Robust Design of a SVC Controller to Improve Damping Power System Low Frequency Oscillations Considering Time Delay of Feedback Signals

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Received May 2013 Revised August 2013 Accepted Dec. 2013

ABSTRACT:
This paper presents the design of Static var compensator (SVC) controller for damping power system low frequency oscillations considering delayed arrival of feedback signals. The controller is designed based on H∞ mixed-sensitivity method and the controller parameters are resolved by the Linear Matrix Inequality (LMI) technique. The designed controller is applied on a Single machine infinite bus (SMIB) system model. The computer simulations are performed for pulse disturbance as well as system operating changes and the results show improvement of damping in low frequency oscillations and keeps robustness with load variations. It was founds that time delay has significant influence to damping power system oscillations, especially when the time lag is large. Therefore, for reduce effect of time delay, the robust controller is designed considering time delay of feedback Signals.

KEYWORDS: Low frequency oscillations, Linear Matrix Inequality (LMI), Robust control, Static var compensator (SVC), Time delay.

1. INTRODUCTION

Low frequency oscillations (LFO) in the range of 0.1Hz to 3Hz are frequent adverse phenomenon which increase the risk of instability for the power system and thus reduce the total and availability transfer capability [1], [2]. These oscillations occur due to inadequate damping torque in the mechanical mode of some generators [3].
Power system stabilizers (PSS) have been widely used in practice to enhance the damping of such oscillations [4]. However, this device may not produce adequate damping during some operating conditions [5].
Recent development of power electronics introduces the use of Flexible AC Transmission Systems (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system [6]. Static var compensators (SVC) are a kind of FACTS devices and have been employed to an increasing extent since dynamic reactive power control gives considerable advantages for power system operation. Besides to the voltage control as a main task SVC may also be employed for additional tasks resulting in improvement of damping power oscillations [7].
The conventional damping controller design synthesis is simple but tends to lack of robustness even after careful tuning [8]. Robust control technique has been applied to power system controller design to guarantee robust performance and robust stability, due to uncertainty in plant parameter variations[9].
One of the methods recently used to provide a supplementary control signal of FACTS devices for small disturbance rejection is the H∞ control. H∞ is a method used to design a controller by minimizing the disturbance effect on the system outputs. The H∞ problem has been solved using the Linear Matrix Inequality (LMI) technique [10].
Time delays are present in many physical systems. These time delays influence the stability of the systems and might degrade the performance of the system, hence they should be properly considered in the controller design [11].
In this paper, the H∞ mixed-sensitivity based LMI approach considering signals transmission delay has been applied to design SVC controller for damping low

frequency oscillations in a sixth order single machine infinite bus (SMIB) system.
The simulation results show the designed controller can be improve damping low frequency oscillations in various condition of loading and it take the power system stable under impulse disturbance. According to simulations, it is found that the overshoot value of active power variation increases and the settling time is lengthened when time delay occurs and the closed-loop control system may become unstable when the time delay is over a certain value. Therefore, for reduce effect of time delay, the robust controller is designed considering time delay of feedback Signals.

2. POWER SYSTEM MODELING

2.1. Single machine infinite bus system

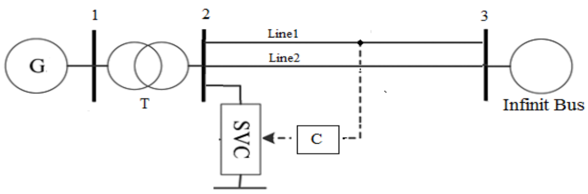


Fig.1. Single machine infinite bus system installed with SVC

The schematic diagram of the study system of this work, i.e. the single machine infinite bus system without automatic voltage regulator (AVR) and power system stabilizer is shown in Fig. 1. The generator is described by the sixth order (sub transient) model with electromechanical equations, rotor winding, one damper winding in direct axis and two damper winding in the quadrature axis. The nonlinear equations governing dynamic behavior of generator is given by [13].

