WIDE-AREA TCSC CONTROLLER DESIGN IN CONSIDERATION OF FEEDBACK SIGNALS' TIME DELAYS

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Abstract – Recent technological advances in the area of wide-area measurement system (WAMS) has enabled the use of a combination of measured signals from remote locations for centralized control purpose. However, the impact of time delays introduced by remote signal transmission and processing in WAMS has to be considered. This paper investigates the wide-area controller design problem of power system in the presence of output feedback delays in WAMS. Firstly, an example of single-machine infinite bus power system is given to demonstrate the negative effects of feedback signals' time delays of WAMS on the dynamic performances of Thyristor Controlled Series Compensator (TCSC). In order to eliminate the negative effects of time delays, a novel approach based on linear matrix inequality (LMI) technique and Hankel model order-reduced algorithm is proposed to design an effective TCSC controller. New England test power system (NETPS) is presented to verify that the derived TCSC controllers can stabilize the systems for various time delays.

Keywords: Linear matrix inequality (LMI), Thyristor Controlled Series Compensator (TCSC), time delay, wide area measurement system (WAMS).

1 INTRODUCTION

Due to the large scale and intricate structure of modern power system, the demand for structuring wide-area measurement systems (WAMS) has been increasing. WAMS provides a dynamic coverage of the wide-area power network and are also able to handle cascaded outages through coordinated and optimized stabilizing actions. Emerging techniques such as computer technology, communication technology and PMU technology are being used in WAMS and form the basis for real-time dynamic monitoring, on-line security assessment and wide-area stability control of power system [1, 2, 3]. It can be concluded that WAMS will play a vital role for interconnected power system in the next decades.

Communication links used by WAMS include both wired (telephone lines, fiber-optics, power lines) and wireless (micro-wave, satellites) options. The propagation delay is dependent on the medium characters and the physical route distance in WAMS. For a local controller, the time delay of feedback signals is very small (less than 10ms), so the small time delay is often ignored in the controller design and stability analysis. However, for a wide-area controller, the time delay in an interconnected power system can vary from tens to several hundred milliseconds or more. An experimental research in [4] has shown that the time delays caused by different communication links are different from each other, but all of the delays are more than 100 ms. In the case of satellite link, the propagation delay could be as high as above 700 ms. In the Boneeville Power Administration (BPA) system, the time delay of fiber optic digital communication has been reported as approximately 38ms for one way, while time delay using modems via microwave is over 80ms. The delay of communication system that entail satellites may have several hundreds of ms. There could be a larger delay when a large number of signals are to be routed and remote signals from different areas are waiting for synchronizing. Such large time delays can invalidate many controllers that work well in no delayed-input systems and even cause disaster accidents [5].

The impact of time delay on controller performance has been ignored for a long time in power systems, but it will become a significant topic in the wide-area control. Recent studies demonstrate the time delay effects to wide-area PSS and SVC controller [6,7]. In this paper, the interconnected power system is firstly modeled as a time-delay differential dynamic system. Then, an approach combined with LMI technique and Hankel model order-reduced algorithm is presented to design a wide-area TCSC controller. More precisely, the interest here is to find a delay-output feedback TCSC controller such that the power system closed-loop is asymptotically stable for any delay less than a given value. This paper is organized as follows: firstly, the effects of time delay in WAMS on the dynamic performance of power system are analyzed. Then, a TCSC controller considering time delay of the feedback signals is designed by LMI technique. Finally, simulation results are used to verify the validity of the derived TCSC controller under different feedback delays.

2 THE IMPACT OF TIME DELAYS ON TCSC CONTROLLER

From mathematical viewpoint, the interconnected power system including WAMS delays is a typical nonlinear and time-delay differential dynamical system. Commonly, the stability analysis and control of dynamical systems with delays are more complex and difficult than ordinary differential systems. In the traditional power system analysis, controller designs are usually based on local signals and their time delay is small enough to be ignored. In the wide area system, the stability analysis and control of power system rely on the acquisition, transmission and action of some key signals from the communication system. The reliability and time lag of the communication system have a vital effect on real-time on-line control. In order to consider the effect of WAMS on the dynamic performance of the power system, non-linear differential equations with delays should be used. The following example shows that delays in the feedback signals can lead to instability of the system even if the controller works well for the no time delay system.

