STRUCTURED $H_\infty$ CONTROL-BASED ROBUST POWER SYSTEM STABILIZER FOR STABILITY OF MULTI-MACHINE SYSTEM

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Keywords: Multi-machine system; Power system stabilizer; Structured $H_\infty$ synthesis; Robust control.

A robust design of power system stabilizers (PSSs) using $H_\infty$ output feedback control has been introduced in this work. To facilitate the implementation of the designed PSSs, the proposed technique employs the $H_\infty$ to tune the fixed-structure conventional lead-lag PSS parameters of the multi-machine system. These PSSs are used to improve the damping of the local and inter-area low-frequency oscillations in power systems under different operating conditions. The proposed control is tested on a multi-machine system, which is a three-machine nine-bus system. A comparative simulation study shows a significant enhancement and good performance of the proposed design compared to an IEEE conventional power system stabilizer.

1. INTRODUCTION

The stability of power systems is one of the biggest challenges, the instability can lead to blackouts. The low-frequency electromechanical oscillations are a serious problem in power system stability. The power system stabilizer (PSS) is an effective way to improve the damping of these oscillations, which is used to produce a supplementary signal through the excitation system [1–3].

The lead-lag phase compensator is the base of the conventional power system stabilizers. The current IEEE standard [4] has classified the type of power system stabilizers according to the number of inputs in two categories: single-input like (PSS1A, PSS5C) and dual-input like (PSS2C, PSS3C, PSS4C, PSS6C, PSS7C). Also, the standard has classified according to the bands of the working frequency into two types: single frequency bands like (PSS1A, PSS2C...), and multiple frequency bands like (PSS4C, and PSS5C) which are used to damp separate frequency bands (very low, low, intermediate, and high-frequency modes) [4].

In the literature, different techniques have been designed to damp low-frequency oscillations. The sliding mode control (SMC) is presented in paper [5], a farmland fertility algorithm (FFA) in [6] but the FFA is highly reliant on accurate and extensive data which can be challenging to acquire, a genetic algorithm in [7] which requires many iterations and evaluations, making it slow for complex problems like multi-machine system, a particle swarm optimization (PSO) in [8] but this algorithm performance critically depends on fine-tuning parameters, making it complex and less robust, a chaotic sunflower optimization algorithm in [9] which requiring careful tuning of chaotic parameters, struggles with local optima, prioritizing exploitation (refining good solutions) over exploration (finding new, potentially better regions) leading to missed global optima, a moth search algorithm in [10] but it lacks the rigorous mathematical backing of some established optimization methods, raising concerns about stability and global convergence guarantees, bio-inspired algorithms in [11] which is highly dependent on fine-tuning specific parameters, impacting effectiveness and requiring more expertise, a sliding mode control in [12]. Moreover, artificial intelligence-based training and tuning techniques have been used to develop a PSS as a Deep reinforcement learning-based method in [13], a neuro-adaptive predictive control in [14], a fuzzy-based controller in [15–17], damped Nyquist plot for the phase and gain optimization in [18] but all these algorithms may require intensive computations compared to simpler algorithms, especially for complex problems. Furthermore, robust control theories have been employed in the design of $H_\infty$-based robust power system stabilizers [19] in the case of one machine connected to the electrical grid. It is noted that $H_\infty$ control is inherently robust, providing stability and performance guarantees even in the presence of uncertainties and disturbances. Unlike some optimization methods which may rely on specific models, the $H_\infty$ method utilizes a systematic approach that considers worst-case scenarios, making it suitable for a wide range of complex systems. Moreover, the $H_\infty$ approach excels in addressing uncertainties and variations in system dynamics, ensuring stability and performance under diverse operating conditions. Besides, it is effective in dealing with time-varying systems, offering a reliable solution for dynamic processes that evolve.

At the nominal operating conditions, the conventional power system stabilizer (CPSS) works efficiently, but its performance decreases if the operating point has changed [20]. In this case, the CPSS does not guarantee the power system robustness for different ranges of operating points.