$$\dot{\delta} = \omega_b(\omega - 1) \tag{1}$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1))/M \tag{2}$$

$$\dot{e}'_q = (-e'_q - (x_d - x'_d + \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d))i_d + (1 - \frac{T_{AA}}{T'_{d0}}v_f))/T'_{d0} \tag{3}$$

$$\dot{e}'_d = (-e'_d - (x_q - x'_q - \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q))i_q)/T'_{q0} \tag{4}$$

$$\dot{e}''_q = (-e''_q + e'_q - (x'_d - x''_d + \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d))i_d + \frac{T_{AA}}{T'_{d0}}v_f)/T''_{d0} \tag{5}$$

$$\dot{e}''_d = (-e''_d + e'_d - (x'_q - x''_q + \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q))i_q)/T''_{q0} \tag{6}$$

Where

$$P_e = (v_q + r_a i_q)i_q + (v_d + r_a i_d)i_d \tag{7}$$

And the following relationships between voltages and currents hold:

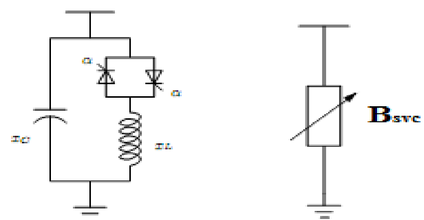
$$0 = v_q + r_a i_q - e''_q + (x''_d - x_l)i_d \tag{8}$$

$$0 = v_d + r_a i_d - e''_d - (x''_q - x_l)i_q \tag{9}$$

Description of the equations variables and the nominal parameters of generator, transformer and lines are given in Appendix1.

2.2. SVC

SVC is basically a shunt connected static var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables [14].
The admittance is varied using a thyristor-based switch, as shown in Fig. 2.



(a) (b)

Fig. 2. SVC scheme: (a) firing angle model and (b) equivalent susceptance model

A common approximation consists in assuming that the controlled variable is B_{svc} and not the firing angle α (see fig.1) [2] and following differential equation holds [10]:

$$\dot{B}_{svc} = (K_{R_1}(V_{ref} - V_m) - B_{svc})/T_{R_1} \tag{10}$$

Where $T_{R_1}, K_{R_1}, V_{ref}$ and V_m the SVC time constant, gain, reference voltage and measured voltage, respectively. This model is completed by the algebraic equation expressing the reactive power injected at the SVC node:

$$Q = B_{svc}V^2 \tag{11}$$

3. CONTROLLER DESIGN

3.1. $H\infty$ Mixed Sensitivity

The mixed sensitivity formulation for output disturbance rejection and control effort optimization is shown in fig.3 where G(s) is open loop system model, K(s) is the controller to be designed, $W_1(s)$ and $W_2(S)$ are associated weight function [5]. For minimizing the impact of any disturbance on the measured output and to optimize the control effect within a limited bandwidth, it is required to minimize H∞ norm of transfer function between the disturbance input *w* and the measured output y(s) [10,15]. Thus the minimization problem can be summarized as follows:

$$\underset{K\in S}{Min}\left\|\begin{bmatrix} S \\ KS \end{bmatrix}\right\|_{\infty} \quad \text{or} \quad \underset{K\in S}{Min}\left\|\begin{bmatrix} T_{yd} \\ T_{ud} \end{bmatrix}\right\|_{\infty} \tag{12}$$

Where S is sensitivity function.

Normally in $H\infty$-Mixed-sensitivity method, weights are applied on (13) and the aim of the controller design is to find a controller K(S) from a set of internally stabilizing controller such that [5]:

$$\underset{K\in S}{Min}\left\|\begin{bmatrix} W_1 T_{yd} \\ W_2 T_{ud} \end{bmatrix}\right\|_{\infty} \langle \gamma \quad \text{or} \quad \underset{K\in S}{Min}\left\|T_{wz}\right\|_{\infty} \langle \gamma \tag{13}$$

Where γ is the bound on H_∞ norm?

