Selective Damping of Inter Area Oscillations Using Phasor Measurement Unit (PMU) Signals

I. Erlich, *Senior Member, IEEE,* A. Hashmani, F. Shewarega, *Member, IEEE*

Abstract**-- This paper deals with the design of an H_∞-based decentralized power system stabilizer (PSS) controller, which uses selected suitable wide area PMU signals as supplementary inputs to achieve a better damping of specific inter-area modes. The wide area or global signals are taken from network locations where the oscillations are well observable, and the PSS controller uses only those local and remote input signals in which the assigned single inter-area mode is most observable, and it is located at a generator most effective in controlling that mode. The PSS controller works mainly in a frequency band given by the natural frequency of the assigned mode. Pade approximation approach is used to model the time delay and uncertainty with regard to its value. This model is then merged with the delay-free power system model to obtain the overall power system model. Finally, the controllers are redesigned for the delayed-input system considering delay uncertainty. The effectiveness of the resulting PSS controllers in achieving improved damping of inter-area modes is demonstrated through simulation studies conducted on a test power system.**

Index Terms**-- Inter-area oscillations, PSS, Remote signals, Wide area measurements, Uncertainty in time delay, Robust H_∞ control.**

I. INTRODUCTION

THE deregulation in the electricity market and the extensions of large interconnected power systems led to a situation whereby many tie lines operate near their maximum capacity, especially those connected to areas of high load density. Stressed operating conditions can increase the possibility of inter-area oscillations between different control areas and can even lead to the breakup of the whole system [1]. Weakly damped low frequency inter-area oscillations, inherent in large interconnected power systems during transient conditions degrade the reliability and performance of such systems. With even heavier power transits in the future likely, the damping of these oscillations will decrease unless new lines are built or other heavy and expensive high-voltage equipment such as series-compensation is deployed.

Fig. 1 and Fig. 2 show the time-domain behavior of frequency, electrical power and rotor mode shape respectively, with the modes in the East (Poland) and the West (Spain) excited. The figures show that generators in the east (Poland) form a group and swing against the group of generators in the western part (Spain). This indicates that the full utilization of the available transmission capacity without countermeasures to improve system damping may compromise the operational security. One such measure is a coordinated control using wide area signals designed to achieve a better system damping.

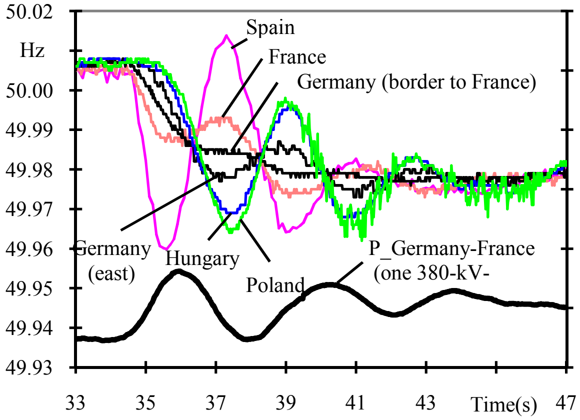

Fig. 1. Power and frequency oscillations with the East (Poland)-West (Spain) mode excited (Source: Grebe, RWE).

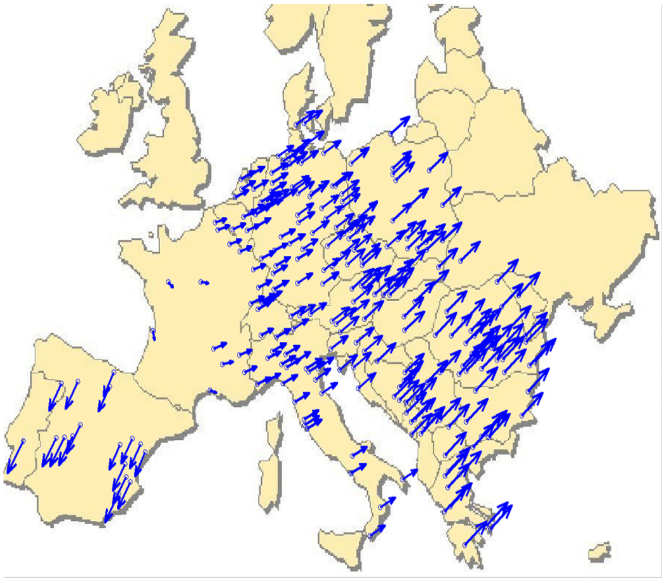

Fig. 2. Rotor mode shape: East (Poland)-West (Spain) mode excited.

