Robust Damping Controller Design for Damping Enhancement of Inter-Area Oscillations Considering Communication Network Constraints

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***Abstract*—In this paper, a dynamic output feedback controller designed for damping enhancement of inter-area oscillations using wide-area signals as their feedback signals. The packet-based communication network is used to transfer wide-area signals. Communication network constraints such as networked induced delays, packet dropouts, and packet disorder are captured in the closed-loop power system by constructing as networked control system (NCS) model. Stabilization of closed-loop system with aforesaid problems have been formulated as the delay-dependent control problem. Sufficient conditions for the design of a dynamic controller are formulated in form of linear matrix inequalities by using quadratic Lyapunov criterion. In addition to the dynamic controller, a robust pole placement approach is applied to place the closed-loop poles in the prescribed stability region. Nonlinear simulations on a case study namely a two-area four-machine power system is performed to evaluate the performance of the proposed controller and its performances are compared with power oscillation damping (POD) controller and H_∞ controller.**

***Keywords*—Inter-area oscillations, communication network, network control systems (NCS), Lyapunov criterion, robust pole placement, LMIs.**

I. Introduction

Mitigation of low-frequency inter-area oscillations (LFIOs) is the main concern of the power system operators. Inter-area oscillations are resulted from large power systems coupled by weak transmissions lines those transfer heavy power flow. The insufficient damping of LFIOs can decrease the maximum power transfer capability between interconnected power areas and deteriorate the power system stability or, worse than that, the amplitude of these oscillations grow within few seconds which can lead to voltage collapse or generators may lose synchronism ultimately resulting in system separations and blackouts. A famous example of a blackout caused by these oscillations is Western Electricity Coordination Council Region on August 10, 1996 [1]. Traditionally, Power system stabilizers (PSSs) are used to suppress LFIOs by providing supplementary control action through an AVRs of generators or, alternatively, flexible AC transmission systems (FACTS) devices with their supplementary damping controllers. This controller provides sufficient damping to the local modes by using local signals as their feedback signals, but the effectiveness of these damping controllers lessen when coming to the inter-area modes because inter-area oscillations modes are not observable and controllable from the local signals of the generators.

To effectively remove or suppress the effect of inter-area oscillations, remote or wide-area signals use as feedback input signals for PSS and FACTS devices [2]. The damping controllers which use remote signals as feedback signals, we can call them wide-area damping controllers (WADCs). Packet based communication network used to transfer these signals to and from the plant and controllers. The usage of a communication network in the control loops is called networked control systems (NCS) [3]. NCS suffers from some problems such as networked induced delays, Packet dropout, and packet disordering. These factors may lead to the performance degradation of wide-area damping control or may even make the closed-loop system unstable.

In the literature [4]–[6], some of the previous works considered aforesaid problems in the design/synthesis of WADC. In [4], [5], Pade's approximation method used to design WADC. In this method, which can approximate time delay during model approximation. Some of the robust controllers presented in [6], [7] by considering the time delay as the system uncertainties, and delay-dependent stability analysis of WADC [8], by calculating the delay margin under which the system can retain stable. Stability analysis of damping controllers considering communication time delays reported in [9], [10]. In [11] WAMS based state feedback controller designed to reduce the effect of networked induced delays.

In this work, we proposed a dynamic output feedback wide-area damping controller with robust pole placement to provide sufficient damping to the inter-area oscillations by placing the closed-loop poles in the prescribed stability region. The proposed controller is compared with two different controllers those are conventional power oscillation damping (POD), and H_∞ controller (these controllers are designed without considering time delay) to validate the performance of the proposed controller under communication network constraints.

II. Power system model

The power system consists of various components such as synchronous generators with their excitation systems, power system stabilizers (PSSs), FACTS controllers such as TCSC, SVC, and several loads. These different components are interconnected through the transmission network. The dynamic behavior of the components is modeled using a set of nonlinear differential and algebraic equations (DAEs) [1].

