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Power System Stabilizer Based on Robust H_∞ Controller for Low Frequency Operating Range

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Abstract: The aim of study is designed of Power System Stabilizer (PSS) based on H_∞ approach for power system stabilization. The uncertainties in power system modeling and operations are considered at designing of H_∞ PSS. The bounds of power system parameters are determined over a wide range of low frequency operating conditions. These bounds are used to design a robust H_∞ PSS. A sample power system composed a synchronous generator connected to infinite bus through transmission line is simulated. The digital H_∞ PSS can achieve good performance over a wide range of operating conditions. A comparison between power system responses at variety of operating conditions using the proposed H_∞ PSS and Linear Quadratic Regulator LQR control have been done. H_2 PSS is designed and compared with the proposed controller.

Key words: H_∞ power system stabilizer, H_{2-} PSS, synchronous machine

INTRODUCTION

H_∞ synthesis is carried out in two phases. The first phase is the H_∞ formulation procedure. The robustness to modeling errors and weighting the appropriate input-output transfer functions reflects usually the performance requirements. The weights and the dynamic model of the power system are then augmented into an H_∞ standard plant in (Yousef and Abdel-Fatah, 2005). The second phase is the H_∞ solution. In this phase the standard plant is programmed by computer design software such as MATLAB, then the weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found. Time response simulations are used to validate the results obtained and to illustrate the dynamic system response to state disturbances. The effectiveness of such controllers is examined at different extreme operating conditions. This article relies on H_∞ approach to design a robust power system stabilizer. The advantages of the proposed controller are addresses stability and sensitivity, exact loop shaping, direct one-step procedure stable and closed-loop always stable as in (Khargonekar *et al*., 1988). Electromechanical oscillations in power systems are a problem that has been challenging engineers for years. These oscillations may be very poorly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable power variations the across important transmission lines. For this reason, the use of the controllers to provide better damping for these oscillations is of utmost importance as in (Shayeghi *et al*., 2010; Ramos *et al*., 2005). Despite the potential of the modern control approaches with different structures, the power system utilities still prefer the conventional lead-lag POD controller structure as in (Gt and Sk, 1993). The reasons behind that might be the ease of on-line tuning and the lack of assurance of the stability related to some adaptive or variable structure approaches. On the other hand, it was shown that the appropriate selection of the conventional lead-lag controller parameters results in effective damping to low frequency electromechanical oscillations (Abido, 2000). Unfortunately, the problem of the conventional lead-lag POD controller design is a multimodal optimization problem (i.e., there exists more than one local optimum). Hence, the conventional optimization techniques are not suitable for such a problem. Thus, it is required that the heuristic methods, which are widely used for the global optimization problems be developed. Typically the concept of H_∞ controller design is fairly easy to grasp. However, as controller synthesis is done numerically, a major problem for people new to the subject is how to write the Matlab code. I will here try to give a short overview of some useful Matlab functions. Hopefully this will help when trying to design your first H_∞ controller. There are many H_∞ related functions available in Matlab and its tooles. The important toolboxes are, in addition to the Control System Toolbox, the mu-Analysis and Synthesis Toolbox (mu-tools), the Robust Control Toolbox (RCT) and the LMI Control Toolbox. LMI and mu-tools are both included in RCT v.3.0.1 which comes with Matlab 2010,

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in earlier versions they are separate. A mixed H_2/ H_{inf} synthes is problem will be used to illustrate the use of a handful of useful functions in (Safonov *et al*., 1981).

With the development of control theory, a class of modern optimal control approaches, such as H_2/ H_{inf} and L_l control methods based on PID-type controllers, lead/lag or other fixed structure and low order controllers, have been receiving increasing attention as in (Yinya *et al*., 2008; Tantaris *et al*., 2006). Among these design approaches based on PID-type controllers, a general transfer function model is required and then a numerical optimization method is used to minimize a certain performance criterion by searching in the admissible parameter space of controllers. Such allowable ranges are always stabilizing ones of PID-type controller coefficients. For saving the optimal controller tuning time, recently, several methods of characterization of all stabilizing PID-type controllers for a given Linear Time-Invariant (LTI) plant have been investigated as in (Ho *et al*., 1997), which a linear programming method of computing the entire set of stabilizing PID-type controller based on a generalization of the Hermite-Biehler theorem was developed.

H_∞ approach is particularly appropriate for the stabilization of plants with unstructured uncertainty as in (Kassem and Yousef, 2008; Bouhamida *et al*., 2005). In which case the only information required in the initial design stage is an upper band on the magnitude of the modeling error. Whenever the disturbance lies in a particular frequency range but is otherwise unknown, then the well known LQG (Linear Quadratic Gaussian) method would require knowledge of the disturbance model. However, H_∞ controller could be constructed through the maximum gain of the frequency response characteristic without a need to approximate the disturbance model. The design of robust H_∞ controllers based on a polynomial system philosophy has been introduced by (Kwakernaak, 1986; Grimble, 1997). design LMI-based robust H_2 control with regional pole constraints for damping power system oscillations and this control uses full state feedback. The feedback gain matrix is obtained as the solution of a Linear Matrix Inequality (LMI) by (Hardiansyah and Irisawa, 2005). Also, the designed based on the time-delay system model, robust damping controller is employing mixed-sensitivity H_∞ control theory and pole placement approach in the Linear Matrix Inequality (LMI) framework as in (Qi *et al.*, 2009)

In this study, H_∞ and H_2 power system stabilizers has been designed and applied to synchronous machine connected to infinite bus through transmission line.

