. 2, where $G_o(s)$ is the nominal plant, $K(s)$ denotes the controller, u is the input to the plant. The signals r , d , v , n , are reference input, input disturbance, output disturbance and measurement noise, respectively. It is known that this configuration, if it is stable, has the following input-output property

$$y = T(s)r + S(s)G_o(s)d + S(s)v - T(s)n \quad (3)$$

where $S(s) := (I + G_o(s)K(s))^{-1}$, $T(s) := I - S(s)$ and $S(s)G_o(s)$ are the sensitivity function, the complementary sensitivity function and the input disturbance sensitivity function, respectively [15].

Fig. 2 General Feedback control Configuration

From (3) it can be seen that stability, robustness and disturbance attenuation can only be influenced by feedback. We also observe that plant disturbance attenuation and measurement noise attenuation are contradictory design requirements. That is, by making $S(s)$ smaller, $T(s)$ becomes bigger. Furthermore, command tracking and disturbance attenuation cannot be reached independently, i.e., minimizing the effect of disturbance v will inevitably increase the effect of the reference error r . Therefore, the controller $K(s)$ should be chosen so as to find a compromise between these two objectives. In a typical H_∞ control problem, the nominal performance design goals such as tracking, disturbance rejection and sensor noise attenuation are achieved by minimizing the H_∞ -norm of a related closed-loop transfer function. For example, to reduce the effect of the output disturbance on the plant output and maintain the tracking error below certain level, the H_∞ norm of the sensitivity function $S(s)$ is minimized.

3.1 Standard H_∞ Approach

3.1.1 The Mixed Sensitivity Problem

In this paper, standard H_∞ approach means the design approach that is solely based on the H_∞ optimal control theory (state-space approach) where uncertainties are modeled in additive and/or multiplicative ways with respect to the nominal system model [4-14]. In this approach, the robust stability goal is met by minimizing either the complementary sensitivity function $T(s)$ for the multiplicative uncertainty or the control sensitivity function $R(s) := K(s)S(s)$ for the additive uncertainty. For more details see [4-9, 11-16]. Since the design objectives are contradictory, i.e., $S(s)$ and $T(s)$ cannot be minimized simultaneously, frequency weighting functions are used to guide the design so that a trade-off can be obtained. For this reason, $S(s)$ is minimized in the low-frequency ranges where low-frequency disturbances are important and $T(s)$ is minimized in high-frequency ranges. In general, a high gain, low-pass weighting function $W_1(s)$ representing the desired disturbance attenuation level is used to penalize $S(s)$, while a high-pass weighting function $W_3(s)$ representing the maximum allowable multiplicative perturbations is used to penalize $T(s)$. The standard H_∞ optimal controller $K(s)$ is then found by solving the following mixed sensitivity minimization problem:

$$\min \| \begin{bmatrix} W_1(j\omega)S(j\omega) \\ K(s)W_3(j\omega)T(j\omega) \end{bmatrix} \|_\infty \quad (4)$$

Where $\| \cdot \|_\infty$ denotes the maximum magnitude of the vector over all ω [15-18].

The order of the controller is equal to that of the generalized plant (nominal system plus weights). Furthermore, the performance and robustness of the controller depend heavily on the weighting functions.

3.1.2 Pole-zero Cancellation Problems

As discussed earlier, in the mixed sensitivity problem formulation, the 'all-pass' property of the optimal H_∞ control laws ensures that the singular value Bode plots will precisely conform to those specified by the weighting functions. However, there is a serious drawback to this property. Namely, the resulting standard H_∞ -PSS always cancels the stable (possibly poorly damped) poles of the plant [16-17]. This is known as the pole-zero cancellation phenomenon. When this phenomenon occurs in a system with poorly damped modes, the closed-loop system will have within its roots the weakly damped modes and all the unstable poles that have been mirrored in the left half s -plane. This means that, the time response of system will present poorly damped oscillations at the resonance frequency. In power systems, this is not desirable because these modes cannot be stabilized. A simple and more direct method to solve these problems will be discussed in the next section.

4. Design of the Proposed PSS

4.1 Uncertainty Representation and Mixed Sensitivity

In this paper, the uncertainties are described as a combination of both the additive and the multiplicative uncertainty representations. The relation between perturbed plants $G(s)$ and the nominal plant $G_o(s)$ is given by:

$$G(s) = \{ [I + \Delta_m(s)]G_o(s) + \Delta_a(s) \} \quad (5)$$

where $\Delta_a(s) = G(s) - G_o(s)$ and $\Delta_m(s) = [G(s) - G_o(s)]/G_o(s)$ denote additive and multiplicative uncertainty, respectively.