The standard practice, therefore, is to select $W_1(s)$ as an appropriate low pass filter for output disturbance rejection and $W_2(s)$ as a high-pass filter to reduce the control effort over the high frequency range [15].

A modified plant G(s) which includes the weighting function and a controller which is to be obtained by H_∞ optimization, is shown in Fig 4.

The state space description of G(s) is

$$\begin{bmatrix} \dot{x} \\ z \\ y \end{bmatrix} = \begin{bmatrix} A & B_w & B_u \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}\begin{bmatrix} x \\ w \\ u \end{bmatrix} \tag{14}$$

Where

x: state variable vector w: disturbance input

u: control input y: measured output

z: regulated output

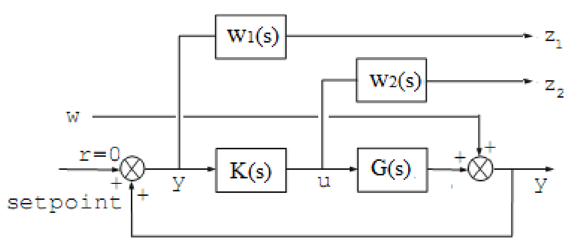


Fig. 3. Mixed-sensitivity formulation

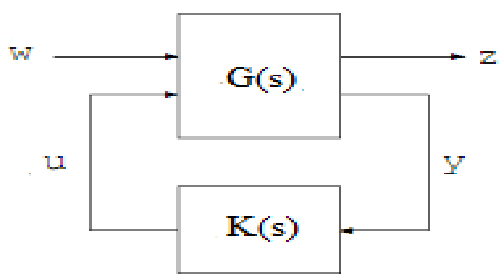


Fig. 4. Closed-loop system via $H\infty$ control

3.2. Generalized $H\infty$ Problem in Power System

In power systems, the entries of the D_{22} matrix are zero as there is no direct influence of the control input on the FACTS device by the measured signals [14] and due to the nature of the disturbance considered such as mechanical power of generator or real power of load, there is no direct effect of disturbance on the power system output i.e D_{21} is equal to zero [10]. The disturbed plant with FACTS devices and $H\infty$ controller K(s) is shown in Fig. 5.

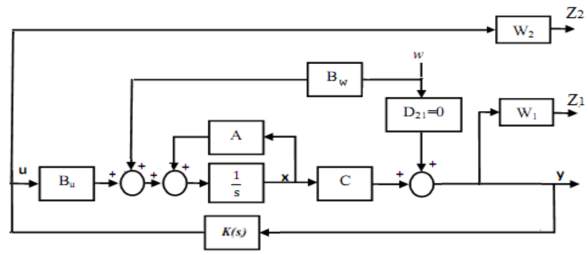


Fig. 5. Schematic diagram of the disturbed plant with controller

For $H\infty$ controller design its necessary to find an LTI control law $u=K(s)y$, for some $H\infty$ performance $\gamma\rangle 0$ such that $\|T_{wz}\|\langle\gamma$. If the state space representation of LTI controller in given by [10], [15]:

$$\begin{bmatrix} \dot{x}_k \\ u \end{bmatrix} = \begin{bmatrix} A_k & B_k \\ C_k & D_K \end{bmatrix}\begin{bmatrix} x_k \\ y \end{bmatrix} \tag{15}$$

Then the closed-loop transfer $T_{wz}(s)$ from w to z is given by:

$$T_{wz} = D_{cl} + C_{cl}(SI - A_{cl})^{-1}B_{cl} \tag{16}$$

Where

$$A_{cl}\Big|_{D_{21}=0} = \begin{pmatrix} A + B_u D_k C_2 & B_u C_k \\ B_k C_2 & A_k \end{pmatrix} \tag{17}$$

$$B_{cl}\Big|_{D_{21}=0} = \begin{pmatrix} B_w + B_u D_k D_{21} \\ B_k D_{21} \end{pmatrix} \tag{18}$$

$$C_{cl} = \begin{pmatrix} C_1 + D_{12} D_k C_2 & D_{12} C_k \end{pmatrix} \tag{19}$$

$$D_{cl}\Big|_{D_{21}=0} = \begin{pmatrix} D_{11} + D_{12} D_k D_{21} \end{pmatrix} \tag{20}$$

