ROBUST STABILIZER OF ELECTRIC POWER GENERATOR USING H^∞ WITH POLE PLACEMENT CONSTRAINTS

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This paper deals with the application of robust control theory to the design of electric power system stabilisers. The well-known H^∞ technique is combined with pole placement constraints and solved with Linear Matrix Inequalities approach. This convex optimisation problem guarantees robust pole placement and leads to improved closed-loop system robustness and transient response characteristics. Uncertainties are taken into account in a robust fixed parameter and structure control law to allow for parameter variations and perturbations acting on the electrical power system. The proposed controllers are compared with μ-synthesis under a variety of operating conditions of the electrical power network.

K e y w o r d s: robust control, H^∞, pole placement, LMI, μ-analysis and synthesis, power system stabiliser

1 INTRODUCTION

The electric power generator is a complex system with highly non-linear dynamics. Its stability depends on the operating conditions of the power system and its configuration. Low frequency oscillations are a common problem in large power systems. Excitation control or Automatic Voltage Regulator (AVR) is well known as an effective means to improve the overall stability of the power system. Power System Stabilisers (PSS) are added to excitation systems to enhance the damping during low frequency oscillations. The output of the PSS is applied as a supplementary control signal to the machine voltage regulator terminal. Oscillations of small magnitude and low frequency often persist for long periods of time and in some cases can cause limitations on the power transfer capability. The Power System Stabilizer (PSS) is a device that improves the damping of generator electromechanical oscillations. Stabilizers have been employed on large generators for several decades, permitting utilities to improve stability-constrained operating limits.

The input signal of conventional PSS is filtered to provide phase lead at the electromechanical frequencies of interest (*ie* , 0.1 Hz to 5.0 Hz). The phase lead requirement is site-specific, and is required to compensate for phase lag introduced by the closed-loop voltage regulator.

The PSS conventional and the PSS control based on root locus and eigenvalue assignment design techniques have been widely used in power systems. Such PSS ensure optimal performance only at a nominal operating point and do not guarantee good performance over the entire range of the system operating conditions due to exogenous disturbances such as changes of load and fluctuations of the mechanical power. In practical power system networks, a priori information on these external disturbances is always in the form of a certain frequency band in which their energy is concentrated. Remarkable efforts have been devoted to design appropriate PSS with improved performance and robustness. These have led to a variety of design methods using optimal control [1] and adaptive control [2]. The shortcoming of these model-based control strategies is that uncertainties cannot be considered explicitly in the design stage. More recently, robust control theory has been introduced into PSS design which allows control system designers to deal more effectively with model uncertainties [3], [4], [5], and [6]. H^∞ based control approach is particularly appropriate for plants with unstructured uncertainty.

An effective H^∞ synthesis approach can be formulated as a convex optimisation problem involving Linear Matrix Inequalities (LMI) [7]. Theses LMI's correspond to the inequality counterpart of the usual H^∞ Riccati equations. Because LMI's intrinsically reflect constraints rather than optimality, they tend to offer more flexibility for the combination of several constraints on the closed-loop system.

In this paper, a PSS based on H^∞ with pole placement and LMI constraints is proposed and compared with the well known μ-synthesis robust control technique. Different simulation results are presented to demonstrate the effectiveness of these controllers to improve the overall power network performance.

2 SYSTEM DESCRIPTION

The power system considered in this study is modelled as a synchronous generator connected through a transmission line to infinite bus. A simplified model describing the system dynamics used in this study is given by the following state space equations [5], [10].

$$\dot{\boldsymbol{x}} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_1 w(t) + \mathbf{B}_2 u(t)\,, \tag{1.a}$$

$$\boldsymbol{z}(t) = \mathbf{C}_1\mathbf{x}(t) + \mathbf{D}_{11} w(t) + \mathbf{D}_{12} u(t)\,, \tag{1.b}$$

$$\boldsymbol{y}(t) = \mathbf{C}_2\mathbf{x}(t) + \mathbf{D}_{21} w(t) + \mathbf{D}_{22} u(t) \tag{1.c}$$

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where $\boldsymbol{u}$ represents the PSS output added to the voltage set points ΔV_{ref}, w is an external disturbance represented by the mechanical power ΔP_m. The matrices $\mathbf{A}$, $\mathbf{B}_1$, $\mathbf{B}_2$, the vector $\boldsymbol{z}$, $\boldsymbol{y}$ and the state vector $\boldsymbol{x}$ are defined by