MATERIALS AND METHODS

Power system model: The system is described by the block diagram shown in Fig. 1. This Figure shows the coupling between automatic voltage regulation loop (Concordia model), and simple power frequency loop (load frequency control model).

The linear equations of this model are:

$$\Delta\dot{\delta} = \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = -\left(\frac{K_1}{M}\right)\Delta\delta - \left(\frac{D}{M}\right)\Delta\omega - \left(\frac{K_2}{M}\right)\Delta E_q + \left(\frac{1}{M}\right)\Delta T_m - \left(\frac{1}{M}\right)\Delta P_d \tag{2}$$

$$\Delta\dot{E}_q = -\left(\frac{K_4}{T_{d0}}\right)\Delta\delta - \left(\frac{1}{K_3 T_{d0}}\right)\Delta E_q + \left(\frac{1}{T_{d0}}\right)\Delta e_{fd} \tag{3}$$

$$\Delta\dot{E}_{fd} = -\left(\frac{1}{T_A}\right)\Delta E_{fd} - \left(\frac{K_A K_5}{T_A}\right)\Delta\delta - \left(\frac{K_A K_6}{T_A}\right)\Delta\dot{E}_q + \left(\frac{K_A}{T_A}\right)\Delta U_1 \tag{4}$$

$$\Delta\dot{T} = -\left(\frac{1}{T_t}\right)\Delta T_m + \left(\frac{1}{T_t}\right)\Delta P_g \tag{5}$$

$$\Delta\dot{P}_g = -\left(\frac{1}{RT_g}\right)\Delta\omega - \left(\frac{1}{T_g}\right)\Delta P_g + \left(\frac{1}{T_g}\right)\Delta U_2 \tag{6}$$

The matrix form of this system as:

$$\dot{X} = AX + BU \tag{7}$$

where,

$$X = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta T_m \\ \Delta P_g \end{bmatrix}$$

$$\begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & \frac{1}{M} & 0 & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & \frac{-1}{(K_3 T'_{d0})} & 0 & 0 & \frac{1}{T'_{d0}} \\ 0 & 0 & 0 & \frac{-1}{Tt} & \frac{1}{Tt} & 0 \\ 0 & -\frac{1}{(RT_g)} & 0 & 0 & \frac{-1}{T_g} & 0 \\ -\left(\frac{K_4 K_5}{T_A}\right) & 0 & -\left(\frac{K_A K_6}{T_A}\right) & 0 & 0 & \frac{-1}{T_A} \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1/Tg \\ \frac{K_A}{T_A} & 0 \end{bmatrix}$$

Control input

$$U = \begin{pmatrix} U1 \\ U2 \end{pmatrix}$$

H_∞ controller design: The H_∞ theory provides a direct, reliable procedure for synthesizing a controller which optimally satisfies singular value loop shaping

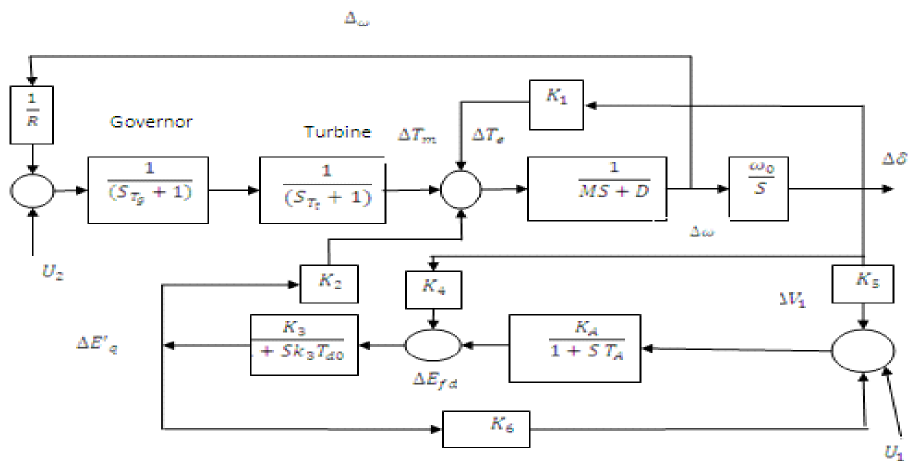

Fig. 1: Block diagram of power system

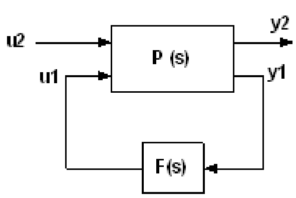

Fig. 2: General setup of the H_∞ design problem

specifications. The standard setup of the H_∞ control problem consists of finding a static or dynamic feedback controller such that the H_∞ norm (a standard quantitative measure for the size of the system uncertainty)of the closed loop transfer function is less than a given positive number under constraint that the closed loop system is internally stable.