For damping the dominant inter-area mode, the signals best suited as input to the controller (frequency, tie-line flows, etc.) would be from the location where the oscillations are well observable, in this case from the eastern and western parts of the grid. It is found that if remote signals from one or more distant locations of the power system are used as input, the system dynamic performance can be improved in terms of

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A. A. Hashmani was a graduate student at the University Duisburg-Essen at the time of the research leading to this paper. I. Erlich and F. Shewarega are with the Department of Electrical Power Systems, University Duisburg-Essen, Duisburg, Germany (e-mail: istvan.erlich @uni-due.de).

better damping of inter-area oscillations [2]. The remote signals contain information about the overall network dynamics as opposed to local control signals which lack adequate observability with regard to some of the significant inter-area modes [3], [4].

Wide area measurement (WAM) technologies using phasor measurement units (PMUs) can deliver synchronous control signals at high speed. PMUs can be deployed at strategic locations on the grid to obtain a coherent picture of the entire network in real time [4], [5]. PMUs measure voltages and currents at different locations of the grid and global positioning system (GPS) technology ensures proper time synchronization among several global signals [6], [7]. The measured global signals are then transmitted via modern telecommunication equipment to the controllers. Fig. 3 illustrates the concept of damping by using remote measurements.

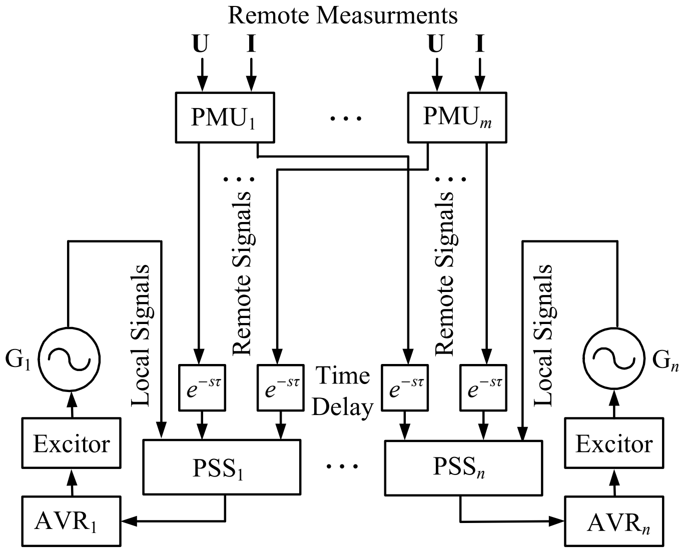

Fig. 3 Multi-machine power system with PSS using WAMs.

Due to the transmission and processing of remote signals in WAMS the signals arrive after a certain communication delay. It is found that a controller designed for delay-free system, if applied to the delayed-input system, the closed-loop system may lose stability. Time delay can make a control system to have less damping and there is a danger of losing synchronism. The design of a controller, therefore, must take into account this time delay.

This paper presents the design of local decentralized PSS controllers using remote PMU signals as supplementary inputs for a better damping of inter-area oscillations considering uncertainty in time delay. Linear fractional transformation (LFT) method is used to describe uncertainty in time delay [8]. Each decentralized PSS controller is designed separately for each of the inter-area modes of interest. Thus, each PSS receives the most suitable measurement information about the inter-area oscillations to be damped. H_∞-based robust control technique is used to design the PSS controllers. Simulation studies on a 16-machine test power system are conducted to investigate the effectiveness of proposed controllers during system disturbances.