To solve the robustness problem, the robust control design guarantees stability under external disturbance or parametric uncertainties. In [21], the authors have designed their PSS using the concept of Glover-McFarlane’s loop shaping design, but it is applied only in the case of one machine connected to the infinite bus. A linear matrix inequalities (LMI) technique is used to synthesize a state feedback robust PSS using pole-placement [22] but it assumes all the system states are measurable which is not the case in an industrial context.

Robust control methods based on $H_2$ and $H_{\infty}$ Norm designed in [19,20] have been only applied on an SMIB.

In this work, a structured $H_\infty$ control approach has been developed to tune control block parameters of conventional CPSS on the Multi-Machine system with two weighting functions. This is the main contribution of this paper. Besides to the authors’ knowledge, this work is not in the literature. Compared to other optimization methods like genetic algorithms (GA), particle swarm optimization (PSO), and others used for control system design, the $H_{\infty}$-infinity method offers several advantages. These include robustness to uncertainties, stability guarantees, and computational efficiency. These features make $H_{\infty}$ control a powerful tool for controlling complex systems in the presence of uncertainties and disturbances.

This paper is organized as follows. Section 2 presents the
description and mathematical model of the multi-machine system. Section 3 gives the structured \( H_\infty \) control design. Section 4 explains the proposed resolution and the chosen weighting functions in the proposed design. Section 5 shows the simulation results, in which a comparative study is performed between the proposed control strategy and the conventional CPSS. Finally, Section 6 ends this paper and gives some concluding observations.

2. PLANT MODEL

The dynamic stability of Multi-Machine power systems can be described by a set of nonlinear differential equations. A multi-machine system of this study consists of three machines and nine buses, as shown in Fig.1. The system data are given in [23].

![Diagram of nine-bus system.](image)

The nonlinear mathematical model of the system is described by the equations given below:

\[
\dot{\delta}_i = \omega_i - \omega_s, \quad i = 1, 2, 3 \tag{1}
\]

\[
\dot{\omega}_i = \frac{\omega_s}{2H_i} \left[ T_{mi} - T_{ei} - D_i (\omega_i - \omega_s) \right], \quad i = 1, 2, 3 \tag{2}
\]

\[
\dot{E}_{qi} = \frac{1}{T_{dqi}} \left[ E_{qi} + (X_{di} - X_{dii}) I_{di} - E_{fqi} \right], \quad i = 1, 2, 3 \tag{3}
\]

\[
\dot{E}_{fqi} = \frac{1}{T_{fqi}} \left[ -E_{fqi} + K_{di} (V_{refi} - V_{ei}) \right], \quad i = 1, 2, 3 \tag{4}
\]

The robust structured HPSS controller is \( K(s) \) which combines tunable parameters \( (K_{si}, T_{si}, T_{si}, T_{si}, T_{si}) \) of conventional CPSS. The external inputs \( w \) are the reference voltage variations \( (\Delta V_{ref1}, \Delta V_{ref2}, \Delta V_{ref3}) \) and the mechanical torque variations \( (\Delta T_{me1}, \Delta T_{me2}, \Delta T_{me3}) \) of the generators G1, G2, and G3 respectively. The measurement outputs \( y \) are the speed deviations \( (\Delta \omega_1, \Delta \omega_2, \Delta \omega_3) \) of the generators G2 and G3 respectively. The control signals \( u \) are the outputs of proposed \( H_\infty \) power system stabilizers (HPSS2 and HPSS3) and the external outputs \( z \) are chosen to be the...
variation of speed deviations $\Delta\omega_{12}$ of the generators $G1$, $G2$ and $\Delta\omega_{13}$ of the generators $G1$, $G3$. These external signals $z$ will be filtered by some weighting functions before their use in the $H_\infty$ optimization problem. More details about the used weighting functions will be given in the next section.

The structured $H_\infty$ synthesis is based on minimization of the $H_\infty$ norm as follows:

$$\|H(s)\|_{\infty}=\max_{\omega} \bar{\alpha}(H(j\omega)) \leq \gamma, \quad (9)$$

where $\bar{\alpha}$ is the maximum singular value, and $\gamma$ is the $H_\infty$ norm to be minimized.

The linear fractional transformation (LFT) representation for $H(s)$ is given as follows:

$$H(s)=F_1(P(s),\text{Diag}(K_1(s),\ldots,K_s(s))), \quad (10)$$

where $F_1$ represents the lower LFT representation and Diag represents a diagonal block of $K(s)$.