The H_∞ synthesis is carried out in two stages:

- **Formulation:** Weighting the appropriate input-output transfer functions with proper weighting functions. This would provide robustness to modeling errors and achieve the performance requirements. The weights and the dynamic model of the system are then augmented into H_∞ standard plant.
- **Solution:** The weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found.

Figure 2 shows the general setup of the H_∞ design problem where:

P(s): The transfer function of the augmented plant (nominal plant G(s) plus the weighting functions that reflect the design specifications and goals)

u2: The exogenous input vector, typically consists of command signals, disturbance, and measurement noises

u1: The control signal

y2: The output to be controlled, its components typically being tracking errors, filtered actuator signals

y1: The measured output

The objective is to design a controller F(s) for the augmented plant P(s) such that the input/output transfer characteristics from the external input vector u2 to the external output vector y2 is desirable. The H_∞ design problem can be formulated as finding a stabilizing feedback control law u1(s) = F(s) . y1(s) such that the norm of the closed loop transfer function is minimized as shown in Fig. 3. In the power generation system including H_∞ controller, two feedback loops are designed; one for adjusting the terminal voltage and the other for regulating the system angular speed as shown in Fig. 4. The nominal system G(s) is augmented with weighting transfer functions $W_1(s)$, W_2 (s) and W_3 (s) penalizing the error signals, control signals, and output signals respectively. The choice of proper weighting functions is the essence of H_∞ control. A bad choice of weights will certainly lead to a system with poor performance and stability characteristics, and can even prevent the existence of a solution to the H_∞ problem.

Consider the augmented system shown in Fig. 4. The following set of weighting transfer functions are chosen to reflect desired robust and performance goals as follows:

A good choice of $W_1(s)$ is helpful for achieving good tracking of the input references, and good rejecting of the disturbances. The weighted error transfer function matrix Z_1; which is required to regulate, can be written as:

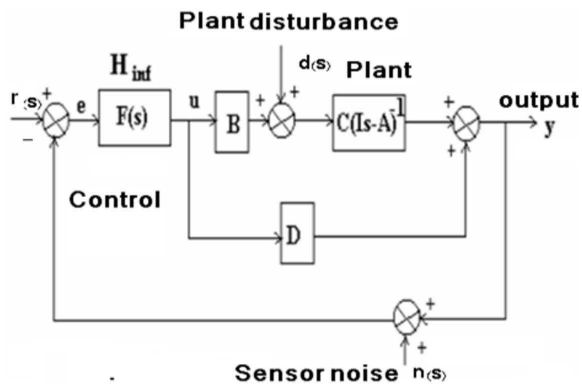

Fig. 3: Standard H_∞ controller feedback system

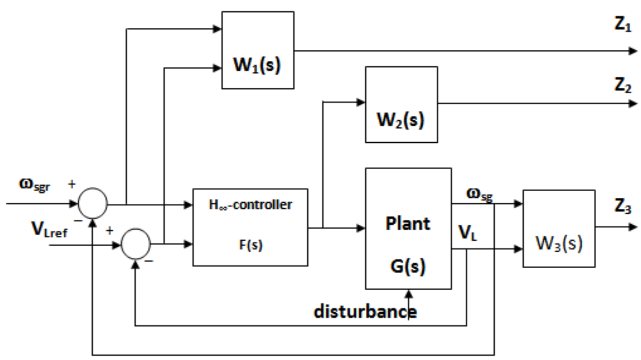

Fig. 4: Simplified block diagram of the augmented plant including H_∞ controller

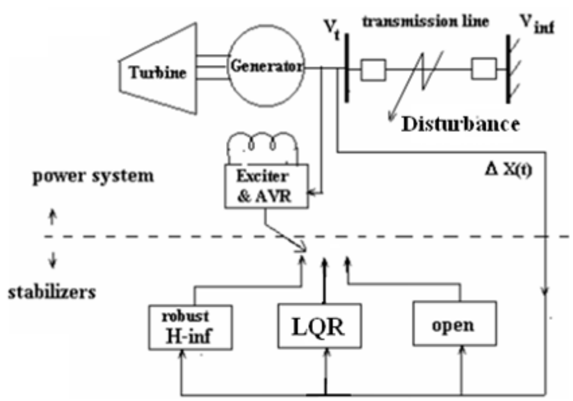

Fig. 5: Schematic diagram of power system model with Hinf power system stabilizers

$$Z_1 = W_1(s)\begin{bmatrix} V_{Lref} - V_L \\ \omega_{sgref} - \omega_{sg} \end{bmatrix} \tag{8}$$