$$\mathbf{A} = \begin{bmatrix} 0 & 2\pi f & 0 & 0 \\ -K_1/M & -D/M & -K_2/M & 0 \\ -K_4/K_3T'_{d0} & 0 & -1/K_3T'_{d0} & 1/T'_{d0} \\ -K_AK_5/T_A & 0 & -K_AK_6/Y_A & -1/T_A \end{bmatrix};$$
$$\mathbf{B}_1 = [0 \;\; 1/M \;\; 0 \;\; 0]^\top, \quad \mathbf{B}_2 = [0 \;\; 0 \;\; 0 \;\; K_A/T_A]^\top; \tag{2}$$
$$\boldsymbol{z} = [\Delta P_e \quad \Delta\omega \quad \Delta V_t]^\top, \quad y = \Delta P_e,$$
$$\boldsymbol{x} = \left[\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{FD}\right]^\top,$$

where δ, ω, E'_q, E_{FD}, P_e and V_t are respectively the torque angle, the angular velocity, the internal machine voltage, the excitation voltage, power output and generator terminal voltage. T'_{do} is the open-circuit transient time constant, Δ represents a small deviation around the operation point The operating conditions for the above systems are completely defined by the values of the real (P_a) and reactive (Q) powers at the generator terminals and the transmission line impedance X_e. These quantities are assumed to vary independently over the ranges given in Tab. 1.

We note that the constants K_i $(i = 1,\dots,6)$ are uncertain and depend upon the network parameters, the quiescent operating conditions and the infinite bus voltage (Tab. 2). A detailed bloc diagram of the generator system is shown in Fig. 1.

The variation of K_i and the related uncertainty are given by

$$K_i - \varepsilon_i \le K_i \le K_i + \varepsilon_i \quad (i = 1,\dots,6)$$

where ε_i represents the error on the K_i $(K_1, K_2, \dots K_6)$ parameter.

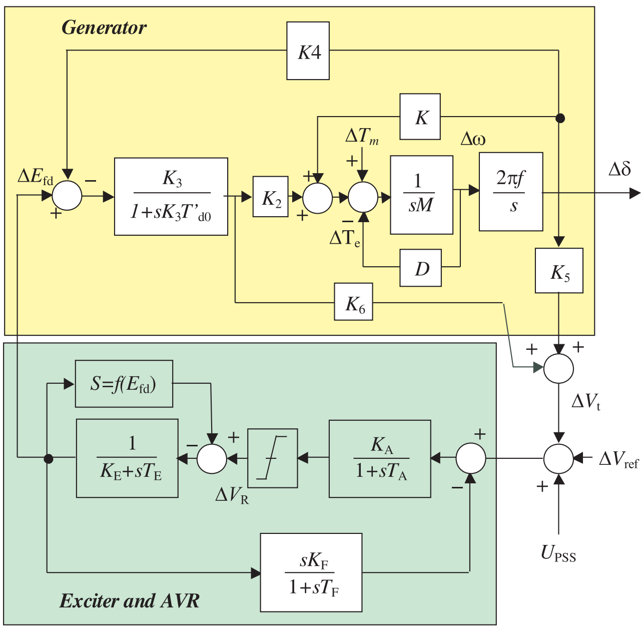

Fig. 1. Combined block diagram of linear synchronous machines.

Table 1. Operating points

Operating point	P_a	Q	X_e
ξ_1	0.4	−0.2	0.2
ξ_2	0.4	0.5	0.2
ξ_3	0.4	−0.2	0.7
ξ_4	0.4	0.5	0.7
ξ_5	1.0	−0.2	0.2
ξ_6 (nominal)	1.0	0.5	0.2
ξ_7	1.0	−0.2	0.45
ξ_8	1.0	0.5	0.7

Table 2. The points of functional dependences K_i

ξ_i \ K_i	K_1	K_2	K_3	K_4	K_5	K_6
ξ_1	1.3599	1.5956	0.2343	2.1999	0.1485	0.4022
ξ_2	1.4414	0.8946	0.2343	1.3899	0.0565	0.4424
ξ_3	0.8578	0.9499	0.3938	1.2898	0.1371	0.6354
ξ_4	1.0584	0.5250	0.3938	1.0625	0.0327	0.7140
ξ_5	2.4766	2.5323	0.2343	3.4699	0.0780	0.2757
ξ_6 (nominal)	2.1950	1.8272	0.2343	2.7257	0.0841	0.3842
ξ_7	1.6870	1.8354	0.3233	2.4721	−0.0089	0.3674
ξ_8	1.3207	1.0815	0.3938	1.8788	−0.0228	0.6024

3 CONTROLLER DESIGN

The designed PSS must achieve the following requirements:

(i) Ensures sufficient closed loop stability margins to allow for fluctuations in the closed loop transfer function parameters such as those which might arise from unmodelled low-damped high frequency modes of oscillations.

(ii) Provides satisfactory performance over a wide range of operating conditions.

3.1 PSS design based on robust pole placement using LMI technique (PPLMI)

3.1.1 LMI formulation for pole placement objectives

This section introduces the LMI-based characterisation for a wide class of pole clustering regions as well as an extended Lyapunov theorem for such regions [7].

