Delayed-Input Wide Area Power System Stabilizer for Mode Selective Damping of Electromechanical Oscillations

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RECEIVED ON 13.06.2010 ACCEPTED ON 03.01.2011

ABSTRACT

A long time delay due to the transmission and processing of remote signal may degrade stability of power system. This paper discusses the design of H_∞-based local decentralized delayed-input PSS (Power System Stabilizer) controllers for a separate better damping of inter-area modes. The controllers use selected suitable remote signals from whole system as supplementary inputs. The local and remote input signals, used by the controller, are the ones in which the assigned single inter-area mode is most observable. The controller is located at a generator which is most effective in controlling the assigned mode. The controller, designed for a particular single inter-area mode, also works mainly in the natural frequency of the assigned mode. Pade approximation approach is used to model time delay. The time delay model is then merged into delay-free power system model to obtain the delayed-input power system model. The controllers are then redesigned for the delayed-input system.

Key Words: **Mode Selective Damping, PSS, Global Signals, Time Delay, Pade Approximation.**

1 INTRODUCTION

Because of the deregulation of electrical energy markets throughout the world, tie lines connected to the heavy load areas, are operating close to their maximum capacity. The possibility of inter-area oscillations increase under stressed operating conditions. Heavy loading conditions may also lead to the breakup of the whole system [1]. Weakly damped inter-area oscillations are harmful for the reliability and the quality of the supplied electrical energy. The damping of inter-area oscillations may increase if new lines are built. However, due to environmental and cost factors, construction of new lines is limited. Therefore, the maximum available transfer capability and better power quality and security can be achieved by that system stability control which improves damping.

The damping of inter-area oscillations can be enhanced, if during the design of the controller, the signals from remote locations of the power system are used [2]. The remote signals contain information about the whole network dynamics while the local signals have less observability of some important inter-area modes [3]. PMUs (Phasor Measurement Units) transfer control signals at higher speed [4]. PMUs, placed at important locations on the

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grid, obtain complete information of whole network in real time [4]. Time synchronization among several remote signals is made by GPS (Global Positioning System) [4]. The measured remote signals are then transmitted to the controllers using telecommunication equipment. Because of the transmission and processing of remote signals in WAMS (Wide Area Measurement Systems), remote signals may reach the controllers after a certain communication delay. Closed-loop system may fail to maintain stability if a controller designed without taking into account time delay is applied to the system which receives delayed signals [5]. Therefore, time delay must be taken into consideration while designing a controller.

The design of delayed-input wide area power system stabilizer for mode selective damping of power system electromechanical oscillations has been presented in this paper. In mode selective damping technique [6], each of the PSS controllers has to be designed separately for each of the inter-area modes of interest. The local and supplementary remote input signals, used by each of the designed PSS controllers, are the ones in which a specific single inter-area mode is most observable. The generator which is highly effective in controlling the assigned mode is selected as the location of the controller. Pade approximation method is used to describe the time delay [5]. The architecture [7] used in this work is shown in Fig. 1. PSS inputs are the measured signals which come from the complete system [7].

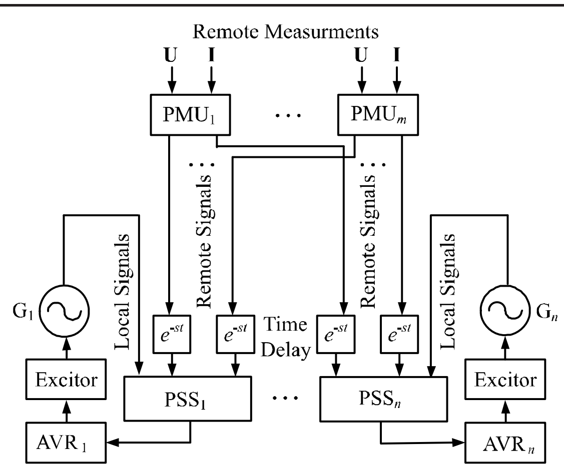

FIG. 1. MULTI-MACHINE POWER SYSTEM WITH PSS USING WAMS

The remaining paper is organized as follows. Section 2 describes the design of robust H_∞-based dynamic output feedback PSS controller. Section 3 presents the application results for a dynamic model of three-machine, three-area test power system. The conclusions are discussed in Section 4. References are given in Section 5.