Consider the following differential algebraic equations to describe the dynamic of the power system.

$$\left.\begin{array}{rcl} \dot{x}_p & = & f(x_p(t), z(t), u(t)) \\ 0 & = & g(x_p(t), z(t), u(t)) \\ y_p & = & h(x_p(t), z(t), u(t)) \end{array}\right\} \tag{1}$$

where $x_p(t) \in \Re^{n_p}, z(t) \in \Re^r, u(t) \in \Re^m$ and $y_p(t) \in \Re^p$ denote the vectors of state variables, algebraic variables, inputs and outputs of power system respectively and f, g and h are vectors of differential, algebraic and output equations respectively.

Linearizing eq(1) around the equilibrium point and eliminating the algebraic variables, the state space representation of linearized power system defining by x_p, u and y_p as the state, input and output vectors, respectively, as follows

$$\left.\begin{array}{rl} \dot{x}_p = & A_p x + B_p u \\ y_p = & C_p x \end{array}\right\} \tag{2}$$

where $A_p \in \Re^{n_p \times n_p}$ is the state matix, $B_p \in \Re^{n_p \times m}$ the input matrix, $C_p \in \Re^{p \times n_p}$ the output matrix.

In low-frequency inter-area oscillation studies, the fast dynamics are not considered. Hence, the full-order model of the system is not necessary to consider in controller design. To simplify and speed up the controller design procedure generally the order of the system is reduced. By employing *Schur* model reduction method [12], only the poorly damped electromechanical modes are obtained in the reduced model. The reduced model of linearized model (2) is written as

$$\left.\begin{array}{rl} \dot{x}_r = & A_r x + B_r u \\ y_r = & C_r x \end{array}\right\} \tag{3}$$

where $A_r \in \Re^{n_r \times n_r}$, $B_r \in \Re^{n_r \times m}$ and $C_r \in \Re^{p \times n_r}$ are the reduced state space matrices. In reduced model, only the state variables and the state matrix are reduced in order, the inputs and outputs are remain same as the full-order model.

III. Network-based output feedback controller

A block diagram of closed-loop power system with the wide-area power system, communication network and Wide-area damping controller (WADC) as shown in Fig.1. The measured output y is sampled periodically and sent to the WADC through a communication network.

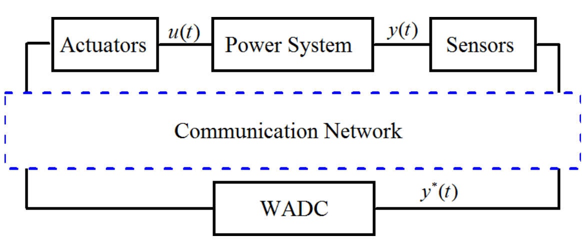

Fig. 1: A block diagram of power system with communication network

Consider d_k is the transmission delay that occurs when the measured output transferred from PMUs to the WADC at the updating instant t_k with sampling period h. The input of the controller is written as

$$\begin{aligned} u(t_k) &= y^*(t_k) \\ y^*(t_k) &= y(t_k - d_k), \quad 0 \le d_k \le \bar{d} \end{aligned} \tag{4}$$

Consider δ_k is the number of accumulated packet dropout since the last updating instant t_{k-1} at the updating instant t_k. Assume that $\bar{\delta}$ is the maximum number of consecutive packet dropout, that

$$0 \le \delta_k \le \bar{\delta} \tag{5}$$

From (4) and (5), it is observed that the upper bound and lower bound of any two successive updating instants are given by

$$h \le t_{k+1} - t_k \le \bar{d} + (\bar{\delta} + 1)h \tag{6}$$

Consider the following state space representation of the dynamic output feedback controller [13]

$$\begin{aligned} \dot{x}_c(t) &= A_c x_c(t) + A_d x_c(t-d) + B_c y^*(t) \\ u(t) &= C_c x_c(t) \end{aligned} \tag{7}$$

where $A_d x_c(t-d)$ term used to make the controller design tractable and d is the time delay.

Assume augmented closed-loop power system from (3) and (7) can be represented as

$$\dot{\xi}(t) = A_{cl}\xi(t) + A_{dl}\xi(t-d) \tag{8}$$

where $\xi(t) = \begin{bmatrix} x^T(t) & x_c^T(t) \end{bmatrix}^T$, $A_{cl} = \begin{bmatrix} A_r & B_r C_c \\ 0 & A_c \end{bmatrix}$, $A_{dl} = \begin{bmatrix} 0 & 0 \\ B_c C_r & A_d \end{bmatrix}$.