A good choice of the second weight $W_2(s)$ will aid for avoiding actuators saturation and provide robustness to plant additive perturbations. The weighted control function matrix Z_2 can be written as:

$$Z_2 = W_2(s).u(s) \tag{9}$$

where u(s) is the transfer function matrix of the control signals output of the H_∞ controller. Also a good choice of the third weight W_3 (s) will limit the closed loop bandwidth and achieve robustness to plant output multiplicative perturbations and sensor noise attenuation at high frequencies. The weighted output variable can be written as:

$$Z_3 = W_3(s)\begin{bmatrix} V_L \\ \omega_{sg} \end{bmatrix} \tag{10}$$

In summary, the transfer functions of interest which determine the behavior of the voltage and speed closed loop systems are:

- Feedback system which the r (s) is input reference, d (s) is the input disturbance and n (s) is the sensor or measurement noise as shown in Fig. 3. Then, the following fundamental relations:

$$y(s) = \frac{G(s)F(s)}{1+G(s)F(s)}\ r(s) + \frac{1}{1+G(s)F(s)}d(s) - \frac{G(s)F(s)}{1+G(s)F(s)}\ n(s) \tag{11}$$

- **Sensitivity function:**

$$S(s) = [1+G(s)F(s)]^{-1} \tag{12}$$

$$S(s) = \frac{1}{1+G(s)F(s)}$$

where G (s) and F (s) are the transfer functions of the nominal plant and the H∞ controller respectively, and I is the identity matrix. Minimizing S at low frequencies will insure good tracking and disturbance rejection.

- **Control function:**

$$C(s) = F(s)[I+G(s)F(s)]^{-1}$$
$$C(s) = -\frac{G(s)F(s)}{1+G(s)F(s)} \tag{13}$$

Minimizing C will avoid actuator saturation and achieve robustness to plant additive perturbations.

- **Complementary function:**

$$T(s) = I - S$$
$$T(s) = \frac{G(s)F(s)}{1+G(s)F(s)} \tag{14}$$

Minimizing T at high frequencies will insure robustness to plant output multiplicative perturbations and achieve noise attenuation. The sensitivity function, complementary function and control function are shown in Fig. 6. Moreover, Fig. 7 depicts the actual and desired sensitivity function.

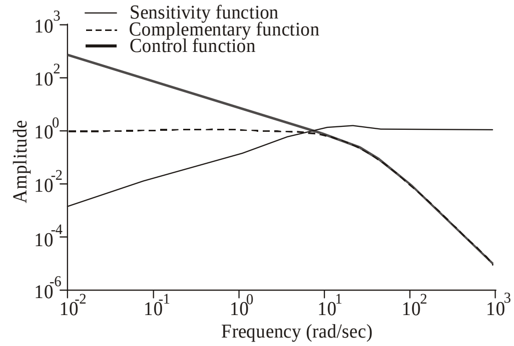

Fig. 6: The sensitivity, complementary and control function of the system

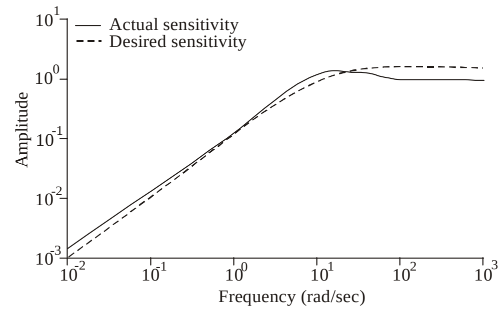

Fig. 7: Actual and desired sensitivity function

RESULTS AND DISCUSSION

The dynamic stability of linearized power system subjected to step disturbances by using the program in MATLAB is proposed by choosing the machine parameters at nominal operating point as:

X_d = 1.6; X_q = 1.55; $X_{d'}$ = 0.32; X_e = 0.4p.u
M = 10; T_{do} = 6; D = 0; T_A = 0.06; K_A = 25
Tt = 0.27; Tg = 0.08; R = 1/(Tg*6.86); ω_o = 377

A, B, matrices are calculated at operating condition (p = 1, Q = 0.25) as follows:

$$A = \begin{bmatrix} 0 & 3770000 & 0 & 0 & 0 & 0 \\ -0.1317 & 0 & -0.1104 & 0.1000 & 0 & 0 \\ -0.2356 & 0 & -0.4630 & 0 & 0 & 0.1667 \\ 0 & 0 & 0 & -3.7037 & 3.7037 & 0 \\ 0 & -6.8600 & 0 & 0 & -125000 & 0 \\ 154703 & 0 & -19.48383 & 0 & 0 & -166667 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5000 \\ 416.6667 & 0 \end{bmatrix}$$