2. DESIGN OF ROBUST H_∞-BASED PSS CONTROLLERS

The overall extended system equations for the augmented system (with the controller merged into the multi-machine power system) are described as follows [6-7]:

$$\dot{\mathbf{x}}_{ex}(t) = \mathbf{A}_{ex}\mathbf{x}_{ex}(t) + \mathbf{B}_{ex}\mathbf{w}(t) \tag{1}$$

$$\mathbf{z}(t) = \mathbf{C}_{ex}\mathbf{x}_{ex}(t) + \mathbf{D}_{ex}\mathbf{w}(t) \tag{2}$$

where $\mathbf{x}_{ex}(t)=[\mathbf{x}^T(t)\ \mathbf{x}^T_{com}(t)]^T$ is the augmented state vector for the closed-loop system, $\mathbf{x}(t)$ is state vector of open-loop system augmented by weighting functions, and $\mathbf{x}_{con}(t)$ is state vector of the controller. Designing an H_∞ controller for the system is equivalent to that of finding the controller matrix, in Equations (1-2), that internally stabilizes closed loop transfer functions $\mathbf{T}_{zw}(s)$ and fulfills an H_∞ norm bound condition on $\mathbf{T}_{zw}(s)=\mathbf{C}_{ex}(sI-\mathbf{A}_{ex})^{-1}\mathbf{B}_{ex}$ from disturbance $\mathbf{w}(t)$ to the regulated outputs $\mathbf{z}(t)$ (Fig. 2) [5-7], i.e. for a certain prescribed disturbance attenuation level $\gamma > 0, \left\|\mathbf{T}_{zw}(s)\right\|_\infty < \gamma$. To implement aforementioned described control technique, an ARE (Algebraic Riccati Equation) approach [8] can be applied. For the design of proposed PSS controller, sequential design [9] has been used.

3. APPLICATION RESULTS

3.1 Power System Simulation Model

Three-machine, three-area test power system [5], shown in Fig. 3, has been chosen to apply and show the effectiveness of proposed controller design approach. The considered test power system has three equivalent synchronous generators, each representing one of the three areas. The generators are connected with long transmission lines, therefore, system experiences inter-area oscillations during disturbances. All generators are equipped with identical IEEE standard exciters (IEEE type DC1A excitation system). Loads are represented as constant impedances and are connected to buses 4, 5, 6, and 7. The generators are represented by their fifth-order models. The fault used in the time domain simulation is located at bus 4. Detailed information about this test system is given in [5]. The i^{th}-generator and the n^{th}_{ci}-order PSS controller in a multi-machine power system given in [6] is considered for all simulation studies and the PSS design.

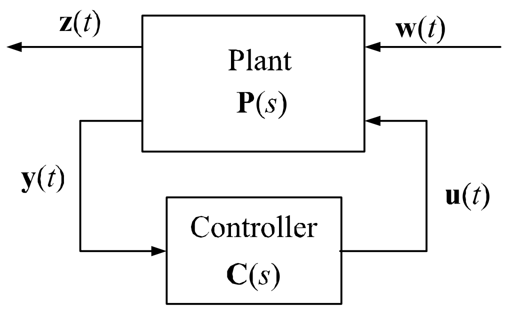

FIG. 2. LFT FRAMEWORK REPRESENTING A GENERAL INTERCONNECTED SYSTEM

3.2 Selection of Suitable Local and Remote Input Signals and Locations for PSS Controllers

3.2.1 Engineering Pre-Selection of Features or Measurements

Table 1 provides the detail of the features selected by engineering judgment [5] for the test system shown in Fig. 3.

3.2.2 Features' Selection Using Cluster Algorithm

Final pre-selected features are obtained by using k-Means cluster algorithm [5] and including engineering knowledge [5] in the selection process. Table 2 lists final pre-selected features. Fig. 4 shows the amplitude gains of frequency responses of final pre-selected features, listed in Table 2.