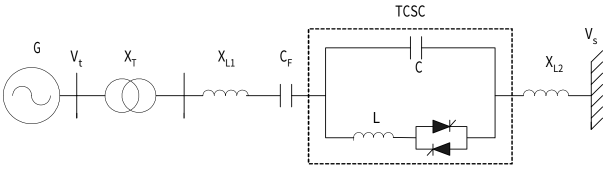


Figure 1: Single machine infinite bus power system with a TCSC

Figure 1 describes a single-machine infinite-bus (SMIB) system with a TCSC. TCSC is modeled as a controlled capacitor whose reactance is limited to the range of [-0.2, 0.2]. The system parameters are given as follows: transmission line and transformer: $x_T = 0.1$, $x_{L1} = 0.4$, $x_{L2} = 0.6$. Generator: $x_d = 1.2$, $x_d' = 0.2$, $x_q = 1.2$, $x_q' = 0.1$, $M = 6.0$, $T_{d0}' = 10.0$. The following non-linear equations are used to denote the system:

$$\begin{cases} \dot{\delta} = \omega_0(\omega - 1) \\ \dot{\omega} = (T_m - T_e)/M \\ \dot{E}_q' = \left[E_{fd} - E_q' - (x_d - x_d')i_d\right]/T_{d0}' \\ \dot{E}_{fd} = [K_e(V_{ref} - V_t) - E_{fd}]/T_e \end{cases} \tag{1}$$

where $T_e \approx P_e = \dfrac{E_q' V_0 \sin\delta}{x_e + x_d'} + \dfrac{(x_d' - x_q)V_0^2 \sin 2\delta}{2(x_e + x_d')(x_e + x_q)}$,

$i_d = \dfrac{E_q' - V_0 \cos\delta}{x_e + x_d'}$, $i_q = \dfrac{V_0 \sin\delta}{x_e + x_q}$,

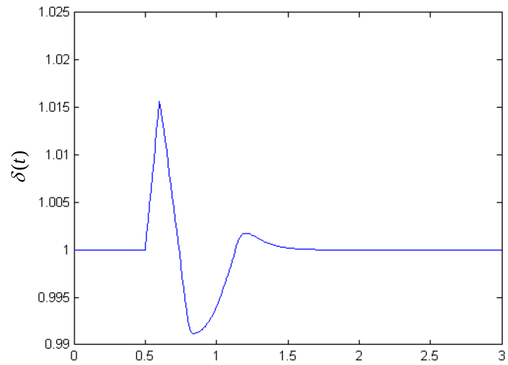
$x_e = x_T + x_{L1} + x_{L2} - x_c$, $V_d = x_q i_q$, $V_q = E_q' - x_d' i_d$,

$$V_t = \sqrt{\left(\frac{x_q}{x_e + x_q} V_0 \sin\delta\right)^2 + \left(\frac{x_e}{x_e + x_d'} E_q' + \frac{x_d'}{x_e + x_d'} V_0 \cos\delta\right)^2}$$

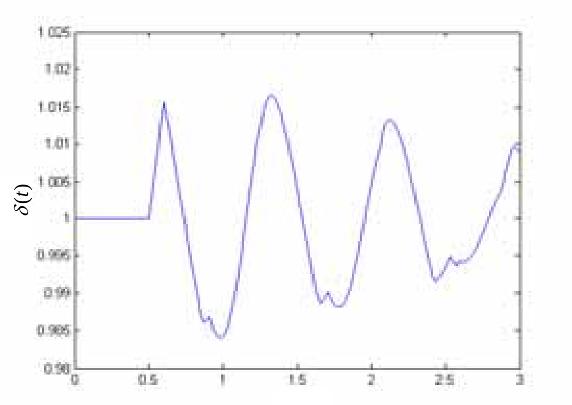
For this SMIB system, reference [8] presents a nonlinear adaptive TCSC controller, which uses two remote signals, generator power angle δ and rotor speed ω, as feedback signals, i.e.

$$x_c = \frac{E_q' V_0 \sin\delta}{P_m - D\dfrac{\Delta\omega}{\omega_0} + \dfrac{M}{\omega_0}(k_1\Delta\delta + k_2\Delta\omega)} - x_{L\Sigma}$$

