A Proposed Approach for Modeling of Power System Uncertainties to Design Robust PSS

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Abstract—This There are so many parameters which are effective on calculations of a power system especially for controller design and variations of their values (uncertainties) can influence the performance of the controllers such as the power system stabilizers (PSS). To overcome these problems, $H\infty$ control has been applied to design of robust PSS. One of the difficulties is selection of the weighting function (for uncertainty model) which has a very effective role in $H\infty$ control design. In this paper, an effective approach is presented to determine the weighting function; this approach is based upon transfer functions obtained through various operation scenarios of power systems. To show the efficiency of the proposed approach, the uncertainty model is utilized to design a robust $H\infty$ PSS by using the feedback control configuration. The simulation results of various operation scenarios show that the obtained $H\infty$ PSS using this approach is robust enough to damp the power system oscillations.

I. INTRODUCTION

Analysis of power system dynamic behavior requires models with certain parameter values. There are so many parameters which are effective on calculations of a power system especially for controller design and on the other hand variations of the values (uncertainties) can influence the performance of controllers. An important type of these controllers is power system stabilizer (PSS).

PSS is designed to add damping to the generator rotor oscillations by proper modulation of its excitation voltage [1]. The PSS provides oscillation damping by producing an electrical torque component in phase with the rotor speed deviations. The basic structure of the PSS comprises a gain, phase compensation blocks, a washout filter and output limiters. With rotor speed employed as the PSS input signal, a torsional filter is also commonly used.

The phase compensation blocks are used to provide a phase lead that compensates for the phase lag between the exciter input and the generator electrical torque. In practice, the phase-lead network should provide compensation over the entire frequency range of interest (0.1–2 Hz) and under different operating scenarios. It is generally desirable to have some under-compensation so that in addition to significantly increasing the damping torque, the PSS would promote a slight increase in the synchronizing torque [1]. To design a robust PSS, once the phase compensation blocks are specified, the gains should be coordinated to confer sufficient oscillation damping without having to resort to high values of PSS gain and, consequently, cause excessive adverse transients and interactions among controllers [2].

The conventional PSSs have to be tuned for various operating conditions and some methods are proposed for this object such as non-linear least squares based multivariable root locus following technique for multiple operating scenarios [2, 3].

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. To overcome these problems, $H\infty$ control has been applied to design of robust PSS [4, 5]. In these works, the designed $H\infty$ PSS via mixed sensitivity approach have confirmed the significant performance and high robustness. In this method, the weighting function (for uncertainty model) which has a very effective role in $H\infty$ control design is so complicated to select. In this paper, an approach to determine the weighting function for the design of $H\infty$ PSS is presented; this approach is based upon transfer functions obtained through various operation scenarios of power systems. To show the efficiency of the proposed approach, the uncertainty model is utilized to design a robust $H\infty$ PSS by using the feedback control configuration according to [6]. The obtained robust PSS guarantees desirable performance requirements imposed on the system.

II. UNCERTAINTY AND CONTROLLER DESIGN

To perform 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 and damping. Robust performance specifications
describe how the closed-loop system would behave if some parts of the system were changed or perturbed.

Each control area of power systems contains different kinds of uncertainties because of plant parameter variations, load changes and system modeling errors due to some approximations in model linearization and un-modeled dynamics. Usually, the uncertainties in power system can be modeled as multiplicative and/or additive uncertainties [7, 8].

A. Template Representing Uncertainties

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:

$$G_p(s) = G_n(s)[1 + \Delta(s)W_i(s)]$$  \hspace{1cm} (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 $\Delta$ is said to be allowable. The idea behind this uncertainty model is that $\Delta W_i$ is the normalized plant perturbation away from 1:

$$\left[ G_p - G_n \right] / G_n = \Delta W_i$$  \hspace{1cm} (2)

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

$$\left\| G_p - G_n \right\|_\infty = \|\Delta W_i\|, \quad \forall \omega$$  \hspace{1cm} (3)

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

$$\mathcal{M}$$

B. Maintaining Robust Stability of the $\mathcal{M} - \Delta$ structure

In this theorem, 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 $W_i(\omega)$. 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 $\Delta$ around to the input of $\Delta$ equals $M(s)$, so the block diagram collapses to the configuration shown in Fig. 4.

Fig. 4. $\mathcal{M} - \Delta$ 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:

$$T = 1 - S = G_nK(1 + G_nK)^{-1} = W_i T$$  \hspace{1cm} (4)

Where:

$$M = -W_iG_nK(1 + G_nK)^{-1} = -W_i T$$  \hspace{1cm} (5)

$M$ is the transfer function from the output of $\Delta$ to the input of $\Delta$ 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 $\Delta$ 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 $\Delta$. Thus:

$$R S \iff |M(j\omega)| < 1, \quad \forall \omega \iff \|M\|_\infty < 1$$  \hspace{1cm} (6)

C. Robust Performance and $H_\infty$ 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:
\[ |S(j\omega)| < [W_p(j\omega)]^{-1}, \ \forall \omega \]  
(7)

Or in other words:
\[ [W_p]\|_{\infty} < 1 \]  
(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, are given by:
\[ \begin{bmatrix} e' \\ u' \end{bmatrix} = \begin{bmatrix} S \\ K_S \end{bmatrix} d \]  
(9)

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

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:
\[ NP \iff [W_p]\|_{\infty} < 1, \ \forall \omega \]
\[ \iff [W_p] < |1 + L|, \ \forall \omega \]  
(10)

