A Unified Smith Predictor Approach for Power System Damping Control Design Using Remote Signals

Rajat Majumder, Balarko Chaudhuri, Bikash C. Pal, and Qing-Chang Zhong

Abstract—**This brief illustrates a control design procedure for handling time delays encountered in transmitting the remote signals in power systems. A unified Smith predictor (USP) approach is used to formulate the control design problem in the standard mixed sensitivity framework. The solution to the problem is sought numerically using linear matrix inequalities (LMIs) with additional pole-placement constraints. The predictor based method is applied for designing a damping controller for a prototype power system. Simulation results show that the controller performs satisfactorily even though the feedback signals arrive at the control site after a finite time delay.**

Index Terms—**H-infinity control, interarea oscillations, linear matrix inequality (LMI), model reduction, remote signals, robustness, Smith predictor, swing mode.**

I. INTRODUCTION

INTERAREA oscillations [1] are inherent in large interconnected power systems. These oscillations often suffer from poor damping. The severity might vary with the level of power transfer through tie-lines, strength of the tie-lines, nature of loads etc. For secure system operation, it is, therefore, essential to employ a damping control strategy that provides adequate damping to these oscillations over a range of operating scenarios.

The traditional approach for damping interarea oscillations is through the installation of power system stabilizers (PSSs) [2], that provide damping control action through excitation control systems of the generators. The use of controllable components in electric power transmission has gained increased popularity over the recent years. These controllable components consist of high-power electronic switches that control current through and voltage across large inductor and capacitor, respectively, in different topologies. The electric power transmission system reinforced with these devices are known as flexible ac transmission systems (FACTS). Research in FACTS [1], [2], has shown that damping oscillations could be added benefits apart from the primary function of FACTS, i.e., system power flow and voltage control. There have been some field experiences on damping performance of FACTS devices too. These devices are usually installed in transmission lines and, therefore, have direct access to the quantities which are highly sensitive to interarea oscillations.

One of the facts in a practical system operation is that the number of dominant interarea modes are often larger than the number of such expensive FACTS devices available [3]. Much research is, therefore, focussed on designing new control structure which can improve the damping of many interarea modes with fewer FACTS devices. This is possible if several stabilizing signals capturing all the interarea modes from different locations of the system can be accessed and input to a centralized controller. The recent advances in wide area measurement (WAM) technologies using phasor measurement units (PMUs) can deliver synchronous phasors and control signals at a high speed of about a 30 Hz sampling rate [4]–[6]. However, the cost and associated complexities restrict the use of these sophisticated signal transmission hardware in a large commercial scale. As a more viable alternative, the existing communication channels are being explored to transmit the stabilizing signals from remote locations but with significant amount of delay in the range of 0.5 to 1.0 s. This makes the task of damping control design more difficult. Moreover, long delays influence the closed-loop system response especially in the frequency range of interarea modes. Hence, they should be treated properly in the plant formulation for control design. Our previous work [7] has illustrated a $\mathcal{H}_\infty$ based centralized control design methodology without considering delay (0.02–0.05 s) involved in transmitting the remote signal. In that case, the delay was assumed to be much less than the lowest time period of the interarea modes and therefore could be neglected in design stage.

Our present work addresses the issue of considering time-delays in the design stage by treating the system as dead-time system. It is considered that there is a delay involved in transmitting the measured feedback signals from remote location to the controller site. Control design for such dead-time system is usually not straightforward [8]. Classical Smith predictor (CSP) [9], proposed in early fifties, was the first effective tool for controller synthesis for time delayed system. The problem encountered with CSP is that it is very difficult to ensure a minimum damping ratio of the close-loop system when the open-loop system has poorly damped poles. As an improvement modified Smith predictor (MSP) approach was proposed by Wantanable *et al.* [10]. Some of the drawbacks of CSP can be overcome in MSP formulation but it may give rise to numerical instability for systems with fast stable poles. The concept of unified Smith predictor (USP) has been proposed in [11] to overcome the shortcomings of CSP and MSP. The USP combines advantageous features of both the CSP and MSP. Therefore, this is very effective in designing a centralized controller for the purpose of damping several interarea modes employing only one FACTS device. The delay in signal transmission is considered to be 0.75 s. A $\mathcal{H}_\infty$ controller is designed by solving the problem using linear
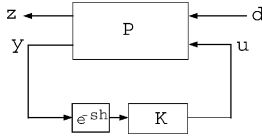
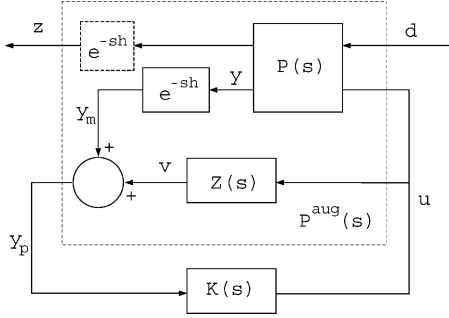Fig. 1.   General control setup for a time delayed system.