II. CONCEPT OF MODE SELECTIVE DAMPING

Assume the controller is described by the following equation:

$$\mathbf{U}(s) = \mathbf{C}(s)\mathbf{Y}(s) \tag{1}$$

where $\mathbf{U}(s)$ is the vector of control input signals for the whole system, $\mathbf{Y}(s)$ contains the measured output signals available to the controller and $\mathbf{C}(s)$ represents the controller transfer function. The complete multivariable controller of the type given in (1) is unwieldy and cannot be implemented for practical use as is. Therefore, it is necessary to use a decomposition approach for the control task. This leads to the application of local, decentralized PSS controllers. The decomposition strategy leads to a decentralized PSS controller structure in which each of the PSS controllers has to be related separately for each of the inter-area modes of interest. Each designed PSS controller uses local and supplementary remote input signals in which a particular 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. Therefore, the controller transfer function matrix $\mathbf{C}(s)$ in (1) attains a block diagonal structure:

$$\mathbf{C}(j\omega) = \mathrm{diag}\left\{\mathbf{C}_{kk}(j\omega)\right\} \tag{2}$$

Each of the PSS controllers belonging to a considered inter-area mode is to be interpreted as a central multiple-input and multiple-output (MIMO)-type system, i.e., each controller sub-matrix $\mathbf{C}_{\mathrm{kk}}$ is a full matrix.

The local and supplementary remote input signals to the local decentralized PSS controller should have maximum observability with respect to the considered single inter-area mode in it. However, the entire data for the interconnected power system has a large number of features or measurements. Therefore, before the selection of supplementary remote input signals, the initial feature set is preselected first by engineering judgment and then using a feature selection technique such as k-Means clustering algorithm [9]. Final selection can be carried out based on the amplitude gains of the frequency responses of the signals [10]. The resulting frequency response curves will exhibit resonance effects in the frequency bands of the selected modes. The most suitable supplementary remote feedback input signal for a local decentralized PSS controller is the signal with frequency response curve showing the maximum value out of frequency response curves for all other remote measurements in the frequency band of the considered mode.

The locations of the local decentralized PSS controllers can also be obtained in a similar manner based on the amplitude gains of the frequency responses of the best suited measurement to the inputs of all generators in the interconnected system. The resulting frequency response curves will exhibit resonance effects in the frequency bands of the selected modes. The generator best suited as the location of a local decentralized PSS controller is the one for which the frequency response curve of the selected measurement shows the maximum value out of frequency response curves for all other generators in the frequency band of the considered mode.

III. DESIGN OF PSS CONTROLLERS

A. Problem Formulation

After augmenting the controller to the multi-machine power system model and incorporating communication delay, the overall extended system equations for the system can be rewritten in a compact form as follows [8] :

$$\dot{\tilde{\mathbf{x}}}(t) = \mathbf{A}_{\mathrm{cl}}\tilde{\mathbf{x}}(t) + \mathbf{B}_{\mathrm{cl}}\mathbf{w}(t) \tag{3}$$

$$\mathbf{z}(t) = \mathbf{C}_{\mathrm{cl}}\tilde{\mathbf{x}}(t) + \mathbf{D}_{\mathrm{cl}}\mathbf{w}(t) \tag{4}$$

where

$$\tilde{\mathbf{x}}(t) = \left[\mathbf{x}^{\mathrm{T}}(t) \quad \mathbf{x}_{\mathrm{c}}^{\mathrm{T}}(t)\right]^{\mathrm{T}} \tag{5}$$

Eq. (5) describes the augmented state vector for the closed-loop system, $\mathbf{x}(t)$ is the state vector of the open-loop system augmented by weighting functions, and $\mathbf{x}_c(t)$ is the state vector of the controller. The performance weighting functions are selected in such a way that the PSS controller belonging to a particular assigned single mode works mainly in the frequency band of that mode, and this makes the separate damping of each mode possible.

B. Robust H_∞ based PSS output feedback controller design

Designing an H_∞ controller for the system is equivalent to finding the controller matrix that satisfies an H_∞ norm bound condition on the closed loop transfer function $\mathbf{T}_{\mathrm{zw}}(s) = \mathbf{C}_{\mathrm{cl}}(s\mathbf{I} - \mathbf{A}_{\mathrm{cl}})^{-1}\mathbf{B}_{\mathrm{cl}} + \mathbf{D}_{\mathrm{cl}}$ from disturbance $\mathbf{w}(t)$ to the controlled outputs $\mathbf{z}(t)$ in Fig. **4** [5], i.e., $\|\mathbf{T}_{\mathbf{zw}}(s)\|_\infty < \gamma$ (for a given scalar constant $\gamma > 0$). An algebraic Riccati equation (ARE) approach [11] can be applied to establish the existence of control strategy that internally stabilizes $\mathbf{T}_{\mathrm{zw}}(s)$ and satisfies a certain prescribed disturbance attenuation (or gain) level $\gamma > 0$ on $\mathbf{T}_{\mathrm{zw}}(s)$. Due to the reasons described in [5], in this study, sequential design [12] is used to design the proposed PSS controllers.

