Mode Selective Damping of Electromechanical Oscillations Using Supplementary Remote Signals and Design of Delay Compensator

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ABSTRACT

The objective of this paper is to design an H_∞-based local decentralized PSS (Power System Stabilizing) controller. The controller is designed for separate damping of specific inter-area modes while considering time-delay. The controller uses remote signals, selected suitably from the whole system, as supplementary inputs. The wide area or global signals have been obtained where the oscillations in the remote network locations could be well observed. The PSS controller uses only those local and remote input signals in which the assigned single inter-area mode is most observable and is located at a generator which is most effective in controlling that mode. A long time-delay due to remote signal transmission and processing in WAMS (Wide Area Measurement System) can cause system instability and degradation of system robustness. Therefore, this paper uses the time-delay compensation method that uses lead or lag adjustment method while integrates the gain scheduling to overcome the impacts of constant time-delay. The effectiveness of the resulting PSS controllers is established through simulations using three machine three area test power system.

Key Words: **Inter-Area Modes, PSS, Remote Signals, WAMS, Time-Delay, H_∞ Control.**

1 INTRODUCTION

With the worldwide rise in electrical energy demand, the large power systems especially those responsible for meeting heavy load demands operate to their maximum capacity. The aforementioned operating conditions enhance the chances of inter-area oscillations that may lead to the breakup of whole system [1]. These systems are especially vulnerable to the weakly damped oscillations between the areas and even the energy may not be supplied to the required quality. The possible increase in the power supplies indicates the possibility of a decrease in damping of oscillations between different areas unless new power transmission lines are constructed. However, the heavy costs and possible adverse impacts on environment bar

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us construction of new lines. Therefore, the maximum available transfer capability and high level of power quality and security can be achieved by better system stability control which leads to damping improvement.

It is reported that the inter-area oscillations can be well damped in case the signals from remote locations of the system are used during the design of the controller [2]. The remote signals are useful as compared to local control signals as the former can provide network dynamic statistics while the latter lack information on inter-area modes [3]. The WAM (Wide Area Measurement) technologies are useful in this regard as they use PMUs (Phasor Measurement Units) that are capable of transferring high speed synchronous control signals [4]. The global signals are measured with PMUs and delivered to the controllers via state of the art telecom tools. The remote signals may arrive after a certain delay, due to their transmission and processing in WAMS. A control system may loose synchronism as time-delay may result in less damping. The time-delay, therefore, should be considered as a prime factor while designing a controller.

The mode selective damping of electromechanical oscillations using supplementary remote signals without time-delay factor has been discussed in [5]. This paper presents the design of local decentralized PSS controller for better separate damping of inter-area oscillations while overcoming the time-delay factor using the lead/lag compensation method [6]. The primary plan for this kind of work is given in Fig. 1 [5,7]. The measured variables are received as inputs for PSS from the whole system [7]. Hence, PSS receives comprehensive measurement information, regarding the damping of inter-area oscillations. The proposed PSS controllers have been designed using H_∞-based robust control technique. In order to demonstrate the usefulness of the suggested controllers, numerical simulations have been carried out on a three-machine, three-area test power system [5].

Besides the introduction given in Section 1, the remaining paper includes Section 2 that describes the concept of mode selective damping. Section 3 illustrates the design of time-delay compensator for compensating the effect of