Fig. 2.   Generalized plant layout.

matrix inequalities (LMIs) with additional pole-placement constraints to ensure minimum damping ratios for all dominant interarea modes. The methodology is applied to design a 3-input 1-output damping controller employing a thyristor controlled switched capacitor (TCSC) in a 16-machine, 68-bus prototype power system. The details of the study system can be found in [7].

II. PREDICTOR BASED CONTROL DESIGN FOR DEAD-TIME SYSTEMS

In dead time systems, measured feedback signals take certain amount of time to reach the controller. Controlling such a time delayed system is difficult. Fig. 1 shows the generalized control design setup. The delayed system is modeled as $P_h(s) = P(s)e^{-sh}$, where e^{-sh} is the block to represent delay in feedback measurement with a dead time $h > 0$. The problem is equivalent to designing a control for a system with control input delay. A predictor for a dead time system is an exponentially stable system Z such that $P_h + Z$ is rational. A predictor based controller for the dead time plant P_h consists of a predictor Z and a stabilizing controller C, as shown in Fig. 2. The CSP [9] was the first effective way to control such systems but later many MSPs were presented [12] for improving performance. Manitius and Olbrot [13] suggested a finite spectrum assignment scheme using predicted delays via state feedback control for an unstable plant. Wantanable and Ito [10] introduced an MSP to overcome limitations in finite spectrum assignment and other process control schemes. Similar predictor blocks have got important role in $\mathcal{H}_\infty$ control of time-delay systems [14]–[16] and in deadbeat control [8]. In MSP approach, a transformation on close loop matrix ensures solvability of robust control problems of dead time systems as in the finite-dimensional situations [8]. The generalized plant $\tilde{P}$ in Fig. 1 is described as

$$\tilde{P}(s) = \left[\begin{array}{c|cc} A & e^{Ah}B_1 & B_2 \\ \hline C_1 & 0 & D_{12} \\ C_2 e^{-Ah} & D_{21} & 0 \end{array} \right] \quad (1)$$

where the state–space representation of the augmented plant including the weights, is given by

$$P(s) = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array} \right] = \left[\begin{array}{cc} P_{11} & P_{12} \\ P_{21} & P_{22} \end{array} \right] \quad (2)$$

and h is the delay associated with measured feedback signal. The MSP based controller design methodology might lead to numerical problems with some fast stable poles. The matrix exponential e^{-Ah} as given in (1) could be noncomputable for such systems [14]. This kind of numerical problems might even arise with delay of very small magnitude if there are some stable poles λ and they are very fast with respect to the delay h. In mixed-sensitivity approach of H_∞ control design which is adopted here, the controller to ensure robustness, might contain fast stable poles. These often leads toward numerical instability while solving the problem using LMIs. These problems are overcome by adopting USP formulation. This is achieved by decomposing the delay free plant P into a critical part P_c and a non critical part P_{nc}. The critical part contains poorly damped poles and non critical part contains sufficiently damped poles located away from imaginary axis. The USP formulation is described in next section.

III. CONTROL DESIGN USING USP APPROACH

An USP proposed by Zhong and Weiss [11] is adopted here to overcome the numerical problem as stated in earlier section. An USP combines the features of the CSP and the MSP and it does not require the computation of the matrix exponential for the fast stable poles. The controller design techniques based on MSP have to be reconsidered for the USP, to make them practically implementable. For that purpose an equivalent representation of the augmented plant has been proposed in [11]. Construction of the predictor for the noncritical part is made using CSP formulation and for the critical part MSP formulation is used. The decomposition of delay free plant is performed by applying a suitable linear coordinate transformation on its state–space representation. The transformation matrix V was chosen in such a way that the transformed matrix $J = V^{-1}AV$ is in the Jordan Canonical form and free from complex entries. The transformation matrix V was obtained using *eig* function and the elements of the transformed matrix J were converted from complex diagonal form to real diagonal form using *cdf2rdf* function available with Matlab. The transformed augmented delay free plant P_{22}^t is given by