A. Robust pole placement

The location of poles will decide the transient response of a linear system. By placing poles of the system in a prescribed region with some specific bounds we can get the satisfactory transient response. The region of interest α-stability region $\mathrm{Re}(s) \le -\alpha$ as shown in Fig.2. To obtain the α-stability region,let image function of transformation operation be [14]

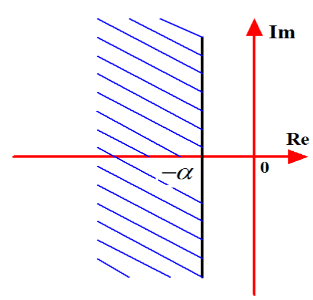

Fig. 2: α stability region

$$\eta(t) = \xi(t)e^{\alpha t} \tag{9}$$

where $\alpha > 0$ is represented as the prescribed degree of stability.

The transformed closed-loop system can be represented as

$$\dot{\eta}(t) = A_\eta \eta(t) + A_{d\eta}\eta(t-d) \tag{10}$$

where $A_\eta = \alpha I + A_{cl}, A_{d\eta} = A_{dl}e^{d\alpha}$.

B. Controller synthesis

Sufficient conditions for a dynamic output feedback controller with robust pole placement are formulated in LMI framework in theorem 1 by using Lyapunov criterion to make the closed-loop system (10) robust and asymptotically stable.

Theorem 1. *For given parameters $h, \bar{d}, \bar{\delta}$, the closed-loop system (10) is asymptotically stable, if there exist a $P = P^T > 0$, $Q = Q^T > 0$, $Y_1 = \begin{bmatrix} y_1 & y_2 \\ * & y_3 \end{bmatrix} > 0$, $Z_1 = \begin{bmatrix} z_1 & z_2 \\ * & z_3 \end{bmatrix} > 0$, $G_1 = \begin{bmatrix} g_1 & g_2 \\ g_4 & g_3 \end{bmatrix} > 0$, $H_1 = \begin{bmatrix} h_1 & h_2 \\ h_4 & h_3 \end{bmatrix} > 0$, A_k, A_{dk}, B_k, and C_k satisfying*

$$\begin{bmatrix} \Lambda_{11} + \Lambda_{11}^T + G_1 + G_1^T + Y_1 & \Lambda_{12} - G_1 + H_1^T & d\Lambda_{11}^T & dG_1 \\ * & -H_1 - H_1^T - Y_1 & d\Lambda_{12}^T & dH_1 \\ * & * & d\Lambda_{33} & 0 \\ * & * & * & dZ_1 \end{bmatrix} < 0 \tag{11}$$

$$\begin{bmatrix} P & I \\ * & Q \end{bmatrix} > 0 \tag{12}$$

where

$$\begin{aligned} \Lambda_{11} &= \begin{bmatrix} (A+\alpha I)P + BC_k & (A+\alpha I) \\ A_k & Q(A+\alpha I) \end{bmatrix}, \\ \Lambda_{12} &= \begin{bmatrix} 0 & 0 \\ A_{dk} & B_k C \end{bmatrix}, \\ \Lambda_{33} &= \begin{bmatrix} r_1 - 2P & r_2 - 2I \\ r_2^T - 2I & r_3 - 2Q \end{bmatrix} \\ d &= 2\bar{d} + (\bar{\delta}+1)h \end{aligned} \tag{13}$$

The following change of variables are used to define dynamic controller matrices

$$\left.\begin{aligned} A_c &= -\alpha I + O^{-1}(A_k - Q(A+\alpha I)P - QBC_k)N^{-T} \\ A_d &= O^{-1}(A_{dk} - B_k CPe^{d\alpha})N^{-T}e^{-d\alpha} \\ B_c &= O^{-1}B_k e^{-d\alpha} \\ C_c &= C_k N^{-T} \end{aligned}\right\} \tag{14}$$

where N and O are non-singular matrices satisfying

$$NO^T = I - PQ. \tag{15}$$

Proof. Consider the following Lyapunov candidate function

$$\begin{aligned} V(t) = &\eta^T(t)X\eta(t) + \int_{t-d}^{t} \eta^T(s)Y\eta(s)ds \\ &+ \int_{-d}^{0}\int_{t+\varphi}^{t} \dot{\eta}^T(s)Z\dot{\eta}(s)dsd\varphi \end{aligned} \tag{16}$$

where $X = X^T > 0, Y = Y^T > 0, Z = Z^T > 0$ are to be determined.