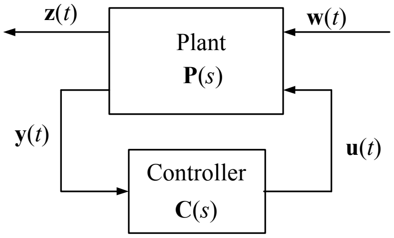

Fig. 4. General LFT framework representing interconnected systems.

IV. DEMONSTRATION EXAMPLE

For the illustration of the proposed methods, the test network shown in Fig. 5 has been used. The network contains 16 machines and 3 areas.

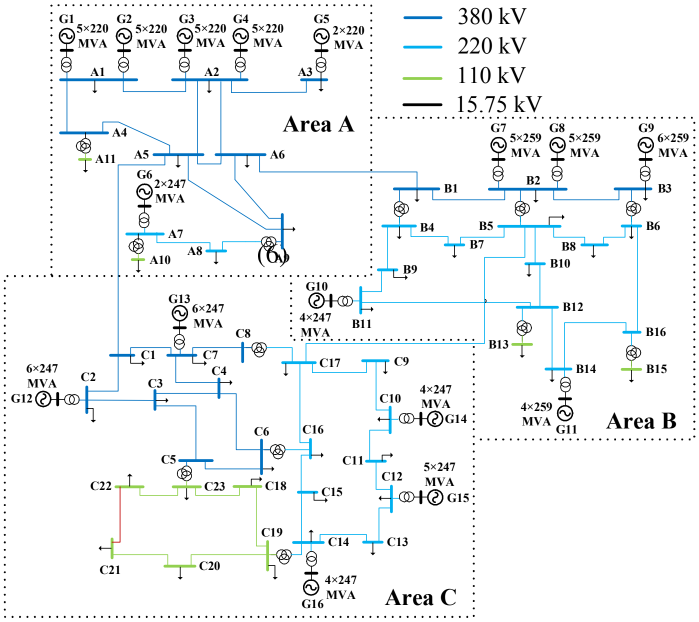

Fig. 5. One line diagram of 16-machine, 3-area test system.

The profile of two least damped rotor angle, low-frequency inter-area modes for the nominal power flow solution of the test system is provided in Table I. As there are two weakly damped inter-area modes in the considered test system, the employed decomposition strategy suggests that there will be two PSS controllers for the considered test system.

TABLE I

WEAKLY DAMPED INTER-AREA MODES OF TEST SYSTEM

No.	Inter-Area Modes	Damping in %	Frequency in Hz
1	-0.0793±j3.8629	2.05	0.61
2	-0.5982±j5.7031	10.43	0.91

Table II summarizes the results for the selection of suitable local and remote input signals and locations of local decentralized PSS controllers to be designed to damp out the two least damped inter-area modes.

TABLE II

SELECTED SUITABLE LOCAL AND REMOTE SIGNALS AND LOCATIONS FOR PSS CONTROLLERS

No.	Local Signals to Controllers	Remote Signals to Controllers	Locations of Controllers to be Designed
1	P_{G15}	P_{B5C17}	Generator G15
2	P_{G4}	P_{A6B1}	Generator G4