The regions of interest are denoted by α-stability regions and are defined by: $\mathrm{Re}(s) \le -\alpha$.

Another interesting region for control purposes in the set $S(\alpha, r, \theta)$ of complex numbers $x + jy$ as shown in Fig. 2.

$$x < -\alpha < 0\,;\; |x + iy| < r\,;\; \mathrm{tg}\,\theta x < -|y|\,.$$

Consider a sub region of the complex left-half plane. A dynamical system $\dot{x} = \mathbf{A}x$ is called D-stable if all its poles lie in D. A subset D of the complex plane is called an LMI region if there exists a symmetric matrix $\alpha = [\alpha_{kl}] \in \Re^{m\times m}$ and a matrix $\beta = [\beta_{kl}] \in \Re^{m\times m}$ such that

$$D = \{z \in C\colon f_D(z) < 0\} \tag{3}$$

where

$$f_D(z) = \alpha + z\beta + \bar{z}\beta^\top = [\alpha_{kl} + \beta_{kl}z + \beta_{lk}\bar{z}]_{1\le k,l\le m}\,. \tag{4}$$

f_D is called the characteristic function of D defined as an LMI region of canonical sector with apex at the origin and inner angle θ.

$$f_D(z) = \begin{bmatrix} \sin\theta(z+\bar{z}) & \cos\theta(z-\bar{z}) \\ \cos\theta(\bar{z}-z) & \sin\theta(z+\bar{z}) \end{bmatrix}. \tag{5}$$

fThe matrix $\mathbf{A}$ is D-stable if only if there exists a symmetric positive definite matrix $\mathbf{X}_D$ such that

$$\begin{aligned} M_D(\mathbf{A},\mathbf{X}_D) &:= \alpha\otimes\mathbf{X}_D + \beta\otimes(\mathbf{A}\mathbf{X}_D) + \beta^\top\otimes(\mathbf{A}\mathbf{X}_D)^\top \\ &= \left[\alpha_{kl}\mathbf{X}_D + \beta_{kl}\mathbf{A}\mathbf{X}_D + \beta_{lk}\mathbf{X}_D\mathbf{A}^\top\right]_{1\le k,l\le m} < 0 \end{aligned} \tag{6}$$

where $\otimes$ denotes the Kronecker product of matrices.

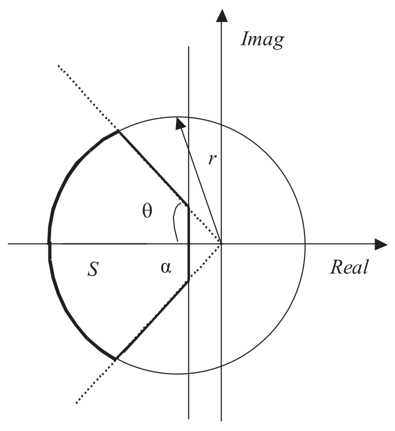

Fig. 2. Region $S(\alpha, r, \Theta)$.

3.1.2 State feedback H^∞ synthesis with pole placement

In order to achieve a prescribed closed-loop H^∞ performance $\gamma > 0$, our constrained H^∞ problem consists of finding a state-feedback gain K that:

- places the closed-loop poles in some LMI stability region D defined by the characteristic function (6)
- guarantees the H^∞ performance $\|T_{zw}\|_\infty < \gamma$.

A state feedback controller of the form $\boldsymbol{u} = \mathbf{K}\boldsymbol{x}(t)$ results in a closed-loop state matrix

$$\mathbf{A}_{cl} = A + B_2\mathbf{K}\,,\ \mathbf{B}_{cl} = \mathbf{B}_1\,,\ \mathbf{C}_{cl} = \mathbf{C}_1 + \mathbf{D}_{12}\mathbf{K}\,,\ \mathbf{D}_{cl} = \mathbf{D}_{11}$$

where $\mathbf{A}$, $\mathbf{B}_1$, $\mathbf{B}_2$, $\mathbf{C}_1$, $\mathbf{D}_{11}$ and $\mathbf{D}_{12}$, are defined by (1a, 1b, 1c).