3.2.3 Selection of Suitable Locations for Controllers

Following the procedure described in [5], θ_{V5} is found to be the best-suited measurement. Now, for finding suitable locations of two controllers, the frequency responses of θ_{V5} are obtained to the inputs at generators G1, G2, and

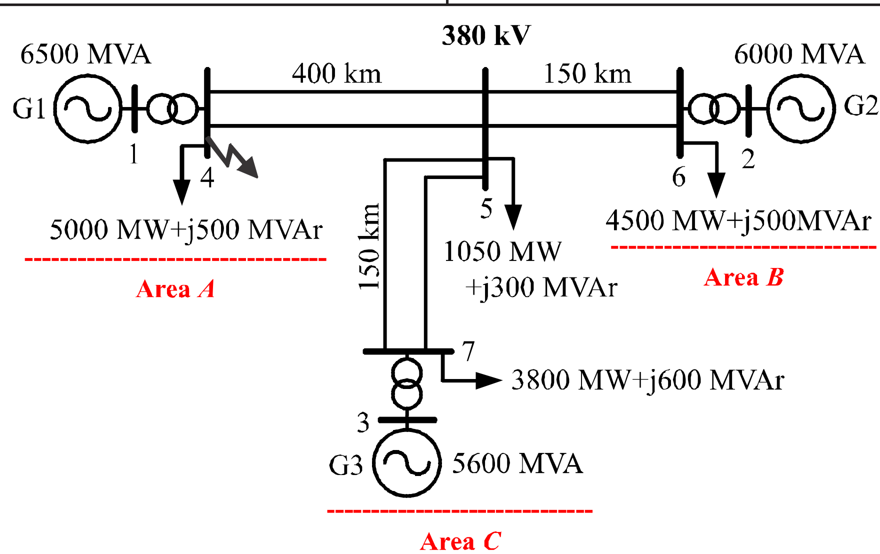

FIG. 3. ONE LINE DIAGRAM OF A THREE-MACHINE, THREE-AREA TEST POWER SYSTEM

G3. Fig. 5 shows the frequency responses of θ_{V5} to the inputs at G1, G2, and G3, with PSS controller not added in the test system. Following the procedure given in [5], G1 is found to be suitable as the location of PSS controller to be designed to damp inter-area mode 1 and G3 is found to be suitable as the location of PSS controller to be designed to damp inter-area mode 2.

3.2.4 Final Selection of Suitable Local and Remote Input Signals

From Fig. 4 and following the procedure described in [5], Q_1 and I_{56} are found to be suitable as local and remote input signals respectively for the controller to be designed to damp inter-area mode 1. Similarly, for the controller to be designed to damp inter-area mode 2, V_3 and θ_{v5} are

TABLE 1. ENGINEERING PRE-SELECTION OF FEATURES

No.	Features' Description	Symbol	No.
1.	Current flowing through transmission lines	I	03
2.	Angles of currents flowing through transmission lines	θ_I	03
3.	Real electrical power output of generators	P	03
4.	Reactive electrical power output of generators	Q	03
5.	Real electrical power flowing through transmission lines	P	03
6.	Reactive electrical power flowing through transmission lines	Q	03
7.	Bus voltages	V	07
8.	Angles of bus voltages	θ_V	07
	Total number of features		32

TABLE 2. FINAL PRESELECTED FEATURES

No.	Description of Features	Symbol
1.	Voltage at bus 3	V_3
2.	Reactive electrical power delivered by bus 1	Q_1
3.	Angle of voltage at bus 1	θ_{V1}
4.	Voltage at bus 5	V_5
5.	Angle of voltage at bus 5	θ_{V5}
6.	Reactive electrical power delivered by bus 2	Q_2
7.	Current flowing through transmission line connected between buses 5 and 6	I_{56}