$$P_{22}^t(s) = \left[\begin{array}{c|c} V^{-1}AV & V^{-1}B_2 \\ \hline C_{2V} & 0 \end{array} \right] = \left[\begin{array}{cc|c} A_c & 0 & B_c \\ 0 & A_{nc} & B_s \\ \hline C_c & C_{nc} & 0 \end{array} \right] \quad (3)$$

where A_c is critical and A_{nc} is noncritical part of A after transforming into Jordan canonical form. This decomposition is made by spilting the complex plane along with a vertical line $Re(s) = \alpha$ with $\alpha < 0$. The value of α is chosen as the maximum negative real part of poorly damped poles. Then the eigenvalues of A_c are all eigenvalues λ of A with $Re(\lambda) > \alpha$,
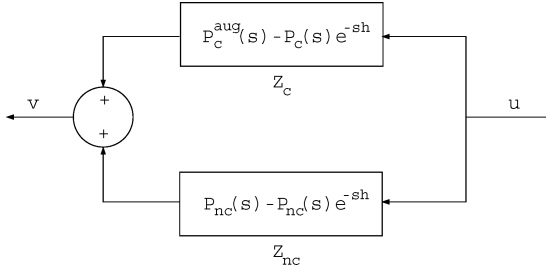
Fig. 3. USP.

while A_{nc} has remaining eigenvalues of A. Now the delay free augmented plant could be split as $P_{22}^t = P_c + P_{nc}$ where

$$P_c(s) = \left[\begin{array}{c|c} A_c & B_c \\ \hline C_c & 0 \end{array} \right] \qquad (4)$$

and

$$P_{nc}(s) = \left[\begin{array}{c|c} A_{nc} & B_{nc} \\ \hline C_{nc} & 0 \end{array} \right]. \qquad (5)$$

The predictor for the critical part P_c is taken as the following MSP formulation:

$$Z_c(s) = P_c^{aug}(s) - P_c(s)e^{-sh} \qquad (6)$$

where

$$P_c^{aug} = \left[\begin{array}{c|c} A_c & B_c \\ \hline C_c e^{-A_c h} & 0 \end{array} \right] \qquad (7)$$

and the predictor for the noncritical part is considered as a classical SP

$$Z_{nc}(s) = P_{nc}(s) - P_{nc}(s)e^{-sh}. \qquad (8)$$

Now clearly the USP is the sum of these two as shown in Fig. 3

$$Z(s) = P_{22}^{aug}(s) - P_{22}^t(s)e^{-sh} \qquad (9)$$

where $P_{22}^{aug} = P_{nc} + P_c^{aug}$ and the a realization of P_{22}^{aug} is

$$P_{22}^{aug} = \left[\begin{array}{c|c} A & B_2 \\ \hline C_2 E_h & 0 \end{array} \right] \qquad (10)$$

where

$$E_h = V \left[\begin{array}{cc} e^{-A_c h} & 0 \\ 0 & I_{nc} \end{array} \right] V^{-1}. \qquad (11)$$

Here, the identity I_{nc} has the dimension as A_{nc} and $E_h A = A E_h$ has been used. Unlike MSP, the impulse response of USP is not finite. The augmented plant P^{aug}, obtained by connecting the original plant and the USP in parallel (as shown in Fig. 2) with new measured output y_p is given by

$$P^{aug} = \left[\begin{array}{cc} P_{11}(s) & P_{12}(s)e^{-sh} \\ P_{21}(s) & P_{22}(s)^{aug} \end{array} \right]. \qquad (12)$$
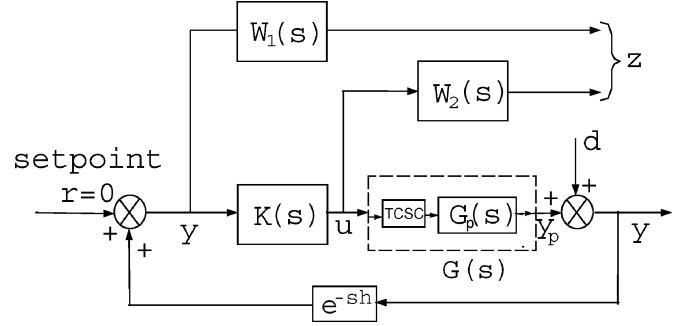

Fig. 4. Mixed-sensitivity output disturbance rejection configuration.