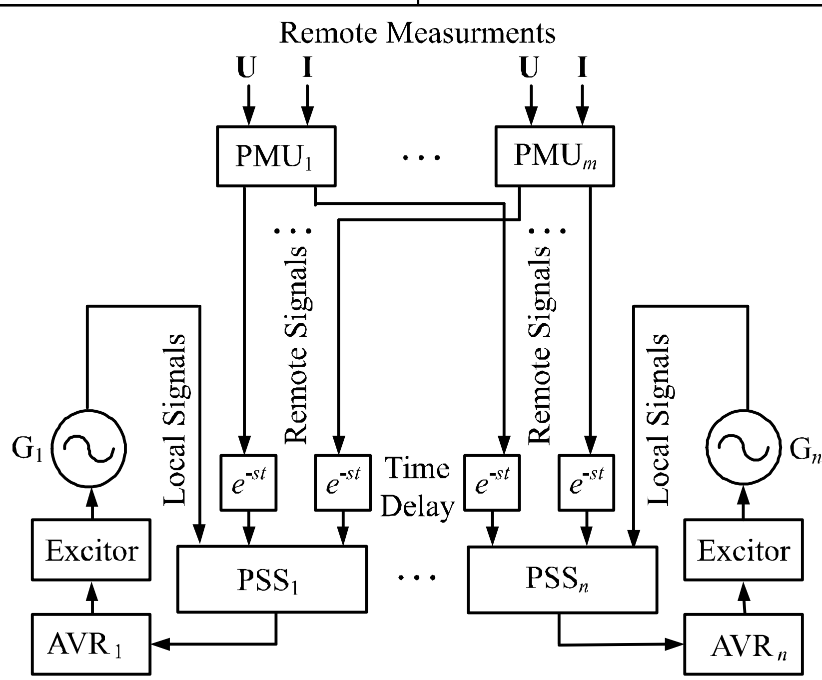

FIG. 1. MULTI-MACHINE POWER SYSTEM WITH PSS USING GLOBAL SIGNALS

time-delay. Section 4 discusses the design of PSS controller that is based on robust H_∞ dynamic output feedback. The application and results for the dynamic model of three-machine three-area test power system are given in Section 5. The conclusions and references are given in Sections 6 and 7, respectively.

2. CONCEPT OF MODE SELECTIVE DAMPING

The mode selective damping strategy requires that each PSS controller systems, like the one in Fig. 1, should be set separately for each inter-area mode under consideration. Each designed PSS controller uses local and supplementary remote input signals in which a specific single inter-area mode is most observable and the designed PSS controller is located at a generator which is most effective in controlling the same single inter-area mode.

3. DESIGN OF TIME DELAY COMPENSATOR

The time-delay factor is controlled by designing time-delay compensator that consists of lead/lag and gain modules. Time-delay causes an oscillatory mode (σ+jω) to initiate a phase lag with regards to angular frequency ω and gain amplification with regards to damping σ. Consequently, whole system could be unstable as eigen value may move to an unacceptable location on complex plane. Phase lag ϕ due to time- delay τ is $\phi=\omega\tau$ while the gain amplification γ_c due to time-delay τ is $\gamma_c=e^{-\sigma\tau}$ [6].

Fig. 2 shows how time-delay could possibly be counter-balanced in phase through gain scheduling and lead/lag compensation block [6]. In Fig. 2, output signals Y_{1df} of delay-free system plant P(s) are the remote input signals of the PSS controller. The time-delay, introduced by the remote input signals' transmission and processing, therefore, occurs only in Y_{1df}. In order to compensate effect of this delay on the system performance, Y_{1df} are added to the delay compensator $H_c(s)$. The output signals Y_{1d} of delay compensator, therefore, represents the delayed supplementary remote input signals of the PSS controller C*(s)*. The output signal Y_{2df} of delay-free system plant is the local input signal to the controller and is, therefore, without time delay [6].

Transfer function of delay compensator is given as under:

$H_c(s) = K[(1+sT_1)/(1+sT_2)]^2$

where

$$T_1 = 1/(\omega\sqrt{\alpha}), T_2 = \alpha T_1, \alpha = [1 - \sin(\phi/2)]/[1+\sin(\phi/2)],$$
$$K = \beta e^{\sigma\tau}, 0 \prec \beta \prec 1$$

Phase lead ($\phi=\omega\tau$) provided by delay compensator balances the phase lag due to time delay τ. Gain K provided by delay compensator decreases the gain amplification γ_c due to time delay τ.