The controller is obtained by the combination of LMI pole placement design with H^∞ constraints

Pole placement: The closed-loop poles lie in the LMI region

$$\begin{aligned} &f_D(\mathbf{A}_{cl},\mathbf{X}_D) < 0 \Rightarrow \\ &\qquad \alpha\otimes\mathbf{X}_D + \beta\otimes(\mathbf{A}_{cl},\mathbf{X}_D) + \beta^\top\otimes(\mathbf{A}_{cl},\mathbf{X}_D)^\top < 0 \end{aligned} \tag{7}$$

$$\begin{aligned} &\alpha\otimes\mathbf{X}_D + \beta\otimes(\mathbf{A}\mathbf{X}_D + \mathbf{B}_2\mathbf{K}\mathbf{X}_D) \\ &\qquad + \beta^\top\otimes(\mathbf{A}\mathbf{X}_D + \mathbf{B}_2\mathbf{K}\mathbf{X}_D)^\top < 0 \end{aligned} \tag{8}$$

$$\begin{aligned} &\left[\alpha_{kl}\mathbf{X}_D + \beta_{kl}(\mathbf{A}+\mathbf{B}_2\mathbf{K})\mathbf{X}_D + \beta_{lk}\mathbf{X}_D(\mathbf{A}+\mathbf{B}_2\mathbf{K})^\top\right] < 0 \\ &{}_{1\le k,l\le m}\quad \mathbf{X}_D > 0 \end{aligned} \tag{9}$$

H^∞ **performance**: The closed-loop RMS (random-mean-squares) gain from w to z does not exceed γ if and only if there exists a symmetric matrix $\mathbf{X}_\infty$ such that [7]:

$$\begin{bmatrix} \mathbf{A}_{cl}\mathbf{X}_\infty + \mathbf{X}_\infty\mathbf{A}_{cl}^\top & \mathbf{B}_{cl} & \mathbf{X}_\infty\mathbf{C}_{cl}^\top \\ \mathbf{B}_{cl}^\top & -\mathbf{I} & \mathbf{D}_{cl}^\top \\ \mathbf{C}_{cl}\mathbf{X}_\infty & \mathbf{D}_{cl} & -\gamma^2\mathbf{I} \end{bmatrix} < 0\,. \tag{10}$$

The system is not convex and a straightforward approach to enforce convexity would be to seek a common solution such that

$$\mathbf{X} = \mathbf{X}_D = \mathbf{X}_\infty > 0\,. \tag{11}$$

Again, the optimization problem is not yet convex because of the products $\mathbf{KX}$ arising in terms like $\mathbf{A}_{cl}\mathbf{X}$. However, convexity is readily restored by rewriting (9)–(10) in terms of $\mathbf{X}$ and the auxiliary variable $\mathbf{L} := \mathbf{KX}$ [11]. This simple change of variable leads to the following suboptimal LMI approach to H^∞ synthesis with pole assignment in LMI regions. $\mathbf{L}$ is subject to the LMI constraints

$$\left[\alpha_{kl}\mathbf{X}_D + \beta_{kl}U(\mathbf{X},\mathbf{L}) + \beta_{lk}U(\mathbf{X},\mathbf{L})^\top\right] < 0\,, \tag{12}$$

$$\begin{bmatrix} U(\mathbf{X},\mathbf{L}) + U(\mathbf{X},\mathbf{L})^\top & \mathbf{B}_{cl} & V(\mathbf{X},\mathbf{L})^\top \\ \mathbf{B}_{cl}^\top & -\mathbf{I} & \mathbf{D}_{cl}^\top \\ V(\mathbf{X},\mathbf{L}) & \mathbf{D}_{cl} & -\gamma^2\mathbf{I} \end{bmatrix} < 0 \tag{13}$$

where

$$U(\mathbf{X},\mathbf{L}) := \mathbf{AX} + \mathbf{B}_2\mathbf{L}\,,\ \ V(\mathbf{X},\mathbf{L}) := \mathbf{C}_1 + \mathbf{D}_{12}\mathbf{L}\,. \tag{14}$$

Assume that (12)–(13) are feasible and let $(\mathbf{X}^*, \mathbf{L}^*)$ be an optimal solution of this minimization problem. Then the state-feedback gain $\mathbf{K}^* := \mathbf{L}^*(\mathbf{X}^*)^{-1}$ has guaranteed H^∞ performance γ and places the closed-loop poles in D region .

Confining the closed-loop poles to this region ensures a minimum decay rate α, a minimum damping ratio ς

and a maximum undamped natural frequency ω. This in turn bounds the maximum overshoot, the frequency of oscillatory modes, the delay time, the rise time, and the settling time. In power systems, a damping factor ς of at least 10 % and a real part.

The model of the power generator system with infinite bus is uncertain. The system matrix $\mathbf{A}$ takes values in the matrix polytope described by:

$$\mathbf{A} \in \left\{ \left(\sum_{i=1}^{64} \rho_i \mathbf{A}_i \right) : \sum_{i=1}^{64} \rho_i = 1 \,,\ \rho_i \geq 0 \right\}. \tag{15}$$

Such polytopic models may result from convex interpolation of a set of models ($\mathbf{A}_i$) identified in different operating points. Note that LMI condition for quadratic H^∞ performance over (15) are obtained by writing (12)–(13) at each vertex of the polytopic plant.