Typical uncertainty percentages in different frequency ranges of a power system are listed in Table 2. It can be seen that the size (i.e., H_∞ -norm) of uncertainty due to unmodeled dynamics is increased from less than 20% to above 100% of the size of the nominal plant in the frequency range of interest. This typical behavior of uncertainty has been suggested by Dole and Stein in [18]. It was used as guideline in [4-7, 9-14] for modeling uncertainty in power systems. In practice the disagreement between the low-frequency responses of the model and the real plant is expected to be small because the low-frequency errors are generally in a highly structured parameterized form which can be less or more accurately represented. On the other hand, in the high frequency region, the unstructured uncertainty cannot be accurately represented or are deliberately neglected in order to achieve a simpler nominal plant [18]. The sources of uncertainties considered in this paper are:

- Parameter variations due to system faults: the uncertainties caused by changes in the system transmission line impedance (during or after a fault was cleared), etc.
- Parameter variations due to linearization: uncertainty due to changes in the system parameters from their nominal values to their maximum or minimum values as given in Table 1.
- Uncertainties due to high-frequency unmodeled dynamics such as parasitic effects in the AVR, governor, generator windings, time delay, etc.

Table 2. Typical Uncertainty Specifications

Frequency range (rad/sec)	Percentage of Uncertainty
$< 10^{-3}$	$< \pm 10\%$
$10^{-3} \sim 10^{-2}$	$\pm 20\%$
$10^{-2} \sim 10^{-1}$	$\pm 50\%$
$10^{-1} \sim 10$	$\pm 90\%$
> 10	$> \pm 100\%$

Fig. 3 Additive Uncertainty and Weight

We have studied various possible variations of the frequency characteristics of the linearized system for the above cases (a) and (b) and this is shown in Fig. 3 for the additive uncertainty case. Since the effect of (c) dominates the high-frequency regions, this is taken into account when selecting the maximum allowable additive weighting function $W_f(s)$. That is, $W_f(s)$ was chosen as a high-pass filter (high gain at high frequency region). It can be seen from Fig. 3 that near the oscillation frequency (10 rad/s) there is potentially more than 100% modeling error, which could increase at high frequencies.

Similarly, the multiplicative uncertainty $\Delta_m(s)$ was evaluated and then multiplicative uncertainty upper bound $W_f(s)$ was chosen by considering the factors (a), (b) and (c) as discussed above. On the other hand, the choice of $W_f(s)$ is not related to the system uncertainty. However, the selection of this weight was done by considering the trade-off between performance and robustness.

For the uncertainty representation (5), the controller is found by solving the following mixed sensitivity minimization problem:

$$\min_{K(s)} \left\| \begin{matrix} W_1(j\omega)S(j\omega) \\ W_2(j\omega)R(j\omega) \\ W_3(j\omega)T(j\omega) \end{matrix} \right\|_{\infty} \quad \dots\dots\dots(6)$$

The reason for considering complex uncertainty representation (5) is that: (i) we desire to represent the system uncertainties as accurate as possible and (ii) this enables us to specify both the control sensitivity function $R(s)$ and the complementary sensitivity function $T(s)$ at a time. Beside the fact that $T(s)$ and $R(s)$ are used to characterize the robustness of the system, they are also related to measurement noise attenuation and limitation of the control signal input (PSS output), respectively.

4.2 The Bilinear Transform

One possibility to deal with the pole-zero cancellation problem is to use the $j\omega$ -axis poles shifting transform also known as bilinear transform [17]. Let the pole-zero configuration of the nominal plant

be as shown in Fig. 4 (a). This plant has a $j\omega$ axis zero and a pair of weakly damped poles. As discussed in section 3.1.2, if the PSS is designed based on this system, the controller if can be computed cannot increase the damping of this mode because of the pole-zero cancellation phenomenon. To prevent this undesirable phenomenon, we transform the original s -plane into a new $\bar{s}$ -plane using the following transformation:

$$s = (\bar{s} + p_1)/(1 + \bar{s} / p_2) \quad \dots\dots\dots(7)$$

where $p_1 < 0$ and $p_2 < 0$ are the end-points of the diameter of a circle in the left s -plane as shown in Figure 4.

Fig. 4 Bilinear Transform

After the transformation (7) is used to alter the pole-zeros of the system as shown in Fig. 4 (b), the controller can be designed based on the transformed plant. The final closed-loop poles will be placed inside the circle as shown in Fig. 4 (c). The actual controller for the original nominal plant is obtained by using the inverse bilinear transform to map the controller back to the original s -plane. It should be pointed out that the resulting controller is sub-optimal for the actual system, but it can prevent the pole-zero cancellation and improve the damping of the poorly damped modes as it will be shown later. That is, time-domain specifications such as settling time, damping ratio, step response behavior, etc., can be directly taken into account in the design.