3.3. LMI Formulation

The bounded real lemma and Schur's formula for the determinant of a partitioned matrix, enable one to conclude that the $H\infty$ constraint $\|T_{wz}\|_{\infty}\langle\gamma$ is equivalent to the existence of a solution $X_\infty = X_\infty^T\rangle 0$ to the following matrix inequality [23]:

$$\begin{pmatrix} A_{cl}X_{\infty} & B_{cl} & X_{\infty}C_{cl}^{T} \\ B_{cl}^{T} & -\gamma I & D_{cl}^{T} \\ C_{cl}X_{\infty} & D_{cl} & -\gamma I \end{pmatrix} \langle 0 \qquad (21)$$

The inequalities in (22) contains $A_{cl}X$ and $C_{cl}X$, i.e. products of X and the controller variables. This problem is therefore nonlinear in X.A change of controller variables is necessary to convert this problem into a linear one [5]. Let X and X^{-1} be partitioned as:

$$X = \begin{pmatrix} R & M \\ M^{T} & U \end{pmatrix}, \quad X^{-1} = \begin{pmatrix} S & N \\ N^{T} & V \end{pmatrix} \qquad (22)$$

For $\prod_1 = \begin{pmatrix} R & I \\ M^{T} & 0 \end{pmatrix}$, $X^{-1} = \begin{pmatrix} I & S \\ 0 & N^{T} \end{pmatrix}$ and X satisfies the identity $X\prod_2 = \prod_1$.

The new controller variables are defined in (24)-(27).

$$\hat{A} = NA_K M^{T} + NB_K C_2 + SB_2 C_K M^{T} + S(A + B_2 D_K C_2)R \qquad (23)$$

$$\hat{B} = NB_K SB_2 D_K \qquad (24)$$

$$\hat{C} = C_K M^{T} + D_K C_2 R \qquad (25)$$

$$\hat{D} = D_K \qquad (26)$$

The identity together with (23) gives:

$$MN^{T} = I - RS \qquad (27)$$

If M and N have full row rank, then given $\hat{A},\hat{B},\hat{C},\hat{D},R,S,M$ and N. Moreover, the controller matrices can be determined uniquely if the controller order is chosen to be equal to that of the generalized regulator.

Pre- and post-multiplying each of the inequalities i.e. the inequality $X\rangle 0$ by $\prod_2^{T}$ and $\prod_2$, and also pre- and post-multiplying the inequality (21) by $diag(\prod_2^{T}, I, I)$ and $diag(\prod_2, I, I)$ respectively, followed by a change of variables according to (23)-(26), the following LMIs are obtained [23]:

$$\begin{pmatrix} R & I \\ I & S \end{pmatrix} < 0 \ , \quad \begin{pmatrix} \psi_{11} & \psi^{T}{}_{12} \\ \psi_{21} & \psi_{22} \end{pmatrix} < 0 \qquad (28)$$

Where

$$\psi_{11} = \begin{bmatrix} AR + RA^{T} + B_2\hat{C} + \hat{C}^{T}B_2 & B_1 + B_2\hat{D}D_{21} \\ (B_1 + B_2\hat{D}D_{21})^{T} & -\gamma I \end{bmatrix} \qquad (29)$$

$$\psi_{21} = \begin{bmatrix} \hat{A} + (A + B_2\hat{D}C_2)^{T} & SB_1 + \hat{B}D_{21} \\ C_1 R + D_{12}\hat{C} & D_{11} + D_{12}\hat{D}D_{21} \end{bmatrix} \qquad (30)$$

$$\psi_{22} = \begin{bmatrix} A^{T}S + SA + \hat{B}C_2 + C_2^{T}\hat{B}^{T} & (C_1 + D_{12}\hat{D}C_2)^{T} \\ C_1 + D_{12}\hat{D}C_2 & -\gamma I \end{bmatrix} \qquad (31)$$