The generalized plant is formulated from P^{aug} as proposed in [11] and is given by

$$\tilde{P} = \left[\begin{array}{cc|cc} A & 0 & E_h^{-1}B_1 & B_2 \\ 0 & A_{nc} & [0 \, e^{A_{nc}h} - I_{nc}]V^{-1}B_1 & 0 \\ \hline C_1 & C_1 V \left[\begin{array}{c} 0 \\ I_{nc} \end{array} \right] & 0 & D_{12} \\ C_2 E_h & 0 & D_{21} & 0 \end{array} \right]. \qquad (13)$$

Having formulated the generalized plant $\tilde{P}$ following the USP approach, the objective is to design a controller C to meet the desired performance specifications. If C ensures the desired performance for $\tilde{P}$, then $K = C(I - ZC)^{-1}$ is guaranteed to achieve the same for the original dead-time system.

IV. CONTROL DESIGN AND IMPLEMENTATION

The control design problem was formulated using standard mixed-sensitivity approach [7], [17] with modification as described in previous sections. The overall control setup is shown in Fig. 4 where $G(s)$ is the open-loop plant consisting of entire power system $G_p(s)$ and the TCSC, $K(s)$ is the controller to be designed and $W_1(s)$ and $W_2(s)$ are weights for shaping the characteristics of the open-loop plant. In a Riccati based approach, the standard practice is to choose the weight $W_1(s)$ as a low-pass filter for output disturbance rejection. The weight $W_2(s)$ should be a high-pass filter in order to reduce the control effort and to ensure robustness against additive uncertainties in the plant model in the high-frequency range. The weights are given as

$$W_1(s) = \frac{100}{s + 100} \qquad W_2(s) = \frac{100s}{s + 100} \qquad (14)$$

The design objective is to minimize a weighted mix of the transfer function $S(s) = (I - G(s)K(s))^{-1}$, which ensures disturbance rejection and $K(s)S(s) = K(s)(I - G(s)K(s))^{-1}$ which handles the robustness issues and minimizes the control effort. This mixed-sensitivity (S/KS) design objective is represented in [18] as

$$\left\| \left[\begin{array}{c} W_1(s)S(s) \\ W_2(s)K(s)S(s) \end{array} \right] \right\|_\infty < \gamma \qquad (15)$$
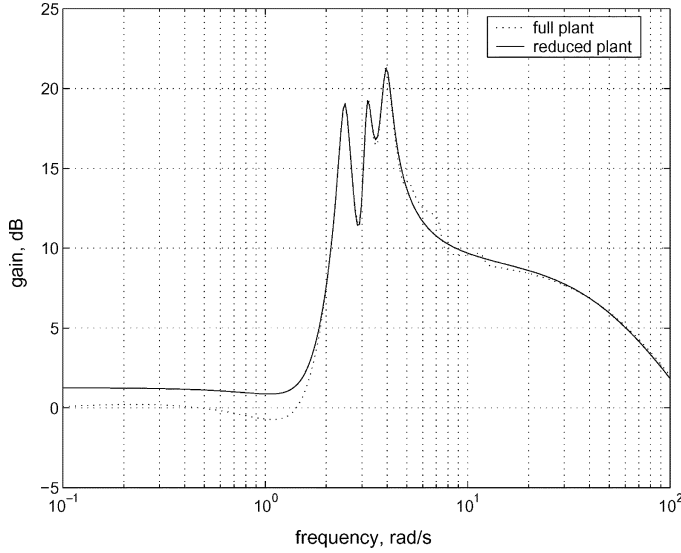
where, γ is the bound on performance.

Fig. 5. Singular value response of the system. Solid: original 132nd-order plant. Dashed: reduced seventh-order plant.
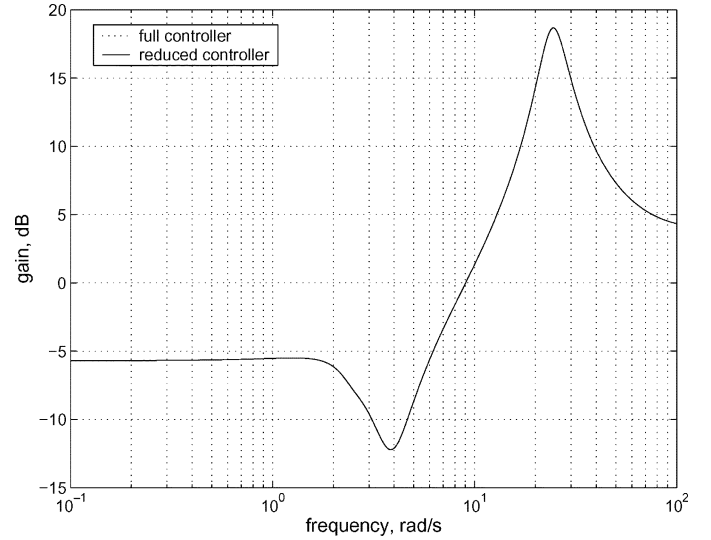

Fig. 6. Singular value response of the controller. Solid: original 16th-order controller. Dashed: reduced eighth-order controller.