The derivatives of $V(t)$ defined in (16) along the trajectories of the closed-loop system (10) yields

$$\begin{aligned} \dot{V}(t) = &\dot{\eta}^T(t)X\eta(t) + \eta^T(t)X\dot{\eta}(t) + \eta^T(t)Y\eta(t) \\ &- \eta^T(t-d)Y\eta(t-d) + d\dot{\eta}^T(t)Z\dot{\eta}(t) \\ &- \int_{t-d}^{t} \dot{\eta}^T(s)Z\dot{\eta}(s)ds \end{aligned} \tag{17}$$

According to Leibniz - Newton formula

$$\eta(t) - \eta(t-d) = \int_{t-d}^{t} \dot{\eta}(s)ds,$$

for any appropriately dimensioned matrices G and H, the following equation hold,

$$0 = 2\left(\eta^T(t)G + \eta^T(t-d)H\right)\left[\eta(t) - \eta(t-d) - \int_{t-d}^{t} \dot{\eta}(s)ds\right] \tag{18}$$

Adding the terms on the right of (18) to $\dot{V}(t)$, it becomes

$$\begin{aligned} \dot{V}(t) = &\eta^T(t)\left(A_\eta^T X + XA_\eta + Y + dA_\eta^T ZA_\eta\right) \\ &+ \eta^T(t-d)\left(A_{d\eta}^T X + dA_{d\eta}^T ZA_\eta\right)\eta(t) \\ &+ \eta^T(t)\left(XA_{d\eta} + dA_\eta^T ZA_{d\eta}\right)\eta(t-d) \\ &+ \eta^T(t-d)\left(-Y + dA_{d\eta}^T ZA_{d\eta}\right)\eta(t-d) \\ &- \int_{t-d}^{t} \dot{\eta}^T(s)Z\dot{\eta}(s)ds + 2\eta^T(t)G\eta(t) - 2\eta^T(t)G\eta(t-d) \\ &+ 2\eta^T(t-d)H\eta(t) - 2\eta^T(t-d)H\eta(t-d) \\ &- 2\left(\eta^T(t)G + \eta^T(t-d)H\right)\int_{t-d}^{t}[\dot{\eta}(s)ds] \end{aligned} \tag{19}$$

$$\begin{aligned} \dot{V}(t) = &\eta^T(t)\left(A_\eta^T X + XA_\eta + Y + dA_\eta^T ZA_\eta + G + G^T\right)\eta(t) \\ &+ \eta^T(t-d)\left(A_{d\eta}^T X + dA_{d\eta}^T ZA_\eta - G^T + H\right)\eta(t) \\ &+ \eta^T(t)\left(XA_{d\eta} + dA_\eta^T ZA_{d\eta} - G + H^T\right)\eta(t-d) \\ &+ \eta^T(t-d)\left(-Y + dA_{d\eta}^T ZA_{d\eta} - H - H^T\right)\eta(t-d) \\ &- \int_{t-d}^{t}\left[\dot{\eta}^T(s)Z\dot{\eta}(s)ds + 2\left(\eta^T(t)G + \eta^T(t-d)H\right)\dot{\eta}(s)ds\right] \end{aligned} \tag{20}$$

Let $\phi(t) = \begin{bmatrix} \eta^T(t) & \eta^T(t-d) \end{bmatrix}^T$, then we can write (20) as follows

$$\dot{V}(t) = \phi^T(t)\psi_1\phi(t) - \int_{t-d}^{t}\left[\dot{\eta}^T(s)Z\dot{\eta}(s)ds + 2\phi^T(t)L\dot{\eta}(s)ds\right] \tag{21}$$

where

$$\psi_1 = \begin{bmatrix} A_\eta^T X + XA_\eta + Y + dA_\eta^T ZA_\eta + G + G^T & XA_{d\eta} + dA_\eta^T ZA_{d\eta} - G + H^T \\ * & -Y + dA_{d\eta}^T ZA_{d\eta} - H - H^T \end{bmatrix}$$

and $L=\begin{bmatrix}G\\H\end{bmatrix}$.