To solve this design problem with the *LMI Control Toolbox* [12], first specify the plant as a parameter-dependent system with affine dependence on K_i ($i = 1 \dots 6$). the structure of the PSS is determined by the function msfsyn. The results of simulations on several points of operations are given in the section comparative study.

3.2 PSS design based on H^∞ and μ-synthesis

3.2.1 Problem formulation

In this section treating the combination of two techniques one has to know H^∞, μ-synthesis with the intention to ensure a robust stability and a robust performance for a power system stabilizer.

H^∞ limitations with respect to parametric robustness are due to the natural tendency of this method to achieve the system inverse, parametric robustness may be taken into account in the design stage which leads to a complete mixed sensibility scheme known as μ-synthesis formulation.

A bloc diagram of the power system closed-loop configuration, which includes the plant feedback controller and elements associated with the uncertainty models and performance objectives, is shown in Fig. 3. A more convenient approach for controller synthesis is to explicitly include the model uncertainty as shown in Fig.4.

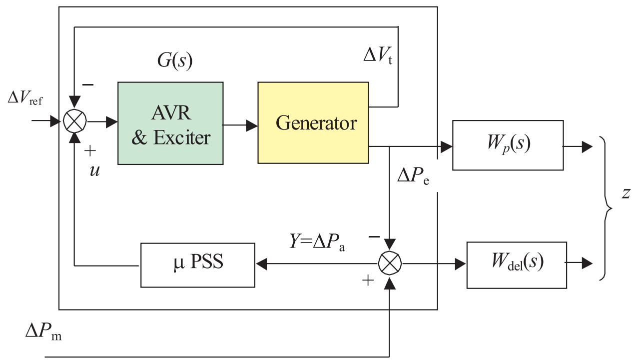

Fig. 3. Structure of the closed-loop system interconnection.

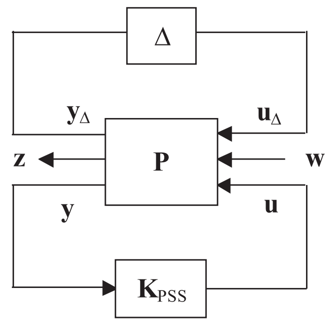

Fig. 4. Control PSS configuration.

With reference to Fig. 4, $\mathbf{P}$ represents the generalized plant (synchronous generator equipped with Automatic Voltage Regulator and weighting functions W_p, W_{del}), $\mathbf{P}(s)$ may be partitioned as

$$\mathbf{P}(s) = \begin{bmatrix} \mathbf{P}_{11} & \mathbf{P}_{12} \\ \mathbf{P}_{21} & \mathbf{P}_{22} \end{bmatrix}, \tag{16}$$

$\mathbf{K}_{PSS}$ denotes the plant controller PSS.

$$F_l(\mathbf{P}, \mathbf{K}_{PSS}) = \mathbf{P}_{11} + \mathbf{P}_{12}\mathbf{K}_{PSS}(I - \mathbf{P}_{22})^{-1}\mathbf{P}_{21} \,. \tag{17}$$

$F_l(\mathbf{P}, \mathbf{K}_{PSS})$ is called a Linear Fractional Transformation (LFT) of $\mathbf{P}$ and $\mathbf{K}_{PSS}$.

We need to check whether the system is stable and has acceptable performance for all perturbations that are included in the model uncertainty set.

The transfer function W_{del} is assumed to be known and reflects the amount of uncertainty in the model. Δ is a multiplicative uncertainty at the plant input assumed to be stable and unknown, except for the norm condition $\|\Delta\|_\infty < 1$. The performance objective is that the transfer function from $\boldsymbol{w}$ to $\boldsymbol{z}$ is small in the H^∞ norm sense for all possible uncertainty transfer functions δ. The weighting function W_p is used to reflect the relative importance of various frequency ranges for which performance is desired. The objective of designing a robust PSS is to make the overall system stable under normal operating conditions and also under faulty situations.

With $\|\Delta\|_\infty < 1$, the perturbed closedloop system remains stable, and the perturbed weighted sensitivity transfer function

$$S(\Delta) = \mathbf{W}_p\big(\mathbf{I} + \mathbf{P}(\mathbf{I} + \mathbf{W}_{del}\mathbf{K}_{PSS}\Delta)^{-1}\big) \qquad (18)$$

is such that $\|S(\Delta)\|_\infty < 1$ for all such perturbations.

A stabilising controller K_{PSS} achieves closed-loop robust performance if only and only if for each frequency $\omega \in \Re^+$, the structured singular values are such that $\mu_\Delta\left[F_L(P, K_{PSS})(i\omega)\right] < 1$.