And the loop transfer functions is:
\[ L = G_yK \]  
(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:
\[ RP \iff [W_p]S_p < 1, \ \forall S_p, \forall \omega \]
\[ \iff [W_p] < |1 + L|, \ \forall L, \forall \omega \]  
(12)

This corresponds to requiring \( |d| < 1, \ \forall \Delta \) in Fig. 5, where we consider Input multiplicative uncertainty, and the set of possible loop transfer functions is:
\[ L_p = G_pK = G_p(s)[1 + \Delta(s)]K = L[1 + W_l\Delta] \]  
(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:
\[ S_p = (1 + L_p)^{-1} = \frac{1}{1 + L[1 + W_l\Delta]} \]  
(14)

And the worst-case (maximum) is obtained at each frequency by selecting \( |\Delta| = 1 \) such that the terms \( (1 + L) \) and \( W_l\Delta \) (which are complex numbers) point in opposite directions. We get:
\[ \max |W_p|^2 S_p + |W_p|^2 T < 1 \]  
(15)

The RP-condition becomes:
\[ RP \iff \max |W_p|^2 S_p + |W_p|^2 T < 1 \]  
(16)

A necessary and sufficient condition for robust performance according to [1] is:
\[ [W_p]\|_{\infty} < 1 \]  
(17)

The RP-condition (16) for this problem is closely approximated by the following mixed sensitivity \( H_{\infty} \) condition:
\[ \left[ \begin{array}{c} W_p \cr W_p \end{array} \right] \|_{\infty} \leq \max |\Delta| \left[ \begin{array}{c} |W_p|^2 S_p + |W_p|^2 T \cr |W_p|^2 S_p + |W_p|^2 T \end{array} \right] < 1 \]  
(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 \( H_{\infty} \) problem.

III. SYSTEM MODELING

To show the effect of the controller designed through the proposed method 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 [1] 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. The two-area system was linearized in the operating condition described with the nominal power flow of 400 MW from Area 1 to Area 2.

![Fig. 6. The Two-Area four-generator test power system](image-url)
The main objectives of this research are to reduce the oscillation in the system and to increase the overall robust performance by a robust controller. The generator with greatest participation in inter-area mode is generator 3, which makes it the most suitable generator to install the controller called robust Power System Stabilizer (PSS).

IV. MODELING OF UNCERTAINTIES AND PSS DESIGN

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](image)

To design the controller, several possible cases (such as three-phase fault in different buses, increase or decrease of loads, outage of lines, etc) are considered and their frequency responses is depicted in Fig. 8.

![Fig. 8. Comparing Bode plots of two contingencies and normal conditions](image)

For example the system transfer functions of two contingencies and normal conditions are shown in Fig. 9. In this figure, $G_n$ is the normal condition transfer function, $G_1$ is the transfer function of the system when one of the inter area links is out of service (tie circuit connecting buses 8 and 9) and the system transfer function is $G_2$ when a three-phase fault occurs at the end of line 8-9.

![Fig. 9. Comparing Bode plots of two contingencies and normal conditions](image)

According to (3), the uncertainty weighting function ($W_i$) can be obtained. The dotted lines in Fig. 10 represent $(G_p - G_n)/G_n$ and the solid line shows the selected $W_i$. It can be observed that $W_i$ have covered the perturbations adequately and it is utilized as uncertainty model to design PSS.

![Fig. 10. Bode plots of $G_p - G_n$ and uncertainty weight](image)

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 and the 34-order is depicted in Fig. 11. It shows that the reduced order controller may be used as HPSS.
V. SIMULATION RESULTS

To show the efficiency of the proposed approach, the designed PSS (HPSS) using the uncertainty model is applied on generator 3 and its effect on damping of the oscillations and the settling time is evaluated in operation scenarios which are described in Table I.

<table>
<thead>
<tr>
<th>Scenario number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A three-phase short-circuit fault occurs at Bus 9 at t=0.3sec and consequently line 8-9 is disconnected by the circuit breakers at t=0.4 sec</td>
</tr>
<tr>
<td>2</td>
<td>A three-phase short-circuit fault at Bus 9 at t=0.3sec and it is cleared at t=0.5sec without line outage</td>
</tr>
<tr>
<td>3</td>
<td>−15% change in load of bus 7</td>
</tr>
<tr>
<td>4</td>
<td>+15% change in load of bus 9</td>
</tr>
<tr>
<td>5</td>
<td>A three-phase short-circuit fault occurs at Bus 8 at t=0.3sec and then consequently line 7-8 is disconnected by the circuit breakers at t=0.45 sec</td>
</tr>
</tbody>
</table>

To achieve better evaluation, the speed deviation of generator 3 with the proposed controller (HPSS) is investigated in comparison with the responses of the generator with conventional PSS (CPSS) [9, 10] and without PSS (NO PSS). The results are depicted in Figures 12-16. According to these figures it is clearly shown the damping of oscillations and the settling time of the generator speed deviation with proposed PSS (HPSS) is better than those with the CPSS and NO PSS.
VI. CONCLUSIONS

To overcome the lack of conventional PSS robustness in multi-machine power systems with variable operating condition, location, and severity of the faults, $H_\infty$ control has been applied to design of robust PSS but the weighting function as a very effective factor is difficult to select. In this paper, an effective approach is presented to determine the weighting function for the design of $H_\infty$ PSS; this approach is based upon transfer functions obtained through various operation scenarios of power systems.

The effectiveness and performance of the proposed approach is tested by applying the designed HPSS (using the resulted weighting function) on a four generators power system under various operating conditions. The simulation results show that the designed HPSS using the proposed approach causes a robust oscillation damping effectively over various conditions and is superior to the conventional PSS.

REFERENCES