$$\begin{aligned}\dot{V}(t)=&\phi^T(t)\psi_1\phi(t)+\int_{t-d}^{t}\phi^T(s)LZ^{-1}L^T\phi(s)ds\\&-\int_{t-d}^{t}\left[\dot{\eta}^T(s)Z\dot{\eta}(s)+\phi^T(t)L\dot{\eta}(s)+\dot{\eta}^T(s)L^T\phi(s)\right]ds\\&-\int_{t-d}^{t}\phi^T(s)LZ^{-1}L^T\phi(s)ds\end{aligned} \tag{22}$$

$$\begin{aligned}\dot{V}(t)=&\phi^T(t)\left[\psi_1+dLZ^{-1}L^T\right]\phi(t)\\&-\int_{t-d}^{t}\left[\phi^T(s)L+\dot{\eta}^T(s)Z\right]Z^{-1}\left[L^T\phi(t)+Z\dot{\eta}(s)\right]ds\end{aligned} \tag{23}$$

From above equation we can see that $\dot{V}(t)<0$ due to

$$\left[\psi_1+dLZ^{-1}L^T\right]<0 \tag{24}$$

and

$$\left[\phi^T(s)L+\dot{\eta}^T(s)Z\right]Z^{-1}\left[L^T\phi(t)+Z\dot{\eta}(s)\right]>0 \tag{25}$$

because of $Z>0$.

By using Schur complement [15] on (24), is equivalent to

$$\begin{bmatrix}\Omega_{11} & XA_{d\eta}+dA_{\eta}^TZA_{d\eta}-G+H^T & dG\\ * & -Y+dA_{d\eta}^TZA_{d\eta}-H-H^T & dH\\ * & * & -dZ\end{bmatrix}<0 \tag{26}$$

where

$$\Omega_{11}=A_{\eta}^TX+XA_{\eta}+Y+dA_{\eta}^TZA_{\eta}+G+G^T$$

Using Schur complement, the above equation is equal to

$$\begin{bmatrix}A_{\eta}^TX+XA_{\eta}+Y+G+G^T & XA_{d\eta}-G+H^T & dA_{\eta}^TZ & dG\\ * & -Y-H-H^T & dA_{d\eta}^TZ & dH\\ * & * & -dZ & 0\\ * & * & * & -dZ\end{bmatrix}<0 \tag{27}$$

To design a dynamic output feedback controller, let us introduce the following non-singular matrices [16]

$$\delta_1=\begin{bmatrix}P & I\\ N^T & 0\end{bmatrix},\quad \delta_2=\begin{bmatrix}I & Q\\ 0 & O^T\end{bmatrix}. \tag{28}$$

Let $X=\delta_2\delta_1^{-1}$, then it is verified that

$$X=\begin{bmatrix}Q & O\\ * & \hat{Q}\end{bmatrix} \tag{29}$$

Define change of variables as follows

$$\left.\begin{aligned}A_k=&Q(A+\alpha I)P+QBC_cN^T+O(A_c+\alpha I)N^T\\A_{dk}=&OB_cCPe^{d\alpha}+OA_dN^Te^{d\alpha}\\B_k=&OB_ce^{d\alpha}\\C_k=&C_cN^T\end{aligned}\right\} \tag{30}$$

By performing a congruence transformation to (27) by $\mathrm{diag}\{I,I,XZ^{-1},I\}$, one gets

$$\begin{bmatrix}A_{\eta}^TX+XA_{\eta}+Y+G+G^T & XA_{d\eta}-G+H^T & dA_{\eta}^TX & dG\\ * & -Y-H-H^T & dA_{d\eta}^TX & dH\\ * & * & -dXZ^{-1}X & 0\\ * & * & * & -dZ\end{bmatrix}<0 \tag{31}$$