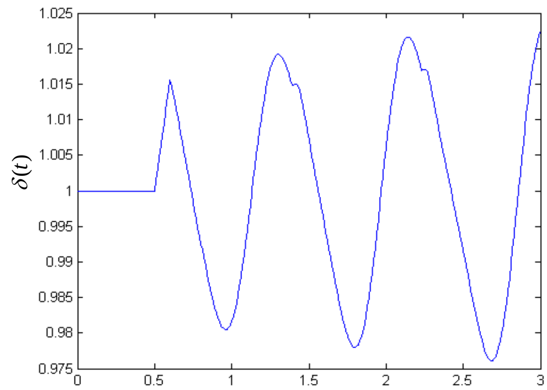
in which $x_{L\Sigma} = x_T + x_{L1} + x_{L2}$. Obviously, time delay of the feedback signals δ and ω is inevitable in the remote transmission and communication system. Our research results demonstrate that the time delay of feedback signals affects greatly the performance of the derived TCSC nonlinear controller. The dynamic responses of the system to a disturbance of a 0.1s 0.15 p.u. step change in the generator rotor angle under different feedback signals delays are investigated. Simulation results are given in Fig. 2. From Fig. 2, it can be seen that the dynamic performance of nonlinear TCSC controller deteriorates sharply with the feedback delay's increase. To improve the TCSC controller performance, an LMI approach is used to design a TCSC controller, which is not sensitive to time delay of remote feedback signals.



(a) time delay＝0ms



(b) time delay＝50ms



(c) time delay＝150ms

Figure 2: Dynamic response of the TCSC controller with different delays

3 TCSC CONTROLLER DESIGN BASED ON LMI TECHNIQUE

When time delays in WAMS are considered, the power system should be modeled as differential-algebraic equations with delays instead of ordinary differential-algebraic equations. LMI technique is one of the basic theories used in delay differential dynamic system. In this paper, LMI technique is applied to design the TCSC controller. Commonly, the state space model of large power systems can be given as follows:

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) \\ \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{2}$$

in which $\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ is the input vector, $\boldsymbol{y}$ is the output vector, $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ are constant matrix.

If the open-loop power system (2) is unstable, a wide-area TCSC controller using remote feedback signals is introduced to ensure the stability of the system. Since the remote feedback signals are considered to be measured in a synchronized manner by PMU, the feedback law has the following representation:

$$u(t) = -\boldsymbol{K}\boldsymbol{y}(t-d) \tag{3}$$

in which $\boldsymbol{K}$ is the tuned parameter vector of TCSC controller, d is the time delay of the remote feedback signals, obviously $d > 0$. Commonly, it is assumed that all the remote signals are synchronized to ensure the feedback signals have the same time delay d. If equation (3) is adopted as TCSC controller's law, then the closed-loop system can be described as follows:

$$\dot{x}(t) = Ax(t) + A_d x(t-d) \tag{4}$$

in which $A_d = -BKC$. Obviously, the closed-loop system (4) is modeled as typical time-delay differential equations. The TCSC controller design problem is addressed as follows: ***find a set of controller parameters*** $\boldsymbol{K}$ ***such that the resulting closed-loop system (4) is asymptotically stable for any delay*** d ***less than a given positive scalar*** d_0**.**

According to the theory of time-delay dynamic system, the stability for linear system (4) can be classified into two types: delay-independent stability and delay-dependent stability. The definitions are given as follows:

Definition 1: Delay-independent stability: when the time-delay dynamical system is stable for any positive time delay *d*, then we say the system has delay-independently stability.

Definition 2: Delay-dependent stability: when the time-delay dynamic system is stable only for some given time delay $0 < d < d_0$, d_0 is a given positive constant, then we say the system has delay-dependently stability.

Ref. [9] addressed the necessary and sufficient conditions of asymptotical stability for the linear dynamic system (4). However, this condition requires a complete understanding of all the eigenvalues of the system (4), which is commonly difficult to satisfy. In the last decades, many simple conditions have been developed to judge the stability of such system. Usually, the results based on the time-independent criteria are too conservative and in some cases we cannot obtain the controller parameters. In most engineering problems, the estimation of the maximum of time delay to keep system stability is enough. So the control problem above is addressed now: find a controller of the form (3) so that the resulting closed-loop system (4) is asymptotically stable for any time delay d less than a given positive scalar d_0.