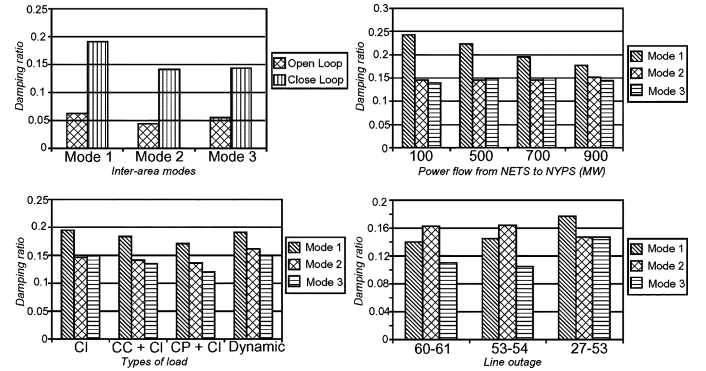Fig. 7. Robustness validation through damping ratio.

The related H_∞ problem as stated in (15) considering the generalized plant formulated previously was solved in Matlab using LMI approach [18] with pole placement as additional constraints for ensuring minimum damping. The *LMI Control Toolbox* available with Matlab [19] has been used to perform the necessary computations. The original system model had 132 states. To expedite the process in the LMI routine, the plant order was reduced to 7. Balanced truncation [18], [20] was used for the reduction of the plant model. Such a drastic reduction in plant model order is perfectly acceptable as long as the frequency response of reduced order plant does not differ appreciably from that of original plant. The singular value plots of original plant and reduced plant shown in Fig. 5 support this.

The order of the controller obtained from the LMI solution is equal to the reduced plant order plus the order of the weights, which is quite high from a practical implementation point of view. Therefore, the controller was reduced to a eighth-order one by the balanced truncation without significantly affecting the frequency response. The frequency response characteristics of the full order controller and reduced order controller is shown in Fig. 6. This reduced order controller was tested on the original system (full order) model.

A. Smith Predictor Implementation

As stated previously, the USP is connected in feedback path with the controller as shown in Fig. 2 for control of the original dead time plant. Now if noncritical part of the USP is implemented as in (8) there would not be any problem since all the poles of this part are well damped. On the other hand the critical part of the USP as in (6) contains the poorly damped open-loop poles of the plant. The predictor has to be implemented in such a way that those poorly damped poles do not appear in the closed loop. One way of doing that is to replace the predictor block by the sum of a series of discrete delays [8], [13], [15]. However, it has emerged very recently that this approximation method cannot guarantee the system stability even when quite accurate

approximation integral laws were used [21]. To overcome this problem, the implementation of predictor in s domain for the critical part suggested in [22] is adopted here and is given by

$$Z = \frac{1 - e^{-h(s+\varepsilon)}}{1 - e^{\varepsilon h}} \frac{1}{(s+\varepsilon)} C_c \left(I_c - e^{-A_c h} \right) A_c^{-1} B_c \quad (16)$$

where, ε is a small number.

V. ROBUSTNESS VALIDATION AND NON-LINEAR SIMULATIONS

The damping action of the designed controller was examined under different types of disturbances in the system. These include changes in power flow levels over key transmission corridors, change of type of loads etc. The damping ratios of the critical interarea modes under these operating conditions are summarized in Fig. 7. Note that in Fig. 7 CI, CP, CC mean constant impedance, constant power and constant current type loads. The damping is found to be highly satisfactory in all the cases.