The goal of μ-synthesis is to minimise the peak value of $\mu_\Delta(\times)$ of the closed-loop transfer function $F_L(P, K_{PSS})$ over all stabilising controllers K_{PSS} which may be formulated as follows

$$\min_{\substack{\mathbf{K}_{PSS}\\ \text{Stabilizing}}} \max_\omega \mu_\Delta\big(F_l(\mathbf{P}, \mathbf{K}_{PSS})(i\omega)\big)\,. \qquad (19)$$

It has been shown [8], that for a constant matrix $\mathbf{M}$ and an uncertainty structure D, an upper bound for $\mu_D(\mathbf{M})$ is an optimally scaled maximum singular value

$$\mu\Delta(\mathbf{M}) \le \inf_{\mathbf{D}\in D_A} \bar\sigma\big(\mathbf{DMD}^{-1}\big)\,. \qquad (20)$$

Using this upper bound, the optimization in equation (19) is reformulated as

$$\min_{\substack{\mathbf{K}_{PSS}\\ \text{Stabilizing}}} \max_\omega \min_{\mathbf{D}_\omega\in D_\Delta} \bar\sigma\big(\mathbf{D}F_l(\mathbf{P}, \mathbf{K}_{PSS})\mathbf{D}_\omega^{-1}\big)\,. \qquad (21)$$

$\mathbf{D}_\omega$ is chosen from the set of scaling D_Δ independently at every ω. Hence, we have

$$\min_{\substack{\mathbf{K}_{PSS}\\ \text{Stabilizing}}} \min_{\mathbf{D},\mathbf{D}_\omega\in D_\Delta} \max_\omega \bar\sigma\big(\mathbf{D}F_l(\mathbf{P}, \mathbf{K}_{PSS})\mathbf{D}_\omega^{-1}\big)\,. \qquad (22)$$

With reference to equation (21) $\mathbf{D}, \mathbf{D}_\omega \in D_\Delta$ defines a frequency-dependent function $\mathbf{D}$ that satisfies $\mathbf{D}_\omega \in D_\Delta$ for each ω. The general expression $\max_\omega \bar\sigma\left[f(\omega)\right]$ is denoted as $\|f\|_\infty$, giving

$$\min_{\substack{\mathbf{K}_{PSS}\\ \text{Stabilizing}}} \min_{\substack{D(s)\in D\\ \text{stable, min-phase}}} \big\|\mathbf{D}F_l(\mathbf{P}, \mathbf{K}_{PSS})\mathbf{D}^{-1}\big\|_\infty\,. \qquad (23)$$

This optimization is solved by an iterative approach referred to as D–K iteration [8].

The PSS based on μ-synthesis design approach is evaluated in simulations under different operating conditions (change of working point, line configuration, reference voltage, as well as the mechanical power). Performance specification and multiplicative uncertainty type are given in terms of bounded power spectra which are specified by weighting function W_p and W_{del} respectively. The weighting function W_{del} is chosen as a low pass filter to achieve disturbance rejection on the output in the low frequency range. At high frequencies, the effect of this performance weight specification can be neglected. W_p is chosen as a high pass filter to take into account modelling errors at high frequencies. This function is also chosen to ensure satisfactory performance of the closed loop system at high frequencies. Hence W_p and W_{del} are chosen as

$$W_{del} = \frac{0.04(s+0.2)}{s+0.004}\,;\; W_p = \frac{0.75(s+0.33)}{s+600}\,. \qquad (24)$$

Using μ-synthesis, it is possible to find a controller that stabilizes the power system under system uncertainty and also achieves robust performance. Nevertheless the software tools [8] employed in the present work, based on the iterative procedure known as D–K iteration, allow an approximate solution. The μ-analysis of H^∞ PSS controller obtained is of 6^{th} order. However, this six state controller can be reduced to four states [9]. The H^∞ controller eigenvalues based on μ analysis for nominal system are listed in Tab. 3.

Table 3. Nominal system model eigenvalues with PSS

Eigenvalues	Frequency (rad/s)	Damping
$-1.11 + 3.10\,i$	3.29	0.339
$-1.11 - 3.10\,i$	3.29	0.339
$-51 + 41\,i$	65.4	0.779
$-51 - 41\,i$	65.4	0.779

The control system is now tested under line reactance fluctuations as well as electric output variation. The reference voltage and the mechanical power P_m have been set to 0.05 p.u. and 0.10 p.u. respectively. A minimum value such that $\mu \le 1$ is desired to satisfy the robust performance criteria. The final result of the robust PSS design and nominal performance are illustrated by Figs. 5 and 6. Robust stability and performance properties with respect to the modelled perturbations are verified since their peak values are less than unity.