Another advantage of using this method is that it becomes easier to deal with the transformed model in a trial and error design process. To be specific, if we encounter a case where there exist no controllers which satisfy our robustness requirements, an appropriate choice of parameters in the bilinear transform may be used to solve this problem. This is because the transformation changes the location of poles and zeros as well as the characteristics of the target plant. The performance and robustness of the controller become adjustable to some extent by the parameters of the bilinear transform.

In our design p_1 was mainly used to shift the lightly damped poles of the nominal system into the right-half plane, i.e., to control the locations of the lightly damped modes. On the other hand, p_2 was used to prevent a non-minimum phase controller (zeros in right-half plane). It should be noted that p_2 was not used in [9].

4.3 Design Requirements

The proposed controller is required to maintain the performance and the stability of the system in the face of uncertainties as described in (5). Besides, robust performance should also be maintained in the presence of disturbances such as three phase faults in the system (3LG), etc. For good robustness against additive and multiplicative uncertainty, the bandwidth of the complementary sensitivity function $T(s)$ was limited to 15 rad/sec. This is also necessary for noise reduction. Moreover, $W_f(s)$ is chosen such that the amplitude of the control signal being applied to the plant input is reduced. The sensitivity function $S(s)$ is required to be small up to the natural frequency (10 rad/s). The closed-loop system is required to

attenuate the disturbances at $\Delta\omega$ and ΔT_e outputs by the factors of 2.88 to 1 and 3.6 to 1, respectively. Furthermore, we specified the damping ratio of the dominant poles to be about 0.4 and settling time less than 2 seconds for the nominal closed-loop system.

4.4 Guidelines and Procedure for Selecting the Weighting Functions

The choice of the weights is important to the design and generally involves considerations about both performances and robustness. Although there are general guidelines available for selecting these weighting functions, there is unfortunately no systematic way to choose them for a given set of control specifications. Therefore, the design approach is iterative through a trial and error process based on the experience of the designer. Guidelines for selecting the weights and the general procedure of the design are given below:

- Step 1** Derive a nominal system $G_d(s)$. Pull out the uncertainties through examinations of various cases of perturbations as shown in Fig. 3.
- Step 2** Based on the above examinations, select simple yet stable low-pass filter $W_1(s)$ for the desired disturbance attenuation and high-pass filters $W_2(s)$ and $W_3(s)$ to achieve good robustness at high frequencies.
- Step 3** Apply the bilinear transform (7) to the nominal plant.
- Step 4** Form the augmented plant of the problem, perform the H_∞ minimization of (6) and find the stabilizing controller $K(s)$. If no controller exists for the problem (6), go to step 2 and select new weighting functions.
- Step 5** Use the inverse transformation of (7) to derive the final controller $K(s)$. If $K(s)$ is unstable or poorly damped, go to Step 3. Choose new parameters p_1 and p_2 .
- Step 6** Check if the performance and robustness specifications (time and frequency domains) are satisfied. If not, go to step 2. Otherwise, stop.

5. Simulation Results

5.1 Weighting Functions and the Controller

To satisfy the design requirements, the weighting functions $W_1(s)$, $W_2(s)$ and $W_3(s)$ were chosen based on the procedure outlined in the previous section. The value of parameters p_1 and p_2 achieving the design specifications have been chosen to be -2.2 and -28, respectively. After careful considerations about both performance and robustness, the following weighting matrices have been selected:

$$W_1 = \frac{s+15}{s+5} \begin{bmatrix} 0.96 & 0 \\ 0 & 1.2 \end{bmatrix} \quad \dots\dots\dots(8)$$

$$W_2 = \frac{6s+10}{0.05s+9} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \dots\dots\dots(9)$$

$$W_3 = \frac{5s+10}{0.09s+1} \begin{bmatrix} 4 & 0 \\ 0 & 1.2 \end{bmatrix} \quad \dots\dots\dots(10)$$

The computation of the controller has been performed using the MATLAB Robust Control software package [16]. The original transfer function for the proposed PSS is proper and has 10 states. For easy implementation, it has been reduced to 4 states using Schur Balanced Truncation model reduction and is given in Appendix A. Likewise, the poles and zeros of the reduced order standard PSS are also shown in Table 4 of Appendix A. The pole-zero cancellation phenomenon can be seen from this Table, where the dominant zeros

of the standard H_∞ -PSS are very close to the dominant poles of the nominal system. Note that the weighting functions $W_1(s)$ and $W_2(s)$ used in the design of the standard H_∞ -PSS are the same as those of the proposed PSS.