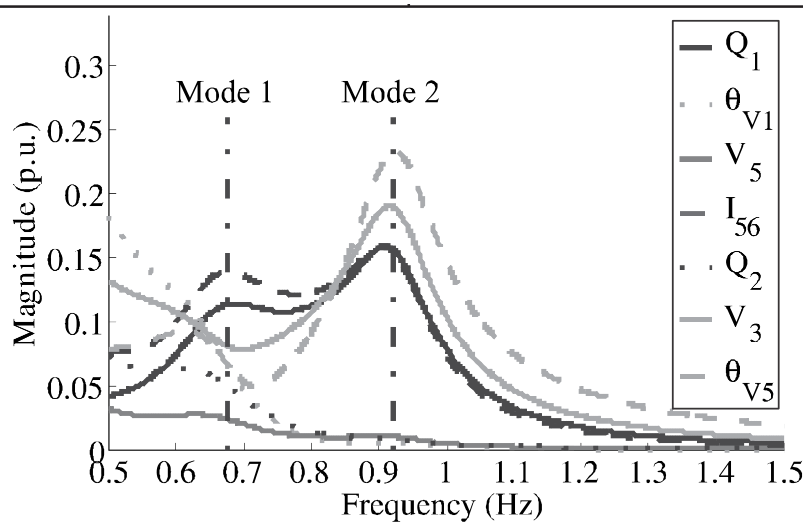

FIG. 4. FREQUENCY RESPONSES OF FINAL PRESELECTED MEASUREMENTS

found to be suitable as local and remote input signals respectively.

The results for the selection of suitable local and remote input signals and locations of PSS controllers are summarized in Table 3.

3.3 Design Results

During the design of PSS controller for inter-area mode 1, $\mathbf{y}(t)=[Q_1(t)\ I_{56}(t)]^T$ and $\mathbf{z}(t)=[Q_1(t)\ I_{56}(t)\ \mathbf{u}_{sG1}(t)]^T$. For the design of PSS controller for inter-area mode 2, $\mathbf{y}(t)=[V_3(t)\ \theta_{v5}(t)]$ and $\mathbf{z}(t)=[V_3(t)\ \theta_{v5}(t)\ \mathbf{u}_{sG2}(t)]^T$. To design the PSS controllers the design procedure of Section 2 is followed. For reducing the order of controllers, balanced residualization technique [10] is used.

3.3.1 Sequential Design of PSS Controllers

The description of two possible sequential designs is given in the following subsections. Note that first control loop consists of plant and the PSS controller, designed for inter-area mode 1 without and with taking into account time delay in its remote input signal, located at G1. On the other hand, the second control loop consists of plant and the PSS controller, designed for inter-area mode 2 without and with taking into consideration time delay in its remote input signal, located at G3.

3.3.1.1 First Sequential Design

First sequential design consists following two steps:

(i) PSS controller for inter-area mode 1 is designed first by keeping the second control loop open;

(ii) PSS controller for the inter-area mode 2 is then designed by keeping the first control loop closed, i.e. with already designed corresponding PSS controller for inter-area mode 1 located at generator G1 in the test system;

Table 4 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 taking into consideration time delay in their remote input signals, located in the system and with no time delay

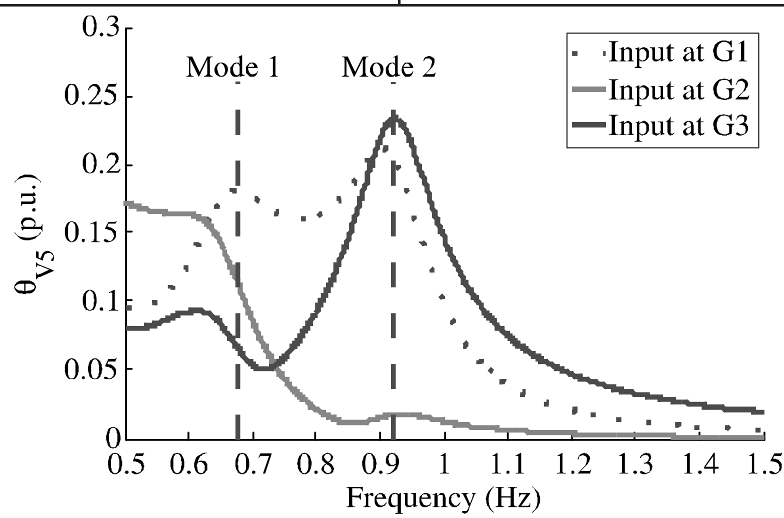

FIG. 5. FREQUENCY RESPONSES OF θ_{V5} TO INPUTS AT GENERATORS G1, G2, AND G3 WITH PSS CONTROLLER NOT ADDED IN THE TEST SYSTEM

TABLE 3. SELECTED LOCAL AND 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.	Q_1	I_{56}	Generator G1
2.	V_3	θ_{v5}	Generator G3

added in the designed controllers' remote input signals during simulation [5]. Table 4 also provides the profile of the same inter-area modes with the controllers designed for inter-area modes 1 and 2, without taking into account time delay in their remote input signals, located in the system and with 700ms time delay added in designed controllers' remote input signals during simulation.