In order to solve the above output feedback controller problem, we cite here a result, which will be used as a theorem.

Theorem [10]**:** Consider the system $\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{A_d}\,\boldsymbol{x}(t-d)$, given a positive scalar d_0, the system is asymptotically stable for any time delay $0 < d < d_0$ if there exists positive matrixes $\boldsymbol{P}$, $\boldsymbol{Q}$, $\boldsymbol{V}$ and a matrix $\boldsymbol{W}$ such that the following LMI is feasible:

$$\begin{bmatrix} \boldsymbol{S} & \boldsymbol{-W^T A_d} & \boldsymbol{A^T A_d{}^T V} & \boldsymbol{d_0 (W+P)} \\ \boldsymbol{-A_d{}^T W} & \boldsymbol{-Q} & \boldsymbol{A_d{}^T A_d{}^T V} & \boldsymbol{0} \\ \boldsymbol{VA_d A} & \boldsymbol{VA_d A_d} & \boldsymbol{-V} & \boldsymbol{0} \\ \boldsymbol{d_0 (W^T+P)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{-V} \end{bmatrix} < 0 \tag{5}$$

in which

$$\boldsymbol{S = (A + A_d)^T P + P(A + A_d) + W^T A_d + A_d{}^T W + Q}.$$

The above theorem and LMI (5) give the sufficient conditions of delay-dependent stability under d_0. However, a more key question is that how to find the maximum permitted time delay without the loss of stability for a given time-delay system (4). Obviously this question can be summarized to the following optimization problem:

$$\min -d_0 \quad \text{or} \quad \max d_0 \tag{6}$$

subject to

$$\begin{bmatrix} \boldsymbol{S} & \boldsymbol{-W^T A_d} & \boldsymbol{A^T A_d{}^T V} & \boldsymbol{0} \\ \boldsymbol{-A_d{}^T W} & \boldsymbol{-Q} & \boldsymbol{A_d{}^T A_d{}^T V} & \boldsymbol{0} \\ \boldsymbol{VA_d A} & \boldsymbol{VA_d A_d} & \boldsymbol{-V} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{-V} \end{bmatrix} < -d_0 \begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{(W+P)} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{(W^T+P)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}.$$

Obviously, the LMI (6) is a standard "global eigenvalue minimum optimization" problem which can be solved by "gevp" solver of LMI toolbox in MATLAB [11] so that the optimal TCSC controller is derived to ensure the stability of the closed-loop system under maximum permitted time delay.

Although the wide-area TCSC controller can be derived by solving the restricted optimization problem (6), there are also some obstacles for this approach to apply in large-scale power system. As we known, the LMI toolbox in MATLAB, which uses the classical interior-point algorithm, only deals with less than fifty-order linear system. However, the mathematical model of a power system has larger than hundreds of state variables commonly. Such a large-order system is questionable to solve by LMI toolbox in MATLAB. So model reduction is necessary for computing an optimal TCSC controller for high-order power systems. Moreover, the full-order model may also contain variables which are not necessary for a particular stability study, such as one treating only inter-area oscillations for example. It is then quite natural to eliminate the unnecessary variables to accelerate the calculations while keeping a representative model of the dynamic behavior of the system.

Till now, there are several excellent model reduction techniques to us widely, such as Schur relative-error model reduction, optimal Hankle reduction, and so on. In this paper, the Hankle model reduction algorithm is used to obtain the reduced-order model of large-scale power system. The Hankle model reduction calculates the singular value of the Hankle matrices associated with the system in question, then a balancing of the values is computed. The use of observability and controllability Grammians allows the reduced model to retain the same characteristics is the full-order model with respect to the desired input and output signals. The critical oscillatory modes are the same for the full-order model and reduced model. In this manner, the dynamics of the reduced system are as close as possible to the dynamics of the full-order system. In MATLAB, there is a standard function "ohkapp" to execute optimal Hankel norm approximation algorithm for model reduction [12].

To practically solve the wide-area TCSC controller design problem for large-scale power system, the following algorithm is then proposed:

(I) Modeling the interconnected power system as nonlinear differential-algebraic equations.