By selecting the weights W_1, W_2 and W_3 to give best performance after 22 iteration in MATLAB program under the tolerance 0.01. The augmented system P(S) can be calculated by calling MATLAB function "*AUGTF*" which contains the plant P(s) where,

$$P(S) = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}$$

The weights W_1, W_2 and W_3 to give best performance as following:

$$W_1(s) = \begin{bmatrix} \dfrac{100S + 0.63}{0.1S + 30} & 0 \\ 0 & \dfrac{100S + 0.63}{S + 300} \end{bmatrix}$$

$$W_2(s) = \begin{bmatrix} \dfrac{50S^2 + 0.3S + 6}{1106S^2 + 166S + 1106} & 0 \\ 0 & \dfrac{1.5S^2 + 2S + 7}{5S^2 + S + 4} \end{bmatrix}$$

$$W_3(s) = \begin{bmatrix} \dfrac{0.1S^2 + 0.107S + 4}{100S^2 + 5000S + 4500} & 0 \\ 0 & \dfrac{0.01S^2 + 0.0725 + 3}{0.1S^2 + 40S + 60} \end{bmatrix}$$

computes the H_∞ controller F(s) and the controller feedback K(s) by using Matlab function H_{inf}. The plant must be stabilizable from the control inputs u_2 and detectable from the measurement output y_2:

- (A,B_2) must be stabilizable
- (C_2,A) must be detectable

After designed the LQR control, the control gain K is:

$$K = \begin{bmatrix} 0.0137 & -0.1547 & 0.0306 & 0.0003 & -0.0115 & 0.0049 \\ -0.0015 & 0.0597 & -0.0041 & -0.0000 & 0.0016 & -0.0003 \end{bmatrix}$$

Solving the H_∞ controller feedback F(s) using U(S) = 0 (default). Also, solving Riccati equations and performing H_∞ existence tests:

1 D_{11} is small enough
State-feedback (P) Riccati A-B2*F is stable
3 Output- injection (S) Riccati A-G*C2 is stable

After applying the robust H_∞ controller to the power system represents in Eq. (7) and using the block diagram shown in Fig. 5, the system can be evaluated with and without proposed controller as follows:

Figure 8 shows the rotor speed deviation response in pu at light load (p = 0.2, Q = 0.0) with and without LQR and H_∞ control. Figure 9 shows the rotor speed deviation response in p.u at normal load (p = 1, Q = 0.25 pu.) with and without LQR and H_∞ control. Figure 10 depicts the rotor speed deviation response in p.u at heavy load (p = 1.2, Q = 0.8 pu.) with and without LQR and H_∞ control. Also the rotor angle deviation response at heavy load (p = 1.2, Q = 0.8 pu.) with and without LQR and H_∞- control

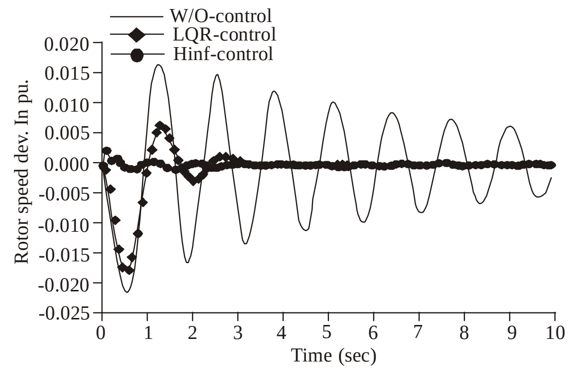

Fig. 8: Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &) controller at (p = 0.2, Q = 0 pu)

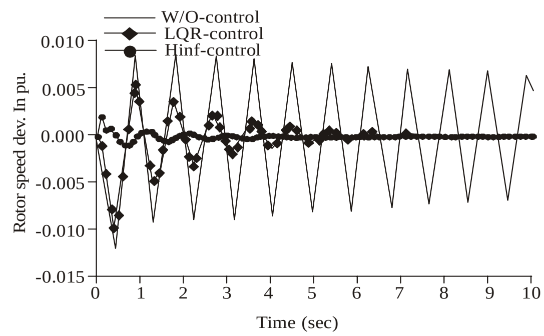

Fig. 9: Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR & H_∞) controller at (p = 1, Q = 0.25 pu)

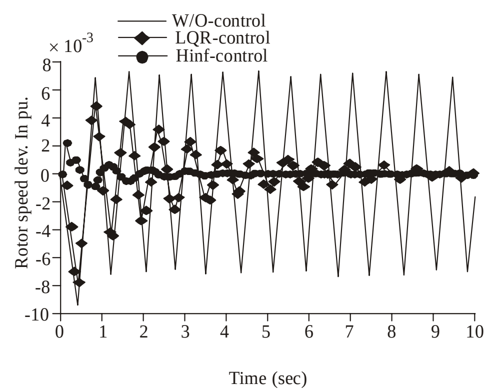

Fig. 10: Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR &) controller at (p = 1.2, Q = 0.8 pu)