One of the concerns of centralized design using remote signals is possible loss of one of the channels leading to unsatisfactory damping performance. Mekki *et al.* [23] have proposed a solution based on the replacement of the lost remote signal by a similar local signal through the use of signal-loss detector. A nonlinear simulation has been carried out for 25 s to further
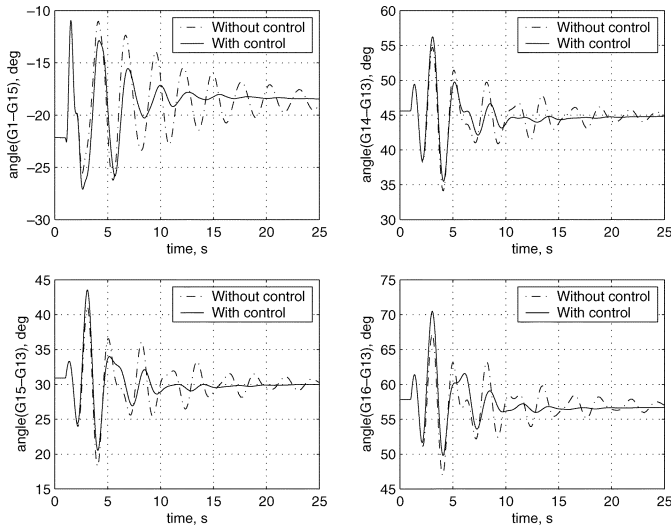
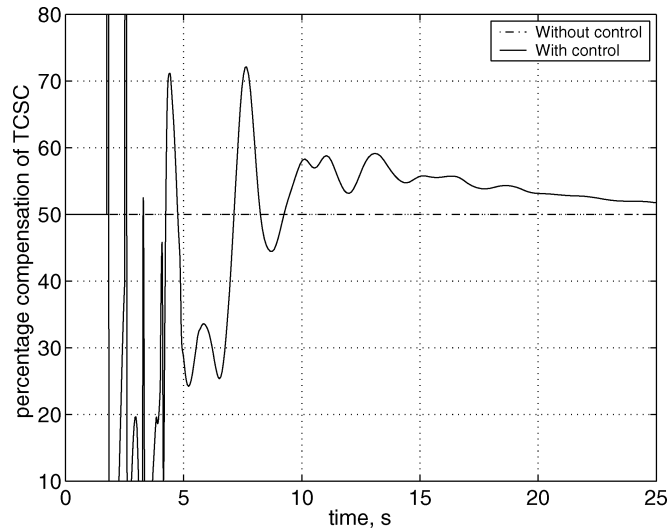Fig. 8.   Dynamic response of the system with centralized control.

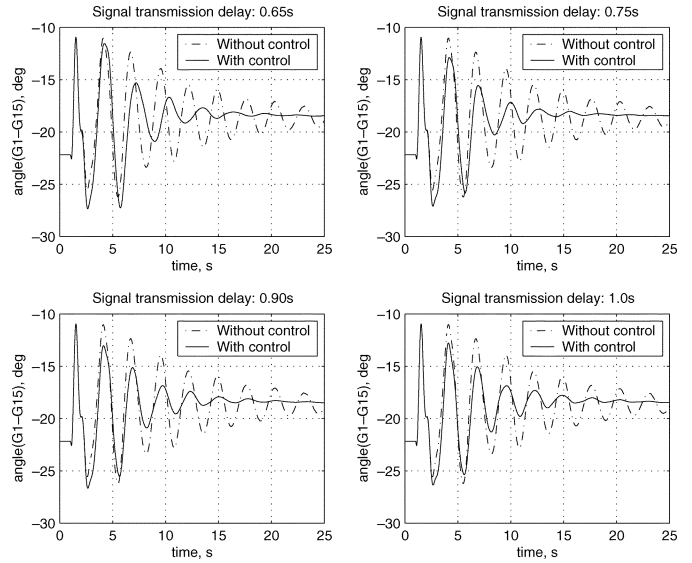Fig. 9.   Controller response.

Fig. 10.   Dynamic response of the system with different delays.
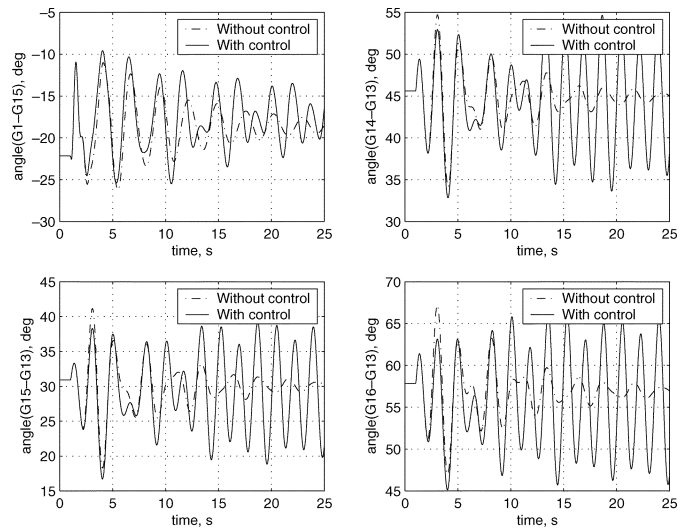
Fig. 11.   Dynamic response of the system with controller designed without considering delay.