(II) The nonlinear model of large-scale power system is linearized to a state-space model, i.e. equation (2).

(III) Identify the feedback law, i.e. equation (3), select the structure and feedback signals of TCSC controller.

(IV) The full-order linearized model is reduced to low-order model by Hankel order-reduced algorithm, which is given by MATLAB.

(V) For the reduced-order model, "gevp" solver of LMI toolbox is used to solve the optimization problem (6) so that a TCSC controller can be designed.

(VI) The derived TCSC controller is inserted into the full-order, nonlinear closed-loop power system, dynamic simulation are then performed in PST (Power System Toolbox) to verify if the design objective has been met.

4 CASES STUDY

In order to demonstrate the proposed approach, New England Test Power System (NETPS) is employed. The detailed description of NETPS including network data and dynamic data for the generators, excitation systems, turbine governors, PSSs can be found in [13]. A single-line diagram of the NETPS test system is shown in Fig. 3. The NETPS comprises 10-generator, 39-bus, and 46-line. Generator 10 is equivalent to a large subsystem of the interconnected power system and its behavior is similar to an infinite bus with low equivalent impedance and high inertia. From damping inter-area low-frequency oscillation viewpoint, the appropriate installation points for TCSC are some area tie lines, such as line 14-15 and line 16-17 which divide the NETPS system into two major areas. So, Line 15-16 is an ideal installation point for TCSC.

For NETPS, the rotor angle δ_1 and rotor speed ω_1 of the generator G_1 are used as the feedback signals of TCSC controller. Assuming these feedback signals measured by PMU, then the feedback law has the following representation:

$$u(t) = -Ky(t-d)$$

in which $K = [k_{\delta_1} \;\; k_{\omega_1}]$, $y = [\Delta\delta_1 \;\; \Delta\omega_1]^T$, $u = \Delta x_c$, i.e. the deviation in the equivalence reactance of TCSC, d is the synchronized time delay of the feedback signals, $d > 0$.

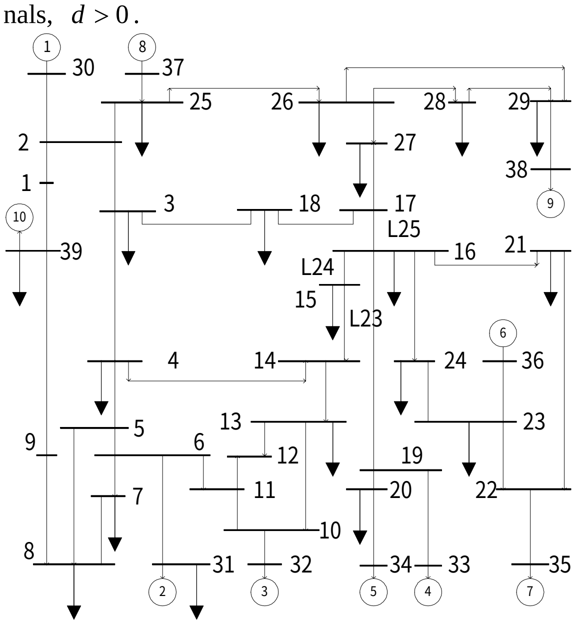


Figure 3: Single-line diagram of NETPS

When the generators, excitation systems and governors are considered in modeling of NETPS, the full-order nonlinear model of NETPS has 99 state variables, generator G_{10} is considered as reference machine because of its low equivalent impedance and high inertia. The full-order nonlinear model is linearized about the nominal operating condition in order to obtain the system matrix $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ of equation (2).

In the next step, the full-order linear model is reduced from 99 state variables to 10 state variables by Hankel approximation algorithm. The frequency responses for the full-order model and reduced-order model are shown in Fig. 4. The full-order system is represented in solid line; the reduced-order model is represented in dotted line. It can be seen that the dynamics of the reduced system are very close to that of the full-order system.

Based on the reduced model, the LMI approach presented in section III are used to solve the optimization problem, i.e. equation (6) by "gevp" solver of LMI toolbox in MATLAB. For the NETPS in Fig. 4, we obtain $d_0 = 500\text{ms}$, the optimal parameters of the TCSC controller are: $K_* = [1.0\ 10.2]$.