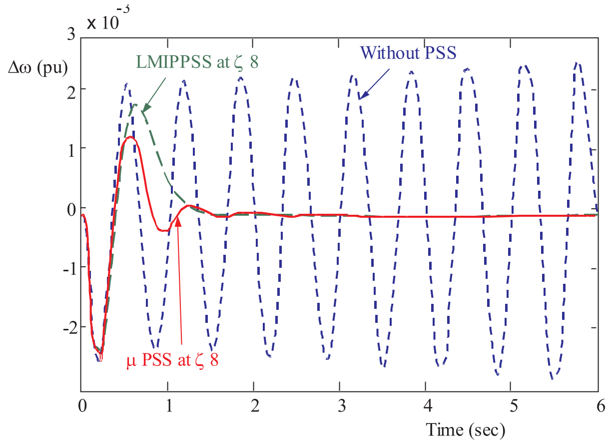

Fig. 11. Transient responses following a 10 % change in load demand at operating condition $\xi_8(P_a = 1,\ Q = 0.5,\ X_e = 0.7)$.

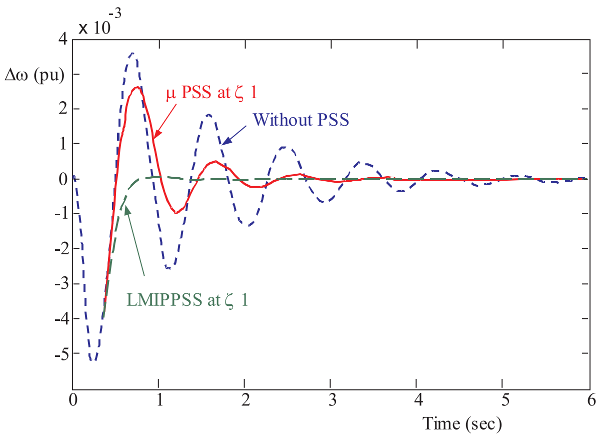

Fig. 7. Transient responses following a 10 % change in load demand at operating condition $\xi_1(P_a = 0.4,\ Q = -0.2,\ X_e = 0.2)$.

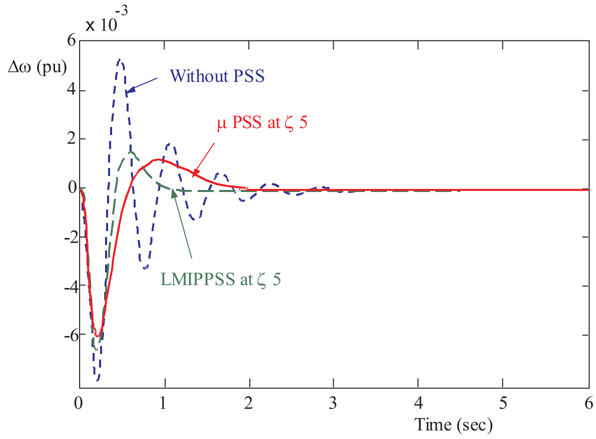

Fig. 8. Transient responses following a 10 % change in load demand at operating condition $\xi_5(P_a = 1,\ Q = -0.2,\ X_e = 0.2)$.

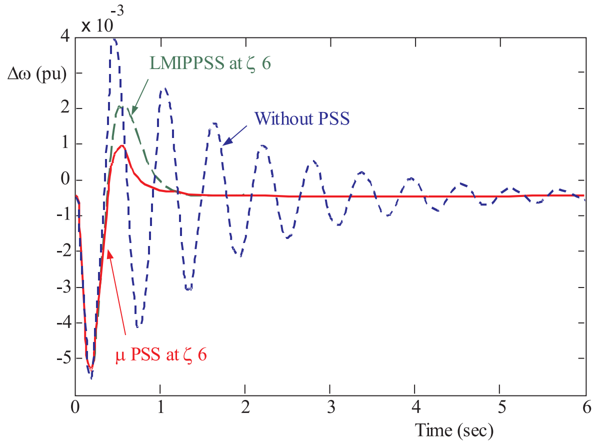

Fig. 9. Transient responses following a 10 % change in load demand at operating condition $\xi_6(P_a = 1,\ Q = 0.5,\ X_e = 0.2)$.

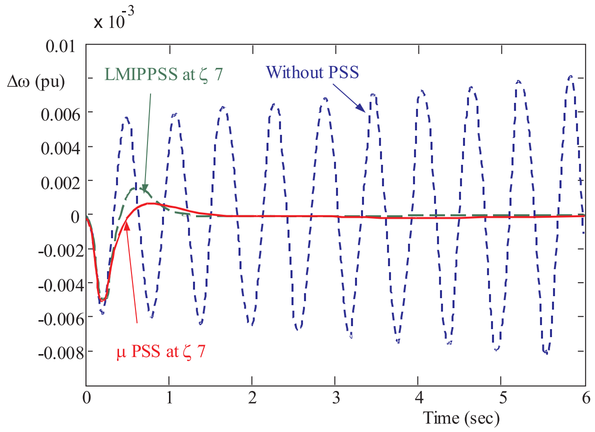

Fig. 10. Transient responses following a 10 % change in load demand at operating condition $\xi_7(P_a = 1,\ Q = -0.2,\ X_e = 0.45)$

It can be concluded that:

- The controlled system achieves nominal performance. This follows from the singular value plot of the nominal weighted output sensitivity function which has a peak value of 0.64.