From $(Z-X)Z^{-1}(Z-X)\geqslant 0$ we know that $-XZ^{-1}X\leqslant Z-2X$. So we can write

$$\begin{bmatrix}A_{\eta}^TX+XA_{\eta}+Y+G+G^T & XA_{d\eta}-G+H^T & dA_{\eta}^TX & dG\\ * & -Y-H-H^T & dA_{d\eta}^TX & dH\\ * & * & d(Z-2X) & 0\\ * & * & * & -dZ\end{bmatrix}<0 \tag{32}$$

By performing a congruence transformation to (32) by $\mathrm{diag}\{\delta_1,\delta_1,\delta_1,\delta_1\}$, we obtain

$$\begin{bmatrix}\delta_1^TA_{\eta}^TX\delta_1+\delta_1^TXA_{\eta}\delta_1+\delta_1^TY\delta_1+\delta_1^TG\delta_1+\delta_1^TG^T\delta_1 & \delta_1^TXA_{d\eta}\delta_1-\delta_1^TG\delta_1+\delta_1^TH^T\delta_1 & \delta_1^TdA_{\eta}^TX\delta_1 & \delta_1^TdG\delta_1\\ * & -\delta_1^TY\delta_1-\delta_1^TH\delta_1-\delta_1^TH^T\delta_1 & \delta_1^TdA_{d\eta}^TX\delta_1 & \delta_1^TdH\delta_1\\ * & * & \delta_1^Td(Z-2X)\delta_1 & 0\\ * & * & * & -\delta_1^TdZ\delta_1\end{bmatrix}<0 \tag{33}$$

Define $Y_1=\delta_1^{-T}Y\delta_1^{-1}, Z_1=\delta_1^{-T}Z\delta_1^{-1}, G_1=\delta_1^{-T}G\delta_1^{-1}$, and $H_1=\delta_1^{-T}H\delta_1^{-1}$. Substitute Y_1,Z_1,G_1,H_1 in (33), we obtain

$$\begin{bmatrix}\delta_1^TA_{\eta}^TX\delta_1+\delta_1^TXA_{\eta}\delta_1+Y_1+G_1+G_1^T & \delta_1^TXA_{d\eta}\delta_1-G_1+H_1^T & d\delta_1^TA_{\eta}^TX\delta_1 & dG_1\\ * & -Y_1-H_1-H_1^T & d\delta_1^TA_{d\eta}^TX\delta_1 & dH_1\\ * & * & dZ_1-2d\delta_1^TX\delta_1 & 0\\ * & * & * & -dZ_1\end{bmatrix}<0 \tag{34}$$

By considering the change of variables, we obtain

$$\begin{aligned}\delta_1^TXA_{\eta}\delta_1&=\begin{bmatrix}(A+\alpha I)P+BC_k & (A+\alpha I)\\ A_k & Q(A+\alpha I)\end{bmatrix},\\ \delta_1^TXA_{d\eta}\delta_1&=\begin{bmatrix}0 & 0\\ A_{dk} & B_kC\end{bmatrix},\\ \delta_1^TX\delta_1&=\begin{bmatrix}P & I\\ * & Q\end{bmatrix}\end{aligned}$$

Hence, (11) is directly obtained from (34), and the proof is completed. □

IV. Case Study: Two-Area Four-Machine Benchmark system

A. System Description

The [17] two-area four-machine IEEE benchmark power system model is considered to validate the proposed controller as shown in Fig.3. The system consists of two areas and each area consisting of two generators and 5 buses. These two areas are weakly connected by tie-line bus, so there are total 11 buses and 4 generators in the whole system. The synchronous generators $G_i(i = 1,2,3,4)$ are represented by sixth order sub-transient model with state variables $\delta, \omega, E_d^{'}, E_q^{'}, \psi_{1d}, \psi_{2q}$, which are equipped with a simple fast acting first-order IEEE-ST1A type static excitation system. To damp out the local area oscillations G_1 and G_3 are equipped with a third-order PSS. The line data, bus data and the parameters of exciters are given in [17].