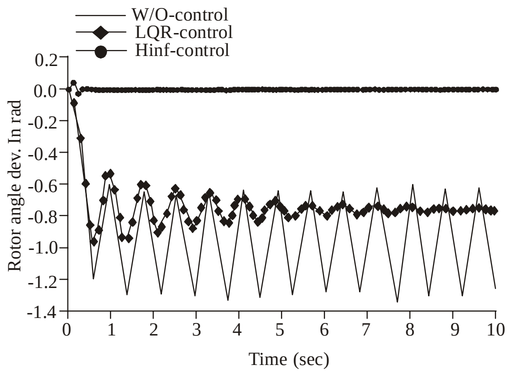

Fig. 11: Rotor angle dev. Response due to 0.05 pu load disturbance with and without (LQR &) controller at (p = 1.2, Q = 0.8 pu)

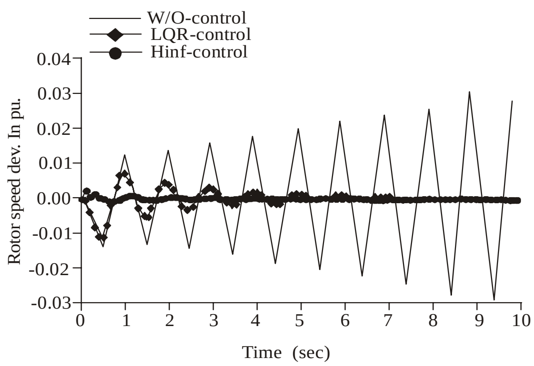

Fig. 12: Rotor speed dev. Response due to 0.05 pu load disturbance with and without (LQR & H_∞) controller at (p = 1, Q = −0.25 pu)

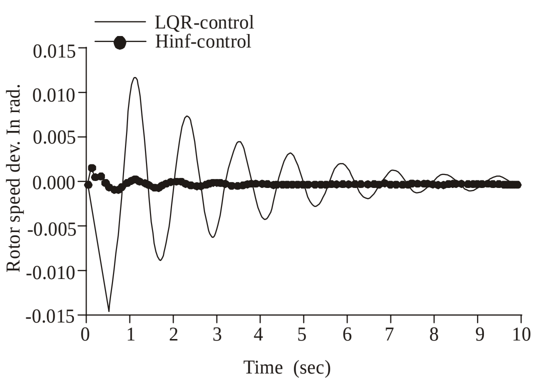

Fig. 13: Rotor speed dev. Response due to 0.05 pu load disturbance with (LQR & H_∞) controller at (p = 0.8, Q = −0.6 pu)

is shown in Fig. 11. Figure 12 shows the rotor speed deviation response in p.u at light lead power factor load (p = 1, Q = -0.25) with and without LQR and H_∞ control. Figure 13 depicts the rotor speed deviation response in p.u at heavy lead power factor load (p = 0.8, Q = -0.6) with LQR and E H_∞ control.

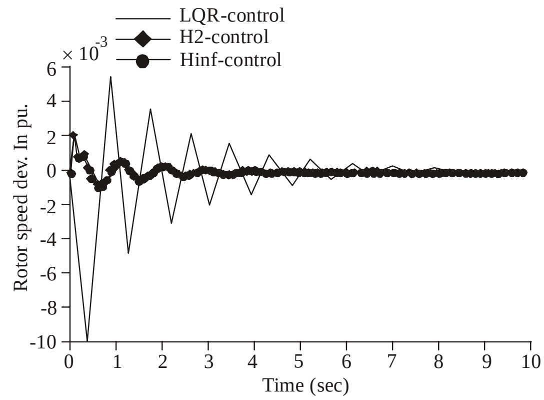

Fig. 14: Rotor speed dev. Response due to 0.05 pu load disturbance with (LQR, and) controllers at (p = 1, Q = 0.25 pu)

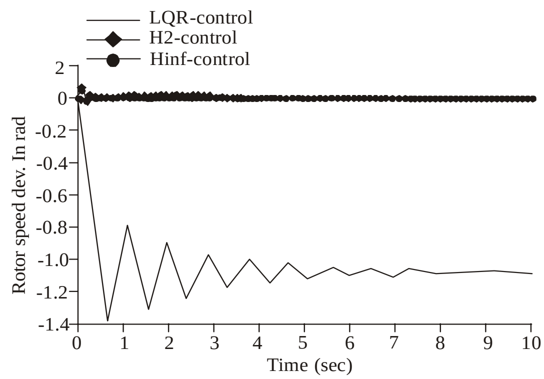

Fig. 15: Rotor angle dev. Response due to 0.05 pu load disturbance with (LQR,H_2 and H_∞) controllers at (p = 1, Q = 0.25 pu)

The rotor speed and rotor angle deviation response in p.u at normal load (p = 1, Q = 0.25 pu) with LQR, H2 and H_∞ control are shown in Fig. 14 and 15, respectively. Moreover, Table 1 describes the eginvalue of the system with and without proposed H_∞ controller. Also, Table 2 depicts the eignvalues of the system compared H2 and proposed H_∞ controller. No change in eignvalues between H2 and H_∞ controller in low frequency operating range