The open-loop transfer from $[Z]$ to $[W]$ is given as follows:

$$[Z]=[P_{11}(s) \quad P_{12}(s)]\begin{bmatrix} P_{21}(s) & P_{22}(s) \end{bmatrix}[W]. \quad (11)$$

The linear fractional transformation (LFT) representation of the system in closed loop is given as follows:

$$T_{zw}(s)=P_{11}+P_{12}K[(I-P_{22})K]^{-1}. \quad (12)$$

4. H. CONTROLLER RESOLVING

It is necessary to include some weighting functions $W_1(s)$ and $W_2(s)$ in the Plant to get some dynamical performances in an $H_\infty$ problem. Figure 4 illustrates the augmented plant with the weighting functions $W_1(s)$ and $W_2(s)$. The new considered external outputs are: $z_1$ and $z_2$, where $z_1$ is the variation of speed deviations $\Delta\omega_1$ and $\Delta\omega_2$ connected to weighting function $W_1(z_1=W_1(s)\Delta\omega_{12})$ and $z_2$ is the variation of speed deviations $\Delta\omega_1$ and $\Delta\omega_3$ connected to weighting function $W_2(z_2=W_2(s)\Delta\omega_{13})$.

Fig. 4 – Weighting functions augmentation of the system.

The choice of these weighting functions is an essential step. The structures of weighting functions $W_1(s)$ and $W_2(s)$ are given by the following equations:

$$W_1(s)=\frac{M_1s + w_{b1}}{s + w_{b1}e_1}, \quad (13)$$

$$W_2(s)=\frac{M_2s + w_{b2}}{s + w_{b2}e_2}, \quad (14)$$

where $M_i$, $w_{bi}$ and $e_i$ are the tuning parameters. The following values satisfy the performance requirements for the considered nominal operating point:

The first weighting function parameters are: $M_1=110$, $w_{b1}=50$ and $e_1=10^4$ and the second weighting function parameters are: $M_2=100$, $w_{b2} = 110$ and $e_2=10^4$.

The obtained numerical values of tuned parameters’ HPSSs are given in the Table 1.

5. SIMULATION RESULTS

To verify the effectiveness and the robustness of the proposed HPSS2 and HPSS3, several studies have been performed on the multi-machine system at different operating points where the data of the system and loading conditions are given in the Table 2 and Table 3. It is noted that “Light load” refers to operating the generator at a fraction of its rated capacity, typically less than 25 %. “Normal load” is the typical operating range for the generator, around 50-75 % of its rated capacity. “Heavy load” refers to running the generator at or near its full capacity, typically 75-100 % of its rated capacity.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{c2}$</td>
<td>43.2826</td>
<td>$K_{c3}$</td>
<td>0.3280</td>
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<tr>
<td>$T_{c2}$</td>
<td>10.00</td>
<td>$T_{c3}$</td>
<td>10.00</td>
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<tr>
<td>$T_{c2}$</td>
<td>1.08984</td>
<td>$T_{c3}$</td>
<td>1.9980</td>
</tr>
<tr>
<td>$T_{c2}$</td>
<td>0.00408</td>
<td>$T_{c3}$</td>
<td>0.0340</td>
</tr>
<tr>
<td>$T_{c2}$</td>
<td>0.19534</td>
<td>$T_{c3}$</td>
<td>2.1973</td>
</tr>
<tr>
<td>$T_{c2}$</td>
<td>0.00434</td>
<td>$T_{c3}$</td>
<td>0.0390</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Generator</th>
<th>Light</th>
<th>Normal</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td>$Q$</td>
<td>$P$</td>
</tr>
<tr>
<td>$G1$</td>
<td>0.362</td>
<td>0.162</td>
<td>0.716</td>
</tr>
<tr>
<td>$G2$</td>
<td>0.800</td>
<td>-0.109</td>
<td>1.630</td>
</tr>
<tr>
<td>$G3$</td>
<td>0.450</td>
<td>-0.204</td>
<td>0.850</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Load</th>
<th>Light</th>
<th>Normal</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td>$Q$</td>
<td>$P$</td>
</tr>
<tr>
<td>$A$</td>
<td>0.65</td>
<td>0.55</td>
<td>1.25</td>
</tr>
<tr>
<td>$B$</td>
<td>0.45</td>
<td>0.35</td>
<td>0.90</td>
</tr>
<tr>
<td>$C$</td>
<td>0.50</td>
<td>0.25</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Furthermore, a comparative study is carried out with CPSSs [23], where a scenario of severe disturbance rejection test is considered. It consists of a standard three phases short circuit near the node 4 at $t=1$s (see Fig.1). After 50 ms, the line (4-5) is opened at $t=1.1$s this line is closed.