Assuming that there is 700ms delay in $I_{56}(t)$ and using 1st-order Pade approximation [6], the matrices A_d, B_d, C_d, D_d for the model of time delay are found as follows:

$$A_d = -\frac{2}{\tau} = -\frac{2}{0.7}, B_d = 1, C_d = \frac{4}{\tau} = \frac{4}{0.7}, D_d = -1$$

The PSS controller obtained is:

$$C_{11cd}(s) = \left[25.278 \frac{(1+s\,0.[illegible]314)(1+s\,2.9918)}{(1+s\,0.[illegible]384)(1+s\,0.[illegible]59)} \quad 13.49 \frac{(1+s\,0.3159)(1+s\,1.6202)}{(1+s\,[illegible]94)(1+s\,0.1519)} \right]$$

Here cd stands for constant time delay. Table 5 provides the profile of two weakest damped inter-area modes of the test system with controller designed for mode 1, taking into account constant time delay of 700ms, located in the system and with 700ms time delay added in designed controllers' remote input signals during simulation.

The PSS controller for inter-area mode 2 is now designed by keeping the first control loop closed, i.e. with the PSS controller already designed for inter-area mode 1, taking into consideration constant delay of 700ms, located at generator G1 in the test system. The designed PSS controller for the inter-area mode 2, taking into account constant time delay of 700ms signal, is given as follows:

$$C_{22cd}(s) = \left[12.30 \frac{(1+s\,0.5014)(1+s\,0.2011)}{(1+s\,0.1327)(1+s\,0.8275)} \quad 20.1 \frac{(1+s\,0.91)(1+s\,0.51)}{(1+s\,0.1327)(1+s\,0.8275)} \right]$$

Table 5 provides the profile of two weakest damped inter-area modes of the test system with controllers designed for modes 1 and 2, taking into consideration constant time delay of 700ms, located in the system and with 700ms time delay added in designed controllers' remote input signals during simulation.

3.3.1.2 Second Sequential Design

Second sequential design consists following two steps:

(i) PSS controller for inter-area mode 2 is designed first by keeping the first control loop open.

(ii) PSS controller for the inter-area mode 1 is then designed by keeping the second control loop closed, i.e. with already designed corresponding PSS controller for inter-area mode 2 located at generator G3 in the test system.

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

Mode No.	With controllers, designed for modes 1 and 2 without taking into consideration time delay, and no delay added in designed controllers' remote input signals during simulation			With controllers, designed for modes 1 and 2 without taking into account time delay, and 700ms delay added in designed controllers' remote input signals during simulation		
	Inter-Area Modes	ζ (%)	Frequency (Hz)	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-1.3874+4.3612	30.32	0.69	-0.5074+4.1632	12.32	0.68
2.	-3.2558+6.8934	42.71	1.10	-0.3958+5.1934	8.71	0.92

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

Mode No.	With controller, designed for mode 1 with taking into account constant time delay of 700, and 700ms delay added in designed controllers' remote input signals during simulation			With controllers, designed for modes 1 and 2 with taking into consideration constant time delay of 700, and 700ms delay added in designed controllers' remote input signals during simulation		
	Inter-Area Modes	ζ (%)	Frequency (Hz)	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-1.6274+4.5632	36.42	0.70	-1.6274+4.5632	36.42	0.70
2.	-0.3958+5.1934	8.71	0.92	-1.7358+6.3934	32.21	0.93

Table 6 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, taking into account constant time delay of 700ms, located in the system and with 700ms time delay added in designed controllers' remote input signals during simulation.

Comparison of the results for the first and the second sequential designs, provided in Tables 5-6 respectively, indicate that the damping of inter-area modes 1 and 2 has enhanced more in the first sequential design than that in the second one. This indicates that first sequential design is better than the second one.