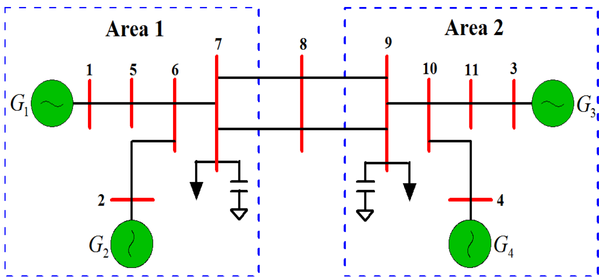

Fig. 3: Line diagram of Two-area four-machine system

B. Modal Analysis and Model-Order Reduction

From eigenvalue analysis, three electromechanical modes of oscillations are presented in the four-machine two-area system as shown in Table 1. Modal controllability and observability have been used to select a suitable controller placement and feedback signals for damping controller design. G_1 as taken the controller location and $\Delta\omega_{13}$ as taken as a feedback signal, these having higher controllability and observability corresponding to the critical oscillatory mode.

TABLE I: Inter-Area Mode of four machine two area System

Mode	ζ	$f(Hz)$
Inter-area	0.0717	0.6534
Local	0.1752	1.2186
Local	0.1684	1.2686

By considering G_1 as the input and $\Delta\omega_{13}$ as feedback output signal, the power system model is linearized at the equilibrium point. The size of the linearized model is 34^{th} order which gives complexity in the controller design. To make the controller design convenient and feasible, the model order reduction is required. By using balanced model reduction method [12], the original system is reduced to 7^{th} order. The reduced order model retains the information about the poorly damped electromechanical oscillatory modes of the full order model. The validation of the reduced model is done by using frequency response as shown in Fig.4. The frequency response of the reduced-order model is the same as the full order model in the desired frequency range and the peak responses of these models occur at a frequency about 4.1 rad/sec, which is the same as the imaginary part of the inter-area oscillation mode. Hence, the 7^{th} order reduced model is used for the design of the proposed controller.

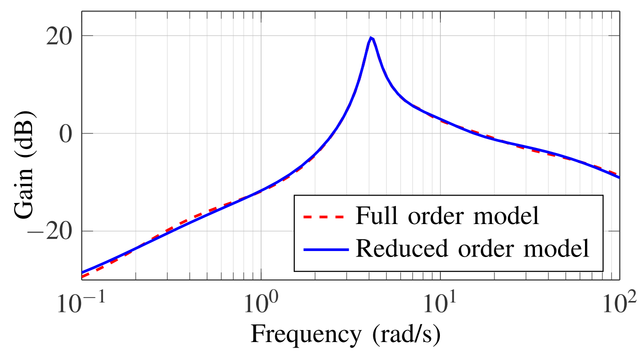

Fig. 4: Frequency response of the full vs. the reduced system

V. Results and Discussion

The 7^{th} order reduced model used to design a dynamic controller to enhance the damping of inter-area oscillations when the feedback signals experience communication network constraints such as networked induced delays, packet dropouts, and packet disordering. To place the closed-loop poles of the system in a prescribed region, the robust pole placement approach is involved in the controller design process. In this work, we placed the closed-loop poles in the left half s-plane with $\alpha-$stability ($\alpha = 1$). The dynamic controller matrices are obtained by solving Theorem 1 given in section III-B by considering $h = 0.01s, \bar{d} = 0.1s$ and $\bar{\delta} = 0$.

Nonlinear simulations are performed in MATLAB/Simulink for validation of the proposed robust dynamic output feedback controller. The disturbance $3-\phi$ ground fault is applied on transmission line #8-#9 at $1sec$ with duration of $100ms$ is considered as the disturbance for the case study. Fig.5, Fig.6, and Fig.7 show the dynamic behavior of the closed-loop system. Performance evaluation of proposed controller is compared with Conventional Power oscillation damping (POD) and H_∞ controller. Fig.5 exhibits the response of the speed deviation of G1 and G3 ($\Delta\omega_{13}$) without delay with different controllers. That controller along with proposed one gives good performance when the feedback signals do not experience any delay. Fig.6 shows the response of the speed deviation of G1 and G3 ($\Delta\omega_{13}$) with a delay with different controllers. From Fig.6 we can see that the oscillations are settled with the proposed controller compared to the remaining controller when the feedback signals experience a delay ($d = 100$ms). The proposed controller stabilizes the test power system even if the delay reaches $d = 400$ms as shown in Fig.7. The robustness of the proposed controller is shown in Figures 7 and 8. Fig.7 and 8 show that response to the speed deviation of G1 and G3 when the delay increases and for random delay respectively. From the above results, it can be seen that the proposed dynamic controller is effectively damp the inter-area oscillation even when the feedback signals experience the networked induced delays.