4 DESIGN OF PSS CONTROLLERS FOR POWER SYSTEMS

4.1 Problem Formulation

After merging the controller in the multi-machine power system, the compact form of overall extended system equations is given [6]:

$$\dot{\tilde{\mathbf{x}}}(t) = \mathbf{A}_{cl}\tilde{\mathbf{x}}(t) + \mathbf{B}_{cl}\mathbf{w}(t) \quad (1)$$

$$\mathbf{z}(t) = \mathbf{C}_{cl}\tilde{\mathbf{x}}(t) + \mathbf{D}_{cl}\mathbf{w}(t) \quad (2)$$

where $\tilde{\mathbf{x}}(t) = \left[\mathbf{x}^T(t) \quad \mathbf{x}_c^T(t)\right]^T$ is the augmented state vector for the closed-loop system, x(t) is the state vector of the

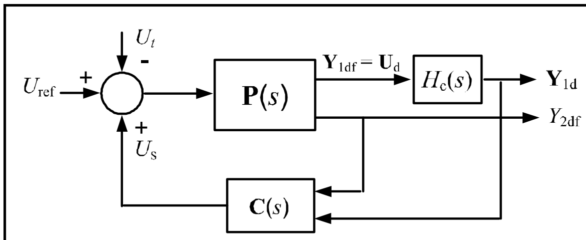

FIG. 2. FRAMEWORK OF WIDE AREA DAMPING CONTROL

open-loop system augmented by weighting functions, and $\mathbf{x}_c(\mathbf{t})$ is the state vector of the controller. Separate damping of each mode is accomplished by selecting performance weighting functions in a way that the PSS controller belonging to a specific assigned single mode works primarily in the frequency band of that mode.

4.2 Robust H_∞ Based PSS Output Feedback Controller Design

In order to design an H_∞ controller for the system, a controller matrix need to be found that assures an H_∞ norm bound condition on the closed loop transfer function $\mathbf{T}_{zw}(s)=\mathbf{C}_{c1}(sI-\mathbf{A}_{c1})^{-1}B_{c1}$ from disturbance $\mathbf{w}(t)$ to the controlled output $\mathbf{z}(t)$ in Fig. 3 [5], i.e. $\|\mathbf{T_{zw}}(s)\|_\infty < \gamma$ (for a given scalar constant γ>0). An ARE (Algebraic Riccati Equation) approach [8] is employed for determining the existence of control strategy. In this study, sequential design [9] is used to design the proposed PSS controllers.

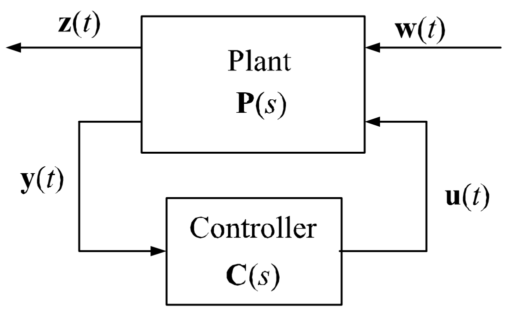

FIG. 3. LFT FRAMEWORK REPRESENTING GENERAL INTERCONNECTED SYSTEM

5. APPLICATION AND RESULTS

5.1 Power System Simulation Model

Three-machine, three-area power system example [5], shown in Fig. 4, is selected to apply the control design approach presented in the previous section. The system in the example consists of three equivalent synchronous generators each representing one of the three areas. The generators are connected with long transmission lines and this set-up causes the system inter-area oscillations. Further detail of the aforementioned test system, controllers and their parameter values, and base operating conditions are given in [5]. The structural detail of the ith generator with-order PSS controller in a multi-machine power system as given in [6] is used for the numerical simulations and PSS design.