The system of LMIs in (29) are solved for $\hat{A},\hat{B},\hat{C},\hat{D},R,S,M$ and N and With known these values he system of linear equations (24)-(27) can be solved for A_K, B_K, C_K and D_K in that order. The controller K is obtained and the resultant controller satisfies $\|T_{wz}\|_{\infty} \langle \gamma$.

3.4. Delay Time

In a dead-time system, either the measured output takes certian time before it effects the control input or action of the control input takes certain time before influences the measured outputs[15], [16]. Usually the time delay between the instant of measurement being taken and the controller is considered the range of 150-300ms [17], depending on distance, protocol of transmission and several other factors [16]. So, in the design of a robust damping controller, selection of the appropriate input and output signal to controller is a main issue [18].

In this work time delay is modelled by Padé approximation. In the pade approximation, time delay is modeled in laplace domain, as $e^{-\tau s}$ and the transformed into rational transfer function for inclusion in the linearized power system [19-21].

The state space of 1^{st} order pade approximation is:

$$\begin{bmatrix} \dot{x}_{\tau in} \\ u_k \end{bmatrix} = \begin{bmatrix} A_{in} & B_{in} \\ C_{in} & D_{in} \end{bmatrix} \begin{bmatrix} x_{\tau in} \\ y \end{bmatrix} \qquad (34)$$

$$\begin{bmatrix} \dot{x}_{\tau out} \\ u \end{bmatrix} = \begin{bmatrix} A_{out} & B_{out} \\ C_{out} & D_{out} \end{bmatrix} \begin{bmatrix} x_{\tau out} \\ y_k \end{bmatrix} \qquad (35)$$

The closed-loop feedback control system with time delay is shown in fig.6[10,17].

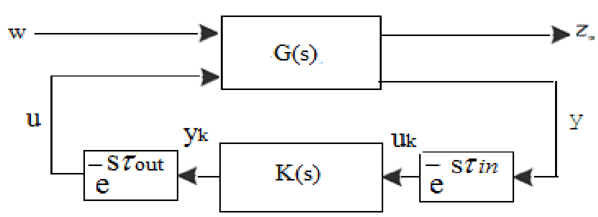


Fig. 6. The closed-loop feedback control system with time delay

Where τ_{in} and τ_{out} are time delay of input signal to controller and time delay of input signal from controller, respeatially.

4. SIMULATION RESULT

Fig. 1 shows the one line diagram of a SMIB system with a SVC installed on bus 2. To small signal analysis and design the SVC controller, SMIB system with SVC is linearized around operating conditions.

The modal analysis results show that there is one low frequency mode that TABLE I show eigenvalues of the linear power system.

The objective of designing a robust controller is increase damping ratio of low frequency oscillations and to make the system stable at extreme operating conditions and applying disturbance.

In this work, ΔP_m and ΔP_{Line1} are selected as input disturbance w and measured output y, respectively.

Table 1. Eigenvalues of Study Power System

Eigenvalues	Damping ratio	Frequency oscillations
-36.7095	0	0
-22.1919	0	0
-0.3118 + 8.3294	0.03	1.32Hz
-8.91	0	0
-2.158	0	0
-0.037	0	0

As mentioned earlier(section 4), the standard practice in $H\infty$ mixed-sensitivity design is to choose the weight $W_1(s)$ as an appropriate low pass filter and $W_2(s)$ as a high-pass filter, so the selected weight functions for SVC controller design is given as follows:

$$W_1 = \frac{5}{s+5} \quad , \quad W_2 = \frac{2s}{s+25}$$

The design problem carried out with the function *hinfmix* which is available in the LMI toolbox of MATLAB [23].