5.2 Time Domain Responses for Small Disturbances

The system under investigation is a pumped storage unit consisting of one machine connected to a major power system (infinite bus) through double-circuit transmission lines [11]. The power system is modeled by a fifth order synchronous machine, a second order exciter and a third order speed governor as shown in Appendices (B) - (E), respectively. In the simulation, the effect of saturation in the generator has been neglected. This nonlinear power system model will be used to check the performances of PSSs which were designed using the simplified nominal model (Heffron-Phillips model).

At the nominal operating condition, the system is poorly damped (damping ratio $\xi = 0.018$). Therefore, the conventional PSS which was optimally tuned for the nominal system, the standard H_∞ -PSS and the proposed PSS are designed to provide the necessary damping to the system. Computer simulations have been performed to evaluate the performance of the PSSs. The responses of the system equipped with each of these PSSs are presented in Figure 5 for a small disturbances of 0.1 p.u. increase in ΔV_{ref} .

Fig. 5 (a) shows the responses of the nominal closed-loop system. It can be seen that the responses of the system equipped with the proposed PSS is well damped as compared to those of the conventional PSS and the standard H_∞ -PSS. On the other hand, it can be observed that due to the pole-zero cancellation problems, the standard H_∞ -PSS was unable to damp the oscillations in the nominal system as expected.

Fig. 5 (b) illustrates the responses of the system for full load, leading power factor. In this case, the system is absorbing reactive power and the PSSs should be able to maintain the stability of the system. It can be seen that the proposed PSS reduces the first swing (enhanced synchronizing torque) and gives better damping than the conventional PSS. Again, the standard H_∞ -PSS exhibits oscillatory, poorly damped oscillations which persist up to 5s.

Figure 5 (c) shows the responses of the electrical power after the outage of one transmission line. In this situation, the oscillations are more pronounced and the controllers should be able to maintain the stability of the system. It can be observed that the proposed PSS gives satisfactory performance with the smallest first swing and overshoot. On the other hand, the conventional PSS gives better responses than the standard H_∞ -PSS.

Fig. 5 (d) depicts the responses for weak transmission line ($x_r = 1.4$ p.u.). This case is equivalent to the situation where power is transferred to electrically far load centers. This situation can cause low-frequency oscillations, especially for a pumped storage plant. As seen in this Figure, the performance of the conventional PSS deteriorates with the increase in transmission line impedance. Meanwhile, the proposed PSS is seen to cope well with these changes. It has a settling time less than 3s and a maximum overshoot about 0.0075. However, the conventional PSS has a maximum overshoot of about 0.01, and a settling time about 3.5s. The oscillatory responses produced by the standard H_∞ -PSS worsen.

5.3 Transient Stability Test

A three phase fault to ground was applied near the sending end of one transmission line and cleared after 6-cycle duration by opening the line when the system was operating at 0.9 p.u. power, 0.9 pf (power factor) lag. To take into account the effect of the uncertainty in the damping coefficient D , the value of D was reduced from 0.22 p.u. (nominal) to -5 p.u. (minimum).

1 : Proposed PSS, 2 : Conventional PSS, 3 : Standard H_∞-PSS

(a) Responses of the nominal closed-loop system

(b) Responses for full load leading power factor

(c) Responses for one line outage

(d) Responses for weak transmission line

Fig. 5 Time Domain Responses for small disturbances

1 : Proposed PSS, 2 : Conventional PSS, 3 : Standard H_∞-PSS

Fig. 6 Transient Stability Test

Fig. 7 Singular-value Bode Plots of $G_o(s)/(I+G_o(s)K(s))^1$

Table. 3 Damping Ratio (ξ) of the Electromechanical Modes

System	Proposed PSS	Conventional PSS	Standard H _∞ -PSS
Nominal	34.0%	20.5%	1.8%
Leading pf	63.5%	30.7%	2.8%
$x_r = 0.7$	33.1%	18.3%	1.3%
$x_r = 1.4$	26.0%	15.0%	-0.2%

The responses of the system are shown in Fig. 6. It can be seen that the proposed PSS and the conventional PSS stabilize the system within 5s. However, the proposed PSS is seen to provide a much better damping than the conventional PSS, with a settling time less than 3s. The settling time of the conventional PSS is about 4s. On the other hand, the standard H_∞-PSS gives poorly damped responses as expected. Power oscillations can be seen to persist up to 5s and continue even after 10s.