The results for the selection of suitable local and remote input signals and locations of local decentralized PSS controllers, designed to damp out the two most weakly damped inter-area modes in the considered test system are give in Table 1 [5].

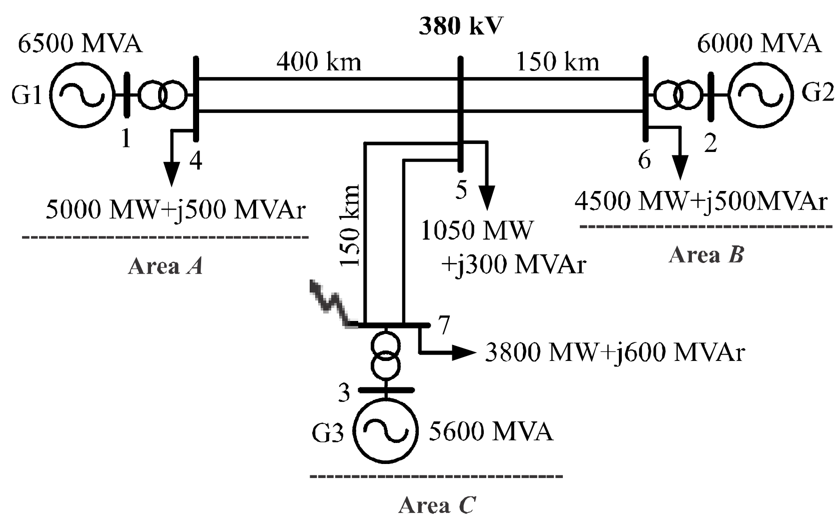

FIG. 4. SCHEMATIC DIAGRAM OF A THREE-MACHINE THREE-AREA POWER TEST SYSTEM

5.2 Design Results

The measured signals P_2 and P_{56} are used as feedback input signal during the design of PSS controller for the inter-area mode 1, i.e. $y(t)=[P_2(t)\ P_{56}(t)]^T$. The inputs to the exciter that includes the measured signals (i.e. P_2 and P_{56}), and the output from the PSS along with the terminal voltage error signals, are taken as regulated signals within the design framework, i.e. $\mathbf{z}(t)=[P_2(t)\ P_{56}(t)\ u_{s1}(t)]^T$. The measured signals P_3 and P_{57} are used as feedback input signals, during the design of PSS controller for the inter-area mode 2, i.e. $\mathbf{z}(t)=[P_3(t)\ P_{57}(t)\ u_{s2}(t)]^T$. The inputs to the regulator of the exciter, that includes P_3 and P_{57}, the output of the PSS and the terminal voltage error signals, are used as regulated signals within this design framework, i.e. $\mathbf{y}(t)=[P_3(t)\ P_{57}(t)\ u_{s2}(t)]^T$. The design procedure described in Section 3 is used to design the controller. Balanced residualization technique [10] is applied to reduce the order of controllers at each of the stages of design.

5.2.1 Sequential Design of PSS Controllers

Table 2 [5] provides description of the sequences for the design of controllers. Note that first control loop consists of plant and the PSS controller together with delay compensator, designed for inter-area mode 1, located at G2 and the second control loop consists of plant and the PSS controller together with delay compensator, designed for inter-area mode 2, located at G3.

5.2.1.1 First Sequential Design

Table 3 provides the profile of two weakest damped inter-area modes of the test system with the controllers designed for inter-area modes 1 and 2 without considering time-delay. The Table 3 describes simulation case 1 where the remote signals are supplied to the controllers with no time-delay and with no time-delay compensator added [5]. Conversely, the table contains the detail of simulation case 2 where the remote signals are supplied to the controllers with time-delay of 500 ms but with no time-delay compensator added.