The discussion, from the previous figures, notes that the system is more damping with conventional LQR control at different operating conditions. This means that the system have less overshoot and less settling time compard with system without controller, but the oscillation is increasing with increase the loads until the system become unstable, which illustrate the rotor speed deviation at heavy lead power factor load at (p = 0.8, Q = -0.6 pu). With the results that, the H_2 and H_∞ controllers is presented in this work. Moreover, the system is more damping with H_∞ control at all operating conditions as H_2 controller. H_∞ controller is the better than LQR

Table 1: Eigenvalues calculation with and without (LQR & H_∞) controllers at different operating conditions

Operating point	Without controller	With LQR controller	With H_∞ controller
p = 0.2, Q = 0 pu	-0.1273 + 4.8103i	-13.8650	-398.49
Light load	-0.1273 - 4.8103i	-13.3919	-300.00
	-13.9563	-1.1628+	-300.00
	-12.4806	4.5001i	-13.08 + 30.72i
	-2.9194	-1.1628 -	-13.08-30.72i
	-3.7225	4.5001i	-49.08
		-2.9062 +	-31.53 + 12.63i
		1.4571i	-31.53 - 12.63i
		-2.9062 -	-13.92
		1.4571i	-0.67 + 6.80i
			-0.67 - 6.80i
			-3.21
			-0.08 + 1.00i
			-0.08 - 1.00i
			-0.92
			-1.51
p = 1, Q = 0.25 pu	-0.0367 + 6.9961i	-0.5150 +	-398.49
Normal load	-0.0367 - 6.9961i	7.0572i	-300.00
	-14.2953	-0.5150-	-300.00
	-12.4821	7.0572i	-13.00 + 30.90i
	-2.7625	-14.3045	-13.00 - 30.90i
	-3.7201	-13.1712	-49.08
		-4.0526	-31.35 + 12.69i
		-2.8368	-31.35 - 12.69i
			-14.32
			-00.67 + 6.80i
			-0.67 - 06.80i
			-2.81
			-0.08 + 1.00i
			-0.08 - 1.00i
			-0.92
			-1.51
p = 1.2, Q = 0.25 pu	0.0005 + 7.9973i	-0.3542 +	-398.49
Heavy load	0.0005 - 7.9973i	8.0952i	-300.00
	-14.0016	-0.3542 -	-300.00
	-12.4831	8.0952i	-12.95 + 31.00i
	-3.1312	-14.0297	-12.95 - 31.00i
	-3.7186	-13.1032	-49.08
		-4.5194	-31.25 + 12.73i
		-3.0344 -	-31.25 - 12.73i
			-14.04
			-0.67 + 6.80i
			-0.67 - 6.80i
			-3.09
			-0.08 + 1.00i
			-0.08 - 1.00i
			-0.92
			-1.51

controller . Moreover, there is compared and evaluated between LQR, H_2 and H_∞ controllers which illustrate that the system is more damping with H_2 and H_∞ controllers as shown in Fig. 8-15. Figure 14, 15 and Table 2 display comparison between LQR, $H_2$and H_∞ control at certain operating point, the results exhibited that the H_2 and H_∞ control are identically in low frequency operating point .

SUMMARY, CONCLUSION AND RECOMMENDATIONS

The present study introduces an application for a robust H_∞ controller to design a power system stabilizer. Moreover, the H_∞ control design problem is described and formulated in the standard form with emphasis on the selection of the weighting functions that assured optimal robustness and performance of the oscillation damping. The robust H_2 and H_∞ feedback controller was designed and simulated using the iterative computing MATLAB software. The investigated power system is subjected to disturbances such as speed deviation, input torque and reference voltage disturbances. Power system speed deviation and torque angle deviation responses due to the above disturbances are obtained both with and without proposed H∞ mechanism signal. H_2 controller is designed and compared with H_∞ controller at different low frequency operating conditions. The H_2 controller is

Table 2: Eigenvalues calculation with and without (LQR, H_2 and H_∞) controllers at different operating condition