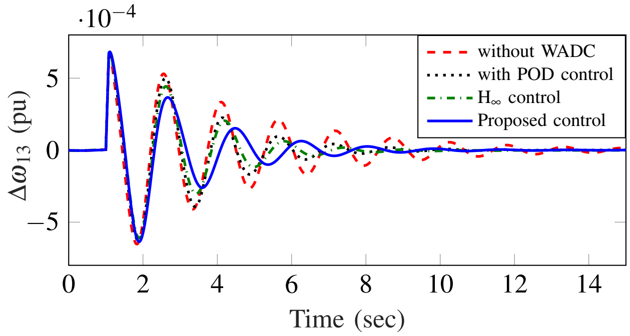

Fig. 5: Speed deviation of G1-G3 without delay

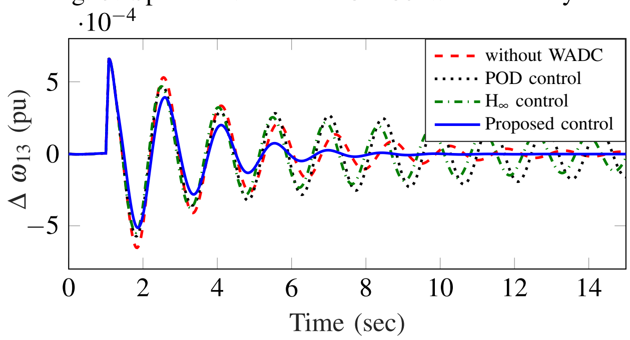

Fig. 6: Speed deviation of G1-G3 with delay

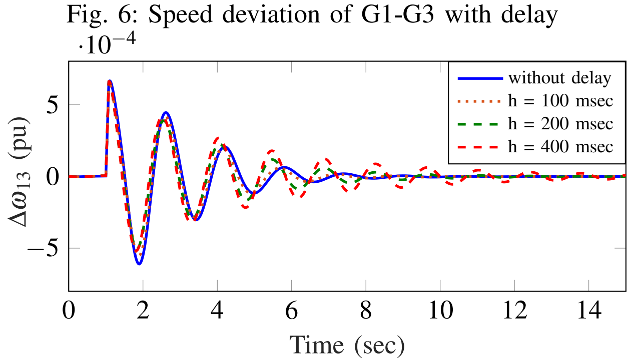

Fig. 7: Speed deviation of G1-G3 with delay proposed control

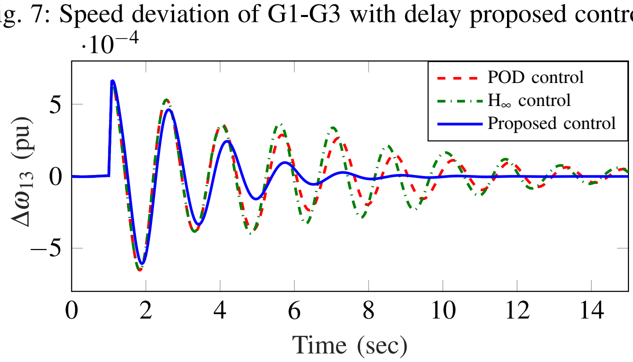

Fig. 8: Speed deviation of G1-G3 with random delay

VI. Conclusion

This paper presents the design of dynamic output feedback controller with robust pole placement to reduce the effect of communication network constraints on the power system performance and stability. Wide-area signals are used as feedback signals to the proposed controller and these signals are transferred by using communication network. The network constraints are described by using networked control system model for the power system. Stabilization of closed-loop system with communication network constraints have been formulated in LMI framework by using quadratic Lyapunov criterion. The designed dynamic damping controller guarantees the asymptotic stability for the closed-loop system with aforesaid problems by provides sufficient damping to the inter-area oscillations. From the results obtained on the two-area four machine case study, it is concluded that the proposed control gives improved results in terms of the settling time and amplitude reduction compared to the conventional POD controller and H_∞ controller.

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