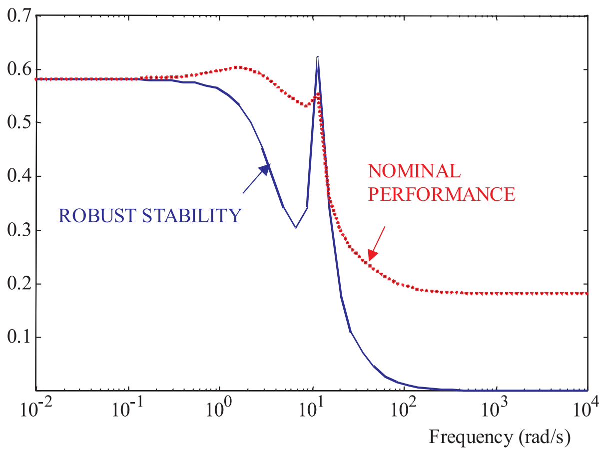

Fig. 5. Robust stability and nominal performance μ-plot

- The controlled system achieves robust stability. This stems from the singular value plot of the nominal weighted input complementary sensitivity function which has a peak value of 0.62.

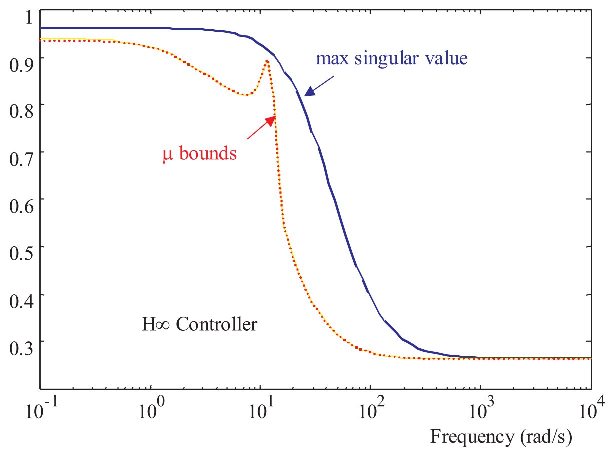

Fig. 6. Maximum Singular value and μ-plot

The proposed technique for the design of robust fixed parameter PSS is seen to provide the desired closed loop performance over the specified range of operating conditions.

4 COMPARATIVE STUDY

In this section a comparative study of the performance and robustness of the PSS based on pole placement with LMI region and μ-synthesis under different operating situations of the electric power network is presented.

The $\mathbf{B}_1$ matrix is given by $\mathbf{B}_1 = [\quad 0\ K_A/T_A]^\top$ and u is a 5 % step change in the reference voltage at the operating points (ξ_i). $\mathbf{B}_2 = [0\ 1/M\ 0\ 0]^\top$ and $w(t)$ is set to a 10 % step change. The transient response of the angular frequency and electrical torque are shown in Figs. 7, 8, to 11, It can be noticed that the PSS based on pole placement with LMI region produces better response characteristics as compared to the μ-synthesis based PSS. The closed loop transient responses confirm the robustness of the proposed controller with respect to modelling errors and operating point changes.

PSS based on μ-synthesis is designed with acceleration power as input and its performance is compared with a *Pole placement-LMI region* (PPLMI) controller and conventionally designed PSS. It can be noticed that the results achieved by PPLMI and H^∞ μ-synthesis are superior to those obtained with a conventional PSS. Furthermore, PPLMI produces better transient response than μ-synthesis technique.

5 CONCLUSION

In this paper the design and evaluation of power system stabilisers based on *pole placement-LMI region* (PPLMI) and μ-synthesis has been considered. The simulation results presented demonstrate the effectiveness of these control techniques to improve the stability and transient response of power systems under a variety of operating conditions. The robustness of the controller has been evaluated with respect to model uncertainties of the power generator. A comparative study of the proposed PPLMI and μ-synthesis PSS with a conventional controller has been conducted. The results demonstrate superior performance of the PPLMI with respect to μ-synthesis controller. Furthermore, μ-synthesis design leads to a higher order controller which is not suitable for real-time implementation.

The main objective of LMI approach is to overcome the problem associated with restrictive constraints in H^∞ design All these methods try to apply a fixed controller to a Linear time invariant (LTI) system by taking the varying parameters (real and/or reactive power) as bounded uncertainties. Since these varying parameters can be measured in a real time, the linear parameter varying (LPV) design is a natural extension and this is currently under investigation with promising results.

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