The Figs. 5 to 7 present a system response using the conventional PSSs (CPSSs) and the proposed stabilizers (HPSSs) to a transient disturbance during nominal operating conditions.

Comparing the simulation results obtained with the HPSSs and with conventional CPSSs shows that the proposed stabilizers achieve good robustness and performances. As can be observed in Figs. 5-13. The Tables 4 and 5 show a quantitative comparison of the proposed HPSS with a conventional CPSS and without PSSs. The Table 4 represents the first oscillation amplitude of the system response. It is noted that the proposed HPSSs gives smaller oscillation in all generators overall operating conditions. The Table 5 shows the settling time for $|\Delta\omega_i| <$
1.5 \cdot 10^{-4}. The proposed HPSSs gives a better settling time in all generators in a heavy load.

In nominal load, it gives a better settling time in two generators (G2 and G3). And in the light load, it gives a better settling time in the generator G2. Besides, the proposed HPSSs gives the best settling time in six out of the tested nine cases. The conventional CPSS gives a better settling time only in the three cases compared to the proposed HPSSs. Furthermore, the proposed HPSSs have the best dynamical performance in terms of oscillations damping.

Fig. 5 – Speed deviation of generator 1 for nominal load.

Fig. 6 – Speed deviation of generator 2 for nominal load.

Fig. 7 – Speed deviation of generator 3 for nominal Load.

Fig. 8 – Speed deviation of generator 1 for light load.

Fig. 9 – Speed deviation of generator 2 for light load.

Fig. 10 – Speed deviation of generator 3 for light load.

Fig. 11 – Speed deviation of generator 1 for heavy load.

Fig. 12 – Speed deviation of generator 2 for heavy load.

Fig. 13 – Speed deviation of generator 3 for Heavy Load.
6. CONCLUSION

In this paper, a robust power system stabilizer design using structured $H_{\infty}$ synthesis is presented to enhance the stability and robustness of the multi-machine system. Three different operating points have been considered.

The proposed HPSS2 and HPSS3 controllers have a simple architecture, good performance and good robustness compared to the conventional CPSS.

The simulation results confirm the great benefit of the proposed HPSSs compared to the conventional CPSS regarding the stability, the disturbance rejection, and the speed deviation dynamical performances in several loading conditions.

APPENDIX

A. THE MULTI-MACHINE DATA

The parameters of the generators are given in Table A.1:

<table>
<thead>
<tr>
<th>Generator</th>
<th>$V_e$</th>
<th>$X_{q}$</th>
<th>$Y_{0.0}$</th>
<th>$X_{1.0}$</th>
<th>$H$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.1460</td>
<td>0.0608</td>
<td>8.0600</td>
<td>0.0969</td>
<td>23.64</td>
<td>9.6</td>
</tr>
<tr>
<td>G2</td>
<td>0.8958</td>
<td>0.1198</td>
<td>6.0000</td>
<td>0.8645</td>
<td>6.40</td>
<td>2.5</td>
</tr>
<tr>
<td>G3</td>
<td>1.3125</td>
<td>0.1813</td>
<td>5.8900</td>
<td>1.2578</td>
<td>3.01</td>
<td>1.0</td>
</tr>
</tbody>
</table>

B. THE SMIB DATA

The numerical values of parameters’ CPSSs [4] are given in Table B.2.