3.4 Time-Domain Simulation Results

For simulating the response of the system to large disturbances, a balanced three-phase fault is applied at bus 4, in the considered test power system, for the duration of 150ms.

3.4.1 First Sequential Design of PSS Controllers

The behavior of deviation of real electrical power delivered by generator G1($\Delta P_{G1}(t)$) with the PSS controllers designed for the inter-area modes 1 and 2, without taking into consideration delay, located in the system and with no time delay added in designed controllers' remote input signals during simulation, with the PSS controllers designed for the inter-area modes 1 and 2, without taking into account time delay, located in the system and with 700 ms time delay added in designed controllers' remote input signals during simulation, and with the PSS controllers designed for the inter-area modes 1 and 2, taking into consideration constant time delay of 700ms in their remote input signals, located in the system and with 700ms time delay added in designed controllers' remote input signals during simulation is shown in Fig. 6. Fig. 6 shows that response of $\Delta P_{G1}(t)$ with PSS controllers designed for inter-area modes 1 and 2, without taking into account time delay, is well damped when during simulation no delay was added in the remote input signals of the controllers. The Fig. 6 also shows that this response becomes oscillatory when during simulation time delay of 700ms was included. This response of the system, for a time delay of 700ms added during simulation, with the PSS controller redesigned, taking into account time delay of 700 ms, is better damped when compared with that with the PSS controller designed without taking into consideration time delay.

TABLE 6. WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

Mode No.	With controllers, designed for modes 1 and 2, with taking into consideration delay, and 700ms delay added in designed controllers' remote input signals during simulation		
	Inter-Area Modes	ζ (%)	Frequency (Hz)
1.	-1.471+4.372	31.32	0.70
2.	-1.3158+5.8934	29.82	0.90

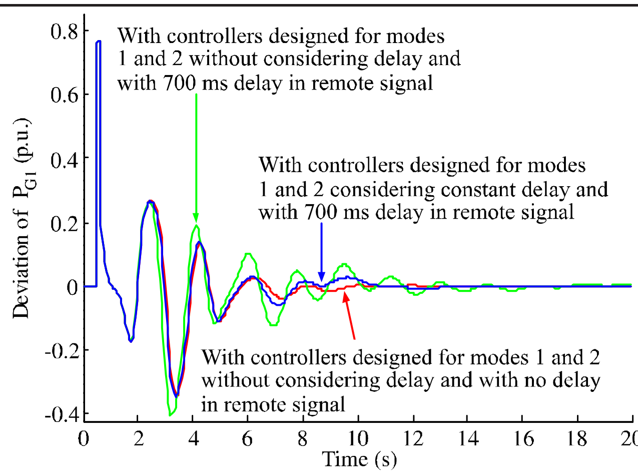

FIG. 6. DEVIATION OF PG1(T) (ΔPG1(T)) FOLLOWING A THREE-PHASE FAULT AT BUS 4 IN THE TEST SYSTEM

4. CONCLUSION

The design of delayed-input local decentralized PSS controller, for the separate damping of inter-area modes of interest, proposed in this paper, is applied on a three-machine, three-area test power system. Two controllers have been designed. PSS controller for an assigned single inter-area mode is designed first without and with taking into account time delay and by keeping the other control loop open. PSS controller for the other assigned single inter-area mode is then designed without and with taking into consideration time delay and by keeping the first control loop closed, i.e. with already designed PSS controller for the first assigned single inter-area mode located in the test system. The local and remote input signals, used by the controllers, have been selected in a way that the assigned modes are highly observable in the input signals of the corresponding controllers. The generators which are highly effective in controlling the assigned modes have been selected as the locations of the controllers. The controllers have been designed in such a way that each of them is effective only in the natural frequency of its assigned mode. The designed controllers, thus, damp only their corresponding assigned modes. The nonlinear simulation results show that the proposed PSS controllers, designed taking into consideration time delay, enhances the damping of inter-area oscillations in the presence of time-delay in the remote input signal of controllers.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. Dr. Ing I. Erlich, Institute of Electrical Power Systems, University of Duisburg-Essen, Germany, for giving guidance. The authors are also grateful to Mehran University of Engineering & Technology, Jamshoro, Pakistan, for providing facilities to perform this research work.

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