TABLE 1. SELECTED LOCAL AND SUPPLEMENTARY REMOTE SIGNALS AND LOCATIONS FOR THE PSS CONTROLLERS

Mode No.	Local Signals to Controllers	Remote Signals to Controllers	Locations of Controllers to be Designed
1	P_2	P_{56}	Generator G2
2	P_3	P_{57}	Generator G3

TABLE 2. TWO POSSIBLE SEQUENTIAL DESIGNS OF CONTROLLERS

Sequential Design No.	Sequences for the Design of Controllers
1	(i) PSS controller for inter-area mode 1 is designed first without considering time delay in its remote input signal and with keeping the second control loop open. Delay compensator for inter-area mode 1 is then designed, to overcome the impact of time-delay in the remote input signal of PSS controller for inter-area mode 1.
	(ii) PSS controller for the inter-area mode 2 is then designed without considering time delay in its remote input signal and with keeping the first control loop closed, i.e., with the PSS controller already designed, without considering delay in its remote input signal, and the delay compensator for inter-area mode 1 located at generator G2 in the test system. Delay compensator is then designed, to diminish the effect of time delay in the remote input signal of PSS controller for inter-area mode 2.
2	(i) PSS controller for inter-area mode 2 is designed first without considering time delay in its remote input signal and with keeping the first control loop open. Delay compensator for inter-area mode 2 is then designed, to diminish the effect of time delay in the remote input signal of PSS controller for inter-area mode 2.
	(ii) PSS controller for the inter-area mode 1 is then designed without considering time delay in its remote input signal and with keeping the second control loop closed, i.e., with the PSS controller already designed, without considering delay in its remote input signal, and the delay compensator for inter-area mode 2 located at generator G4 in the test system. Delay compensator is then designed, to diminish the effect of time delay in the remote input signal of PSS controller for inter-area mode 1.

The H_∞-based PSS controller designed for the inter-area mode 1, without considering time delay in its remote input signal, is given as [5]:

$$\mathbf{C}_{11}(s) = \left[\; 24.878\frac{(1+s\,0.0314)(1+\;s3.9918)}{(1+s\,0.1984)(1+s\,0.2559)} \quad 13.49\frac{(1+s0\,.0159)(1+s\,2.6202)}{(1+s\,0.1984)(1+s\,0.2559)} \;\right]$$

Assuming that the time-delay of the input signal $P_{56}(t)$ to the controller is 500 ms, time-delay compensator could be designed, as per the procedure given in Section 2, as given:

$$0.15\left[\frac{(1+s\,0.7379)}{(1+\;s\,0.0257)}\right]^2$$

Table 4 provides the profile of two weakest damped inter-area modes of the test system with the controller designed for inter-area mode 1 only and controllers for both modes 1 and 2 without considering time-delay. Table shows simulation case 3 where controller designed for inter-area mode 1 is supplied a remote signal with a time-delay of 500 ms and with time-delay compensator added.

The PSS controller for the inter-area mode 2 is now designed keeping the first control loop closed, i.e. with the PSS controller already designed, without considering delay in its remote input signal, and the delay compensator for inter-area mode 1 located at generator G2 in the test system. The H_∞-based PSS controller for the inter-area mode 2, without considering time delay in its remote input signal, obtained is:

$$\mathbf{C}_{22}(s) = \left[\; 10.30\frac{(1+s\,0.1013)(1+s\,0.3014)}{(1+s\,0.3827)(1+s\,0.0185)} \quad 20.1\frac{(1+s\,0.61)(1+s\,0.23)}{(1+s\,0.2627)(1+s\;0.3285)} \;\right]$$

By considering that the time delay in the remote input signal $P_{57}(t)$ of the PSS controller is 500 ms and following the procedure described in Section 2, delay compensator designed is:

$$0.2\left[\frac{(1+s\,0.5217)}{(1+\;s\,0.0291)}\right]^2$$

Table 4 also provides the detail of simulation case 4 where controllers designed for inter-area mode 1 and 2 are supplied remote signals with time-delay of 500 ms and with their corresponding time-delay compensators added.