<table>
<thead>
<tr>
<th>CPSS2</th>
<th>CPSS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$K_{e2}$</td>
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<tr>
<td>$T_{e2}$</td>
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<tr>
<td>$T_{e2}$</td>
<td>0.9728</td>
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<tr>
<td>$T_{e2}$</td>
<td>0.0500</td>
</tr>
<tr>
<td>$T_{e2}$</td>
<td>0.8417</td>
</tr>
<tr>
<td>$T_{e2}$</td>
<td>0.0500</td>
</tr>
</tbody>
</table>

Table 4

Comparison of $1^\text{st}$ oscillation amplitude between the conventional PSSs (CPSSs) and the proposed PSS (HPSSs).

<table>
<thead>
<tr>
<th>Case</th>
<th>PSS Type</th>
<th>$G1$</th>
<th>$G2$</th>
<th>$G3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>2.918</td>
<td>4.994</td>
<td>5.740</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>2.689</td>
<td>4.976</td>
<td>5.467</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>2.427</td>
<td>4.951</td>
<td>5.438</td>
</tr>
<tr>
<td>Light Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>0.974</td>
<td>1.920</td>
<td>2.053</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>0.972</td>
<td>1.896</td>
<td>2.031</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>0.923</td>
<td>1.885</td>
<td>2.029</td>
</tr>
<tr>
<td>Heavy Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>3.931</td>
<td>5.422</td>
<td>7.681</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>3.719</td>
<td>5.410</td>
<td>6.707</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>3.606</td>
<td>5.274</td>
<td>7.456</td>
</tr>
</tbody>
</table>

Table 5

Comparison of the settling time between the conventional PSSs (CPSSs) and the proposed PSS (HPSSs).

<table>
<thead>
<tr>
<th>Case</th>
<th>PSS Type</th>
<th>$G1$</th>
<th>$G2$</th>
<th>$G3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>8.976</td>
<td>&gt;10s</td>
<td>&gt;10s</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>2.328</td>
<td>2.845</td>
<td>2.706</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>2.416</td>
<td>1.877</td>
<td>2.641</td>
</tr>
<tr>
<td>Light Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>3.954</td>
<td>8.176</td>
<td>7.212</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>1.920</td>
<td>2.906</td>
<td>2.813</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>2.565</td>
<td>2.264</td>
<td>2.872</td>
</tr>
<tr>
<td>Heavy Load in 10$^3$ p.u.</td>
<td>Without-PSS</td>
<td>&gt;10s</td>
<td>&gt;10s</td>
<td>&gt;10s</td>
</tr>
<tr>
<td></td>
<td>CPSSs</td>
<td>9.085</td>
<td>9.102</td>
<td>9.053</td>
</tr>
<tr>
<td></td>
<td>HPSSs</td>
<td>3.601</td>
<td>1.996</td>
<td>3.629</td>
</tr>
</tbody>
</table>

NOMENCLATURE

$G_i$ Generator $i$
$H_i$ Inertia constant of $i$
$o_{a}$ Rotor angular speed (rad/s)
$o_{e}$ Synchronous rotor angular speed (rad/s)
$\delta_i$ Power angle (rad)
$I_{d_i}A_{d_i}$ d- and q-axis components (p.u.) of the $i$th generator
$K_{d_i}T_{d_i}$ Gain (p.u.) and time constant (s) of AVR
$E_{d}$ Rotor field voltage (p.u.)
$V_{d}$ Terminal voltage (p.u.)
$V_{ref}$ Reference voltage (p.u.)
$T_{d_i}T_{q_i}$ Electrical and mechanical torque (p.u.)
$E_{a}$ q-axis transient internal voltage (p.u.)
$T_{a}$ d-axis transient open circuit generator time constant (s)
$X_{a},Y_{a}$ Generator d and q-axis reactance (p.u.)
$X_{d}$ Generator d-axis transient reactance (p.u.)
$D_i$ Damping coefficient
$P,Q$ Active and reactive powers (p.u.)
$K_{V_i},K_{W_i}$ Linearized multi-machine system constants
$K_{d_i}T_{d_i}T_{q_i}$ Gain, washout time constant, and time constants of PSS of the $i$th generator
$G_i$ The $i$th generator
$PSS$ Power System Stabilizer
$CPSS_i$ The $i$th conventional PSS
$SMIB$ Single Machine connected to Infinite Bus
$HPSSI$ The $i$th proposed H- PSS
$u, v$ The control signal and input signal of PSS

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