5.4 Robustness and Disturbance Attenuation Analysis

5.4.1 Disturbance Attenuation

Figure 7 depicts the singular value Bode plots of the closed-loop system from disturbance ΔV_{ref} to the output y . It is obvious that the frequency response of the system equipped with the standard H_∞-PSS peaks at the dominant poorly damped mode. In other words, the disturbances are not attenuated by this PSS. On the other hand, the conventional PSS and the proposed H_∞-PSS have noticeably reduced

this peak, i.e., they can attenuate the system oscillations. However, the proposed PSS has the smallest peak. This means that the proposed PSS provides more damping to the system than the conventional PSS.

5.4.2 Robustness Analysis

The stability robustness is tested by considering the damping ratio of the dominant eigenvalues under various operating conditions. The damping ratio is used to measure the rate of the decay of a particular oscillation mode (eigenvalue).

Let the eigenvalues of the system be denoted $\lambda = \alpha + j\omega$. The damping ratio in percentage is defined as [5]:

$$\xi = \frac{-\alpha}{\sqrt{\alpha^2 + \omega^2}} \times 100\% \quad \dots\dots\dots(11)$$

The damping ratio of the dominant poles for each operating condition as shown in Fig. 5 is listed in Table 3. It is known that the larger the damping ratio at an operating condition, the more stable the system is at that condition. It can be seen that both the conventional and the proposed PSS have larger damping ratios. However, the proposed PSS provides the largest damping especially for the worst case disturbance ($x_r = 1.4$). As can be observed, for the nominal closed loop system, the damping ratio of the standard H_∞ -PSS is the same as that of nominal open-loop system and was very small for all other operating conditions. This means that the standard H_∞ -PSS cannot improve the damping of the system as confirmed by the time domain simulation results.

6. Conclusions

A design method combining the bilinear transform and the H_∞ optimal control has been presented. By using the proposed approach, it is possible to prevent the pole-zero cancellation phenomenon and to increase the damping of poorly damped modes. Therefore, the dynamic and transient stabilities of the system can be improved.

Simulation results show that, in terms of increasing the damping of the dominant poles, both the proposed PSS and the conventional PSS give satisfactory performances. However, in a wide range of operating conditions ranging from lagging to leading power factor and weak transmission line, the performance of the proposed PSS is more robust than that of the conventional PSS. Due to the pole-zero cancellation problems, the standard H_∞ -PSS was unable to damp the system oscillations.

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Appendices

A. Transfer functions of the proposed and the standard H_∞-PSS

$$K_{\omega}(s) = 0.52 \frac{(s^2 + 9.04s + 79.39)(s^2 + 2.42s + 88.35)}{(s^2 + 1.87s + 15.86)(s^2 + 6.69s + 11.88)}$$

$$K_{Te}(s) = 7.02 \frac{(s^2 + 1.35s + 31.11)(s^2 + 6.86s + 8.98)}{(s^2 + 1.87s + 15.86)(s^2 + 6.69s + 11.88)}$$

app. Table 1 Poles and zeros of the standard H_∞-PSS

Poles	Zeros ($\Delta\omega$ & ΔTe)
-1.61	-240.09
-4.86	-0.178±j9.92
-4.74±j9.92	

B. Parameters of the machine

Direct axis synchronous reactance: $x_d = 0.87$
 Direct axis transient reactance: $x'_d = 0.36$
 Direct axis subtransient reactance: $x''_d = 0.254$
 Transient open circuit time constant: $T'_{do} = 4.72$
 Subtransient open circuit constant: $T''_{do} = 0.059$
 Leakage reactance: $x_l = 0.179$
 short circuit time constant: $T_s = 0.201$
 Quadrature axis synchronous reactance: $x_q = 0.72$
 Quadrature axis subtransient reactance: $x''_q = 0.284$
 Inertia constant: $M = 5.58$
 System frequency 50Hz, system base: 1000MVA
 All the parameter values are expressed in p.u. except time constants expressed in seconds (Machine base 300 MVA).

C. Block diagram of the conventional PSS

$$K_p = 3.51, T_j = T_2 = 0.36, T_2 = T_d = 0.06, T_w = 8.$$

D. Block diagram of the AVR (Type 1S)

$$K_a = 20, T_a = 0.03, k_f = 0.02, T_f = 0.8$$

E. Bloc diagram of the speed governor

$$K_g = 20, T_s = 0.45, T_g = 4.8, T_7 = 42, T_g = -1.2, T_g = 0.6.$$

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