Small signal analysis and time response of linear closed-loop system is used to verify the performance of the controller. The damping ratio of low frequency mode is improved to 0.62 under closed-loop conditions and Fig. 8 and fig.9 show the frequency and impulse response of the sensitivity function i.e. from the disturbance ΔP_m to the output ΔP_{Line1} and the active power response of generator to impulse disturbance is shown in Fig. 10.

It can be seen the magnitude of the frequency response of the closed loop system is reduced.

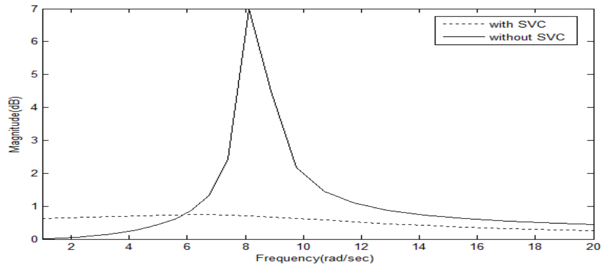


Fig. 8. Frequency response of open loop system and closed-loop system for the sensitivity function

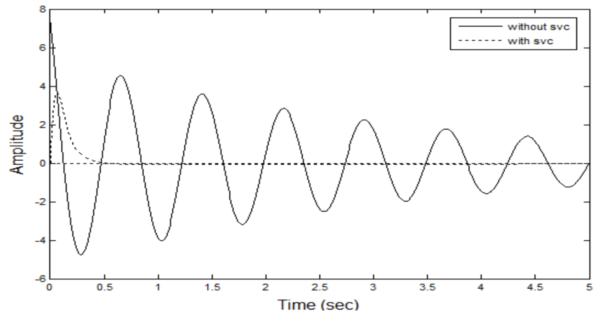


Fig. 9. Impulse response of open loop system and closed-loop system for the sensitivity function

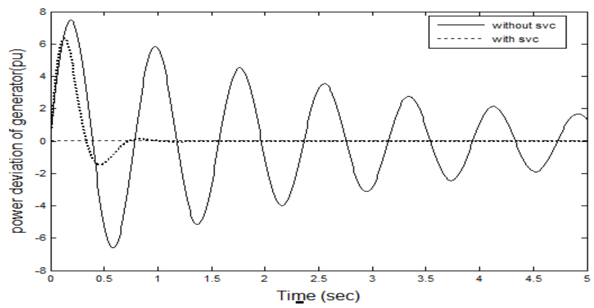


Fig. 10. The active power response of generator to impulse disturbance

The performance of the system under different operating conditions (nominal/heavy loading) are considered and verified with proposed SVC controller, and power deviations of generator is shown in Fig. 11.

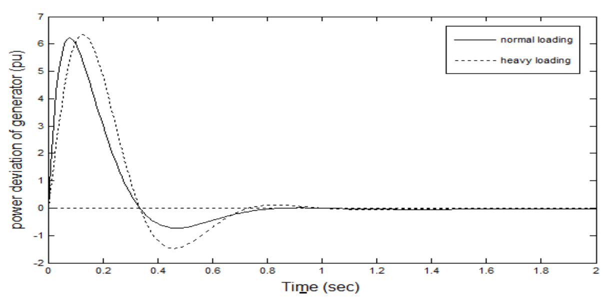


Fig. 11. The power response of generator to impulse disturbance

Fig. 12 shows that without modeling time-delays in the controller design procedure, the system is unstable when time-delays are larger than 20 ms.

In order to reduce the effect of signal time delay and increasing stability, the controller is designed considering delay of 100ms for input and output signal. Fig. 13 and fig.14 show the dynamic response of the system with the designed damping controller for mechanical power input disturbances for different time delays.

The result show that the overshoot and settling time of active power deviations increase when time delay increases and the system led to bad frequency response during low frequency mode.