Operating point	With LQR controller	With H_2 controller	With H_∞ controller
p = 1.0, Q = 0.25 pu	-14.3045	-398.49	-398.49
Light load	-0.5150 +	-300.00	-300.00
	7.0572i	-300.00	-300.00
	-0.5150 -	-13.00 + 30.90i	-13.00 + 30.90i
	7.0572i	-13.00 - 30.90i	-13.00 - 30.90i
	-13.1712	-49.08	-49.08
	-4.0526	-31.35 + 12.69i	-31.35 + 12.69i
	-2.8368	-31.35 - 12.69i	-31.35 - 12.69i
		-14.32	-14.32
		-00.67 + 6.80i	-00.67 + 6.80i
		-0.67 - 06.80i	-0.67 - 06.80i
		-2.81	-2.81
		-0.08 + 1.00i	-0.08 + 1.00i
		-0.08 - 1.00i	-0.08 - 1.00i
		-0.92	-0.92
		-1.51	-1.51
p = 1, Q = -0.25 pu.	-14.9060	-398.49	-398.49
Lead power factor	-13.1803	-300.00	-300.00
	-0.4950 +	-300.00	-300.00
	6.3372i	-13.03 + 30.84i	-13.03 + 30.84i
	-0.4950 -	-13.03 - 3.084i	-13.03 - 3.084i
	6.3372i	-49.08	-49.08
	-2.2020	-31.41 +12.67i	-31.41 +12.67i
	-4.1167	-31.41 - 12.67i	-31.41 - 12.67i
		-15.01	-15.01
		-0.67 + 6.80i	-0.67 + 6.80i
		-0.67 - 6.80i	-0.67 - 6.80i
		-0.08 + 1.00i	-0.08 + 1.00i
		-0.08 - 1.00i	-0.08 - 1.00i
		-2.12	-2.12
		-0.92	-0.92
		-1.51	-1.51
p = 0.8, Q = -0.6 pu.	-15.7666	-398.49	-398.49
Heavy lead power factor	-13.2084	-300.00	-300.00
	-0.3335 +	-300.00	-300.00
	5.2332i	-13.07+30.75i	-13.07+30.75i
	-0.3335 -	-13.07+30.75i	-13.07-3075i
	5.2332i	-31.49+12.65i	-31.49+12.65i
	-3.8501	-31.49-2.65i	-31.49-2.65i
	-1.9029	-49.08	-49.08
		-1595	-15.95
		-0.67 + 6.80i	-.067+680i
		-0.67 - 6.80i	-0.67-680i
		-0.08 + 1.00i	-0.08+1.00i
		-0.08 - 1.00i	-0.08-1.00i
		-1.18	-1.18
		-0.0092	-0.0092
		-0.0151	-0.0151

symmetrical and identical of H_∞ controller in state responses and eigenvalues in low frequency operating range. The digital simulation results validate the effectiveness and power of the proposed power system stabilizer based on H_∞ controller in terms of fast power system mechanical oscillation damping over a wide range of operating conditions.

REFERENCES

Abido, M.A., 2000. Pole placement technique for PSS and TCSC based stabilizer design using simulated annealing. Elect. Power Energ. Syst., 22: 543-554.

Bouhamida, M., A. Mokhtari and M.A. Denai, 2005. Power system stabilizer design based on robust control techniques, ACSE J., 5(3): 33-41.

Ho, M.T., A. Datta and S.P. Bhattacharyya, 1997. A linear programming characterization of all stabilizing PID controllers. In: Proceedings of the American Control Conference. Albuquerque, New Mexico, p: 3922-3928.

Gt, T. and T. Sk, 1993. Refinement of conventional PSS design in multimachine system by modal analysis. IEEE Trans. PWRS, 8(2): 598-605.

Grimble, M.J., 1997. New direction in adaptive control theory and applications. IFAC-IFIP-IMACS Conf., Control of industrial systems, Belfort, France, pp: 95-110.

Hardiansyah, S.F. and J. Irisawa, 2005. LMI-based robust H_2 control design with regional pole constraints for damping power system oscillations. Europ. Transact. Elect. Power, 15(1): 13-29.

Qi, J., J. Quanyuan, W. Guangzeng and C. Yijia, 2005. Wide-area time-delay robust damping control for power system. Europ. Transact. Elect. Power, 19(7): 899-910.

Kassem, A. and A. Yousef, 2008. Robust h∞ control design and dynamic performance analysis of an isolated diesel-generation unit. J. Elect. Eng. Romania, 8(3): 39-46.

Khargonekar, P.P. and I.R. Petersen and M.A. Rotea, 1988. Hinf optimal control with state feedback. IEEE Trans. Automat. Contr., AC-33, pp:783-786.

Kwakernaak, H., 1986. A Polynomial Approach to H_∞ Optimization of Control Systems in Modeling, Robustness and Sensitivity Reduction. Ruth F. Curtain, Springer, Berlin, pp: 83-94.

Ramos, R.A., A.C.P. Martins and N.G. Bretas, 2005. An improved methodology for the design of power system damping controllers. IEEE Trans. Power Syst., 20(4): 1938-1945.

Safonov, M.G., A.J. Laub and G. Hartmann, 1981. Feedback properties of multivariable systems: The role and use of return difference matrix. IEEE Trans. Automat. Contr., AC-26 pp: 47-65.

Shayeghi, H., H.A. Shayanfarb, S. Jalilzadehc and A. Safaric, 2010. TCSC robust damping controller design based on particle swarm optimization for a multi-machine power system. Energ. Convers. Manag., 51: 1873-1882.

Tantaris, R.N., L.H. Keel and S.P. Bhattacharyya, 2006. H_∞ design with first order controllers. IEEE Trans. Automat. Contr., 51: 1343-1347.

Yinya, L., S. Andong and W. Yuangang, 2008. Synthesis of PID-type controllers without parametric models:A graphical approach. Energ. Convers. Manag., 49: 2392-2402.

Yousef, A.M. and A. Abdel-Fatah, 2005. A robust H_∞ synthesis controller for power system stabilization." Autom. Cont. Syst. Eng. (ACSE) J., 05(2): 1-6. ISSN 1687-4811.