5.2.1.2 Second Sequential Design

Table 5 provides the profile of two weakest damped inter-area modes of the test system with the controllers designed for inter-area modes 1 and 2, without considering time-delay. The Table 5 details simulation case 5 where the remote signals are supplied to the controllers with time-delay of 500 ms while the corresponding time-delay compensators were added.

Comparison of results for the first and second sequential designs show that the damping of inter-area modes 1 and 2 has increase more in second sequential design than in the first sequential design. Therefore, it is concluded that second sequential design is better than the first one.

TABLE 3. WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

Inter-Area Mode No.	Simulation Case 1			Simulation Case 2		
	Eigen Value	ζ (%)	Frequency (Hz)	Eigen Value	ζ (%)	Frequency (Hz)
1	-1.3874+4.3612	30.32	0.69	-0.5274+4.5632	13.32	0.68
2	-3.2558+6.8934	42.71	1.10	-0.4358+5.8934	9.71	0.91

TABLE 4. WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

Inter-Area Mode No.	Simulation Case 3			Simulation Case 4		
	Eigen Value	ζ (%)	Frequency (Hz)	Eigen Value	ζ (%)	Frequency (Hz)
1	-1.2274+4.1632	32.32	0.69	-1.2274+4.1632	32.32	0.69
2	-0.4358+5.8934	9.71	0.91	-1.0358+5.8934	25.71	0.92

5.3 Time-Domain Simulation Results

Simulations have been carried out by applying a balanced three-phase fault for 100 ms at bus 7, to study the system response under a situation of disturbance.

5.3.1 Second Sequential Design of PSS Controllers

The behavior of deviation of real power delivered by generator G3 ($\Delta P_{G3}(t)$), with the PSS controllers designed for the inter-area modes 1 and 2 without considering time-delay in their remote input signals, no time-delay in their remote input signals and no delay compensator added. with 500 ms time delay in their remote input signals and no delay compensator added with 500ms delay in their remote input signals and their corresponding delay compensators added as shown in Fig. 5. Fig. 5 indicates that the behavior of deviation of $\Delta P_{G3}(t)$, with PSS controllers designed for inter-area modes 1 and 2 without considering time-delay, becomes oscillatory when a constant delay of 500ms is included in the remote input signals during simulation. However, Fig. 5 shows that for a time-delay of 500ms, the behavior of $\Delta P_{G3}(t)$ is better damped with the PSS controllers, which were designed with no time-delay, while integrated in corresponding compensators.

TABLE 5. WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

Inter-Area Mode No.	Simulation Case 5		
	Eigen Value	ζ (%)	Frequency (Hz)
1	-1.374+4.1632	38.32	0.70
2	-1.2358+5.8934	30.71	0.93