demonstrate performance robustness of the controllers in the presence of system nonlinearities, including saturation. One of the most probable contingencies of the system that triggers interarea oscillations is a three-phase solid fault near bus #53 on one of the tie-lines connecting buses #53–#54. The fault condition was simulated for 80 ms ($\approx$4 cycles) followed by opening of the faulted line. The dynamic response of the system model following this contingency is shown in Fig. 8. The displays in Fig. 8 show the relative angular separation of G#1 with respect to that of G#15 and G#14, G#15 and G#16 with respect to that of G#13. The effect of interarea oscillation is manifested most effectively in these particular relative machine angle differences. This illustrates that the interarea oscillations are damped out in 10–15 s through control action. The controller response is shown in Fig. 9.

As mentioned earlier the delay in the feedback signal transmission can typically be within 0.5 s–1.0 s. But there can always be some uncertainties in the amount of delay. The controller is designed assuming a delay of 0.75 s. The designed controller is then tested with delay of 0.65 s, 0.9 s and 1.0 s in nonlinear

simulation. The response of the relative angular separation of G#1 with respect to G#15 and tie line power flow between buses #60–61 are shown in Fig. 10 for different amount of delays. The performance of the controller is found to be satisfactory in the face of the variable delays.

To demonstrate the drawback of the conventional H_∞ design with a delay free plant, a separate controller was designed for the TCSC without considering delay in the design stage. The design was carried out as described in [7]. The controller found to be acceptable both in time and frequency domain for a delay up to 0.1 s. For lager time delays, the performance starts deteriorating. The simulation results following the same disturbance with a delay of 0.75 s was carried out and shown in the Fig. 11.

It is clear that the controller performance deteriorates considerably if the delay is more than the time-period corresponding to the dominant interarea modes and is not taken into account in the design stage. Therefore, inclusion of the delay in the control synthesis is quite significant and there lies the potentiality

of USP approach for power system damping control design involving finite delay in signal transmission.

VI. CONCLUSION

The use of remote stabilizing signals have been demonstrated for effective damping of multiple swing modes through a TCSC with finite delay in signal transmission. A $\mathcal{H}_\infty$ control design methodology following USP approach is applied for designing a centralized controller through a TCSC. The control algorithm makes it possible to stabilize the system within desired time frame with delays encountered by the feedback signals from geographically separated locations. The performance robustness of the designed controller has been verified in the frequency domain through eigen-analysis and also in the time domain through nonlinear simulations.

APPENDIX

A 3 input 1 output eighth-order centralized controller is designed to improve that damping of interarea oscillations. $K_{11}(s)$, $K_{12}(s)$ and $K_{13}(s)$ are the transfer functions between first input to output, second input to output and third input to output, respectively

$$K_{11}(s) = \frac{N_{11}(s)}{D(s)} \quad K_{11}(s) = \frac{N_{11}(s)}{D(s)} \quad K_{11}(s) = \frac{N_{11}(s)}{D(s)}$$

where

$$N_{11}(s) = 3.395 \times 10^5 s^7 + 1.745 \times 10^8 s^6 + 1.725 \times 10^{10} s^5$$
$$+ 5.65 \times 10^{11} s^4 + 2.67 \times 10^{12} s^3 + 1.456 \times 10^{13} s^2$$
$$+ 2.807 \times 10^{13} s + 5.369 \times 10^{13}$$

$$N_{12}(s) = 1.163 \times 10^8 s^7 + 1.769 \times 10^8 s^6 + 5.784 \times 10^{11} s^5$$
$$+ 3.486 \times 10^{11} s^4 + 9.235 \times 10^{12} s^3 - 1.996 \times 10^{13} s^2$$
$$+ 1.416 \times 10^{13} s - 1.458 \times 10^{14}$$

$$N_{12}(s) = 1.067 \times 10^7 s^7 + 2.004 \times 10^9 s^6 + 1.026 \times 10^{11} s^5$$
$$+ 1.687 \times 10^{12} s^4 + 3.017 \times 10^{12} s^3 + 2.629 \times 10^{13} s^2$$
$$+ 1.88 \times 10^{13} s + 9.382 \times 10^{13}$$

$$D(s) = s^8 + 7.208 \times 10^7 s^7 + 1.054 \times 10^{10} s^6 + 1.671 \times 10^{11} s^5$$
$$+ 6.487 \times 10^{12} s^4 + 2.902 \times 10^{13} s^3 + 1.205 \times 10^{14} s^2$$
$$+ 1.926 \times 10^{14} s + 3.499 \times 10^{14}.$$

REFERENCES

[1] J. Paserba, Analysis and control of power system oscillation, in CIGRE Special Publication 38.01.07, 1996.