In order to verify the validity of the designed optimal TCSC controller, the derived TCSC controller designed for reduced model is inserted to the full-order nonlinear power system. The dynamic responses of the NETPS to a disturbance of a 0.1s 0.15 p.u. step change in the generator rotor angle under different remote signals delays are investigated. Simulation results are given in Fig. 5. From Fig. 5, it can be seen that the derived TCSC controller can effectively ensure the stability of the NETPS when the time lag is large as 300ms.

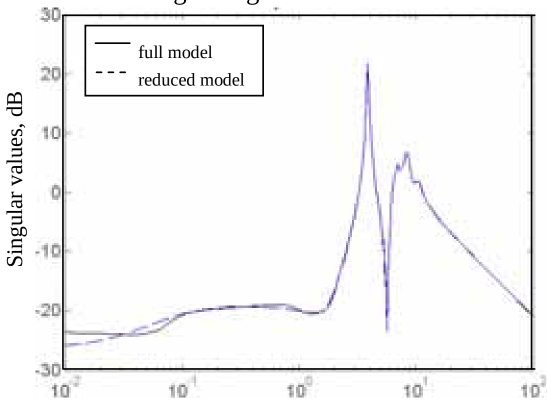
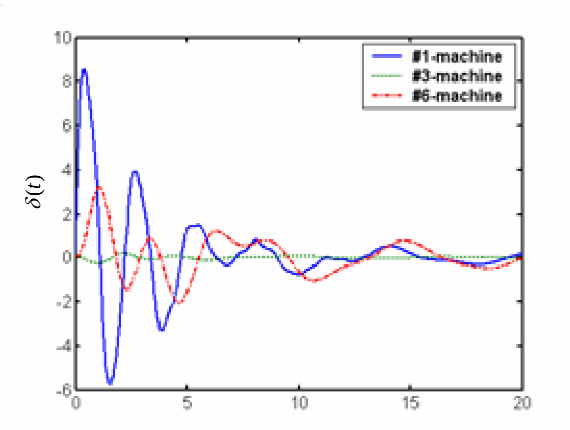
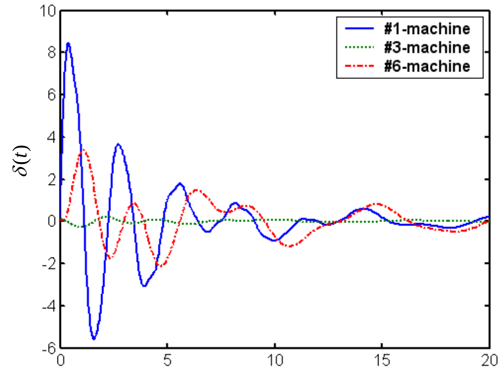


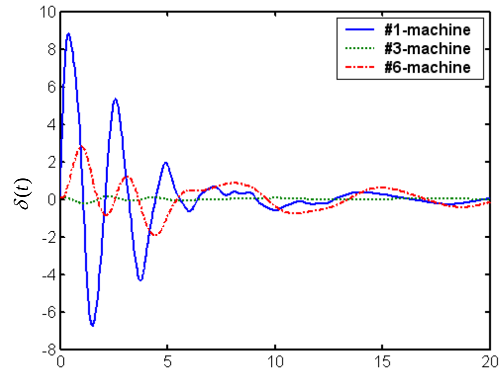
Figure 4: Frequency responses of the full and reduced model of NETPS



(a) time delay=100ms



(b) time delay=150ms



(c) time delay=300ms

Figure 5: Dynamic of NETPS under different time delays

5 CONCLUSIONS

This paper presents a methodology for wide-area TCSC controller design in consideration of time delay of the remote feedback signals. The power systems firstly models as a time-delay dynamic systems. The stability evaluation criteria of time-delay linear systems can be expressed in terms of linear matrix inequalities. The LMI technique combined with Hankel approximation algorithm are proposed to design a TCSC controller which can ensure the stability of large-scale power system even when remote signal transmission delay is considered. One multi-machine power system case study is employed to illustrate the procedure of proposed approach. Nonlinear simulation results have shown that the designed TCSC controller is effective even when the time delay is considered.

6 ACKNOWLEDGMENT

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