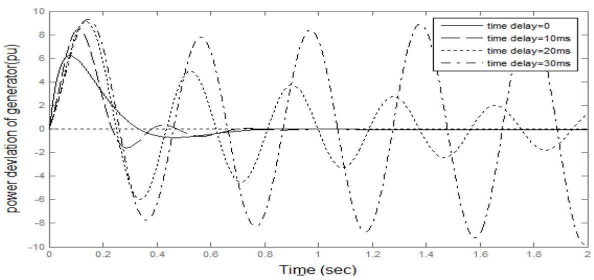


Fig. 12. The active power response of generator to impulse disturbance without considering time delay in the controller design

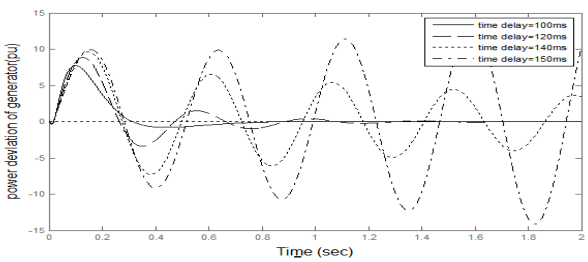


Fig. 13. The active power response of generator to impulse disturbance with considering time delay

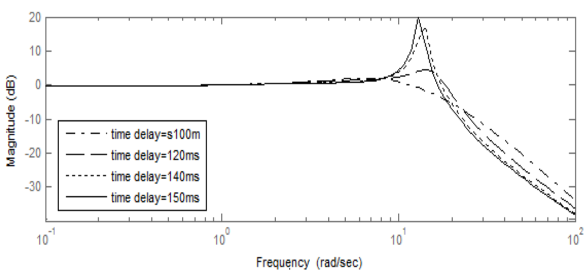


Fig. 14. Frequency response of closed- loop system with different time delay

5. CONCLUSION

In this paper The H∞ mixed-sensitivity based LMI approach considering transmission delay signals has been applied to design SVC controller for damping low frequency oscillations. Power deviation of lines is considered as feedback signal to the controller design and time delay is modeled by 1^{st} order pade approximation. A Single Machine Infinite Bus (SMIB) system is considered to illustrate the effectiveness and robustness of the proposed controller over a wide range of operating conditions. The simulation results indicate that the designed controller can play an effective part in damping low frequency oscillation and represent good robustness under various operating conditions of loading. When the time delay is added to the study system, it is found that overshoot for active power increases and the settling time is lengthened. The system may become unstable when the time delay exceeds a threshold level. Therefore, for reduce effect of time delay, the robust controller is designed considering time delay of feedback Signals.

Appendix

The parameter of the system and nominal/heavy loading operating conditions are presented in Table1.

Table 2. System Parameter and Operating Conditions

Parameters	Description	Values(pu)
	Generator Parameters	
x_d	d-axis synchronous reactance	1.81
x'_d	d-axis transient reactance	0.3
x_q	q-axis synchronous reactance	1.76
x'_q	q-axis transient reactance	0.65
x''_d	d-axis subtransient reactance	0.23
x''_q	q-axis subtransient reactance	0.25
x_l	Leakage reactance	0.15
R_a	Armature resistance	0.003
T'_{d0}	d-axis open circuit transient time constant	8
T'_{q0}	q-axis open circuit transient time constant	1
T''_{d0}	d-axis open circuit subtransient time constant	0.03
T''_{q0}	q-axis open circuit subtransient time constant	0.07
D	Damping coefficient	0
M=2H	Mechanical starting time (2 × inertia constant)	7
ω_b	Based rotor speed	377(rad/s)
T_{AA}	d-axis additional leakage time	0

	constant	
Transformer Parameters		
R	Resistance	0
X	Reactance	0.15
Lines Parameters		
Line1		
R	Resistance	0
X	Reactance	0.5
Line2		
R	Resistance	0
X	Reactance	0.93
Operating conditions of loading		
	P(pu)	Q(pu)
Nominal loading	1	0.49
Heavy loading	1.22	0.63

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