[2] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.

[3] J. Chow, J. Sanchez-Gasca, H. Ren, and S. Wang, "Power system damping controller design using multiple input signals," *IEEE Control Syst. Mag.*, vol. 20, no. 4, pp. 82–90, Aug. 2000.

[4] I. Kamwa, R. Grondin, and Y. Hebert, "Wide-area measurement based stabilizing control of large power systems—a decentralized/hierarchical approach," *IEEE Trans. Power Syst.*, vol. 16, no. 1, pp. 136–153, Feb. 2001.

[5] G. Heydt, C. Liu, A. Phadke, and V. Vittal, "Solutions for the crisis in electric power supply," *IEEE Comput. Appl. Power*, vol. 14, no. 3, pp. 22–30, Jul. 2001.

[6] J. Bertsch, C. Carnal, P. Korba, L. Broski, and W. Sattinger, "Experience and benefits of systems for wide area monitoring," in *Proc. 6th Annu. Western Power Delivery Automation Conf.*, Spokane, WA, Apr. 2004.

[7] B. Chaudhuri and B. Pal, "Robust damping of multiple swing modes employing global stabilizing signals with a TCSC," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 499–506, Feb. 2004.

[8] Q. C. Zhong, "H_∞ control of dead time systems based on a transformation," *Automatica*, vol. 39, pp. 361–366, Feb. 2003.

[9] O. Smith, "Closer control of loops with dead time," *Chem. Eng. Progress*, vol. 53, no. 5, pp. 217–219, 1957.

[10] K. Wantanable and M. Ito, "A process-model control for linear systems with delay," *IEEE Trans. Autom. Control*, vol. AC–26, no. 6, pp. 1261–1269, Dec. 1981.

[11] Q.-C. Zhong and G. Weiss, "A unified smith predictor based on the spectral decomposition of the plant," *Int. J. Control*, vol. 77, no. 15, pp. 1362–1371, 2004.

[12] Z. Palmor, "Time delay compensation-smith predictor and its modifications," in *The Control Handbook*. Boca Raton, FL: CRC, 1996, pp. 224–237.

[13] A. Manitius and A. Olbrot, "Finite spectrum assignment problem for systems with delays," *IEEE Trans. Autom. Control*, vol. AC–24, no. 4, pp. 541–553, Aug. 1979.

[14] G. Meinsma and H. Zwart, "On H_∞ control for dead time systems," *IEEE Trans. Autom. Control*, vol. 45, no. 2, pp. 272–285, Feb. 2000.

[15] Q. C. Zhong, "On standard H_∞ control process with a single delay," *IEEE Trans. Autom. Control*, vol. 48, no. 6, pp. 1097–1103, Jun. 2003.

[16] L. Mirkin, "On the extraction of dead-time controllers from delay-free parameterization," *IEEE Trans. Autom. Control*, vol. 48, no. 4, pp. 543–553, Apr. 2003.

[17] B. Chaudhuri, B. Pal, A. C. Zolotas, I. M. Jaimoukha, and T. C. Green, "Mixed-sensitivity approach to H_∞ control of power system oscillations employing multiple facts devices," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1149–1156, Aug. 2003.

[18] S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control*. New York: Wiley, 2001.

[19] P. Gahinet, A. Nemirovski, A. Laub, and M. Chilali, *LMI Control Toolbox for Use With Matlab*. Natick, MA: Math Works, 1995.

[20] K. Zhou, J. Doyle, and K. Glover, *Robust and Optimal Control*. Englewood Cliffs, NJ: Prentice-Hall, 1995.

[21] V. Assche, M. Dambrine, J. Lafay, and J. Richard, "Some problems arising in the implementation of distributed-delay control laws," in *Proc. 38th IEEE Conf. Decision and Control*, Phoenix, AZ, Dec. 1999, pp. 4668–4672.

[22] Q.-C. Zhong, "Implementation of distributed delay in control laws," *IEEE Trans. Autom. Control*, vol. 49, no. 11, pp. 2074–2080, Nov., 2004.

[23] K. Mekki, A. Snyder, N. HadjSaid, R. Feuillet, D. Georges, and T. Margotin, "Damping controller input-signal loss effects on the wide-area stability of an interconnected power systems," in *Proc. IEEE Power Engineering Soc. Summer Meeting*, vol. 2, Jul. 2000, pp. 1015–1019.