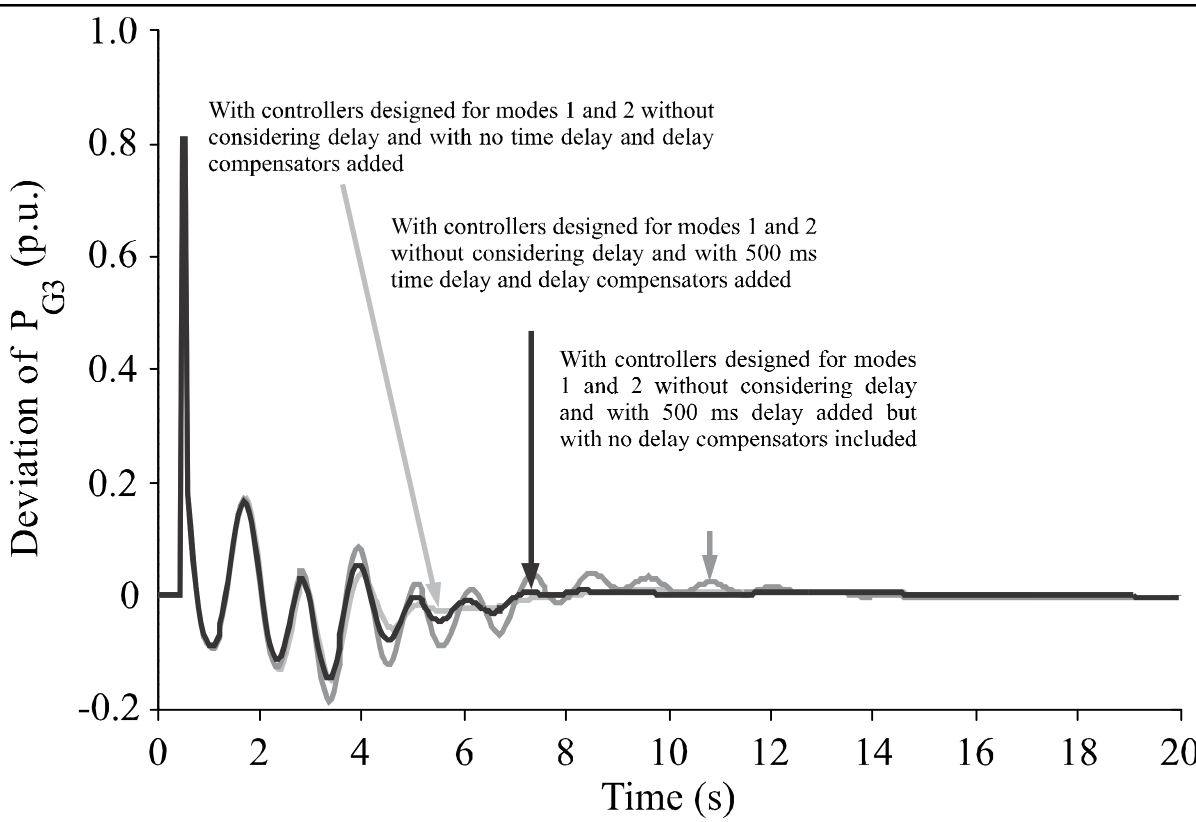

FIG. 5. DEVIATION OF $P_{G3}(t)$ ($\Delta P_{G3}(t)$), FOLLOWING A THREE-PHASE FAULT AT BUS 7 IN THE TEST SYSTEM

6 CONCLUSION

The paper discusses local decentralized control design approach that includes separate damping of inter-area modes and considers time-delay in remote signals. The proposed method is applied on a three-machine, three-area test power system. Two local decentralized robust H_∞-based PSS controllers have been designed for two weakest damped inter-area modes present in the test power system. The PSS controller for an assigned single inter-area mode is designed first without considering time delay in its remote input signal keeping the other control loop open. Delay compensator for that assigned single inter-area mode is then designed, to diminish the effect of time delay in the remote input signal of the corresponding PSS controller, while keeping the other control loop open. Conversely, PSS controller for the other assigned single inter-area mode is then designed without considering time delay while keeping the first control loop closed, i.e. with the PSS controller already designed, without considering delay, and the delay compensator for first assigned single inter-area mode located in the test system. Delay compensator is then designed, to diminish the effect of time delay in the remote input signal of PSS controller for the other assigned single inter-area mode, with keeping the first control loop closed. Each of the two controllers, designed for the test power system uses only those local and remote feedback input signals in which the assigned inter-area mode is highly observable and is located at a generator which is highly effective in controlling the same assigned inter-area mode. The two PSS controllers for the test power system are designed in such a way that each of them is effective only in a frequency band given by the natural frequency of the corresponding assigned mode. The two PSS controllers, therefore, damp only their corresponding assigned inter-area modes. The nonlinear simulation results show that the designed delay compensators, when cascaded with designed controllers, can help to overcome the inter-area oscillations damping problem substantially. This would also enhance small-signal stability in the presence of time-delay in the remote input signal of controllers.

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