A. Design Results

During the design of robust H_∞-based PSS controller for the inter-area mode 1, P_{G15} and P_{B5C17} are used as its feedback input signals, i.e., $\mathbf{y}(\mathrm{t}) = [\mathrm{P}_{\mathrm{G15}}(\mathrm{t}) \quad \mathrm{P}_{\mathrm{B5C7}}(\mathrm{t})]^{\mathrm{T}}$. The measured signals P_{G15} and P_{B5C17}, the output of the PSS together with the terminal voltage error signals (which are the inputs to the excitation control) are used as regulated signals within this design framework, i.e., $\mathbf{z}(t)=[P_{\mathrm{G15}}(t) \quad P_{\mathrm{B5C17}}(t) \quad u_{s1}(t)]^{\mathrm{T}}$. Similarly, during the design of robust H_∞-based PSS controller for the inter-area mode 2, P_{G4} and P_{A6B1} are used as its feedback input signals, i.e., $\mathbf{y}(t)=[P_{\mathrm{G4}}(t) \quad P_{\mathrm{A6B1}}(t)]^{\mathrm{T}}$. The measured signals P_3 and P_{57}, the output of the PSS together with the terminal voltage error signals (which are the inputs to the excitation control) are used as regulated signals within this design framework, i.e., $\mathbf{z}(\mathrm{t})=[\mathrm{P}_{\mathrm{G4}}(\mathrm{t}) \quad \mathrm{P}_{\mathrm{A6B1}}(\mathrm{t}) \quad \mathrm{u}_{\mathrm{s2}}(\mathrm{t})]^{\mathrm{T}}$. The procedure described in Section 4 is used to design the controllers in such a way that minimum disturbance attenuation (from $\mathbf{w}(t)$ to $\mathbf{z}(t)$) is achieved. In this study, balanced residualization technique [13] is used to reduce the order of controllers at each stage of the design.

B. Sequential Design of PSS Controllers

As two PSS controllers need to be designed for the test system, the sequential design can, therefore, be performed in two different ways, depending on the sequence in which the controllers are designed. The description of two possible sequential designs is given in the following subsections. Please note that the first control loop consists of the plant and the PSS controller is designed for inter-area mode 1 without considering time delay and with considering time delay uncertainty in its remote input signal located at G15. The second control loop consists of plant and the PSS controller, designed for inter-area mode 2 without considering time delay and with considering time delay uncertainty in its remote input signal located at G4.

1) First Sequential Design

First, sequential design involves the 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 the already designed PSS controller for inter-area mode 1 located at generator G15 in the test system.

Table III provides the profile of two least weakly damped inter-area modes of the test system with the controllers designed for inter-area modes 1 and 2 without considering the time delay in their remote input signals and with no delay in their remote input signals. Table III also provides the profile of the same inter-area modes with the controllers designed for inter-area modes 1 and 2 without considering time delay in their remote input signals but with a delay of 1s in their remote input signals.

TABLE III
WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM INCLUDING DAMPING CONTROLLER FOR MODES 1 AND 2

	No delay in remote input signals			*1s delay in remote input signals*		
Mode	**Inter-area Modes**	**ξ (%)**	**Freq. (Hz)**	**Inter-area Modes**	**ξ (%)**	**Freq. (Hz)**
1	-1.4794+3.4207	43.70	0.54	-0.3274+3.2632	3.32	0.52
2	-1.2015+5.0564	23.12	0.80	-0.4358+4.8934	11.01	0.75

The time delay of remote input signals including uncertainty can be considered by different methods [8]. In this demonstration example the Pade approximation method has been used. The corresponding reduced-order H_∞-based PSS controller thus obtained is:

$$\mathbf{C}_{11\mathrm{ud}}(s)=\left[8.60\frac{(1+s\,0.3483)(1+s\,0.2614)}{(1+s\,0.5127)(1+s\,0.6295)} \quad 20.1\frac{(1+s\,1.21)(1+s\,0.82)}{(1+s\,0.5127)(1+s\,0.6295)}\right]$$

Table IV provides the profile of two least weakly damped inter-area modes of the test system with the controller designed for inter-area mode 1 by considering time delay uncertainty in its remote input signals and with delay of 1s in its remote input signal.

TABLE IV
WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

	Controller designed for mode 1;1000 ms delay in remote input signals; delay uncertainty considered			*Controller designed for modes 1 & 2;1000 ms delay in remote input signals; delay uncertainty considered*		
Mode	**Inter-area Modes**	**ξ (%)**	**Freq. (Hz)**	**Inter-area Modes**	**ξ (%)**	**Freq. (Hz)**
1	-1.2434+4.3132	30.12	0.69	-1.2494+4.42132	31.02	0.71
2	-0.4359+4.8934	11.56	0.75	-1.3528+5.0914	34.71	0.81

The PSS controller for the inter-area mode 2 is now designed by keeping the first control loop closed, i.e., with the PSS controller already designed, and considering delay uncertainty in its remote input signal, for inter-area mode 1 located at generator G2 in the test system. The H_∞-based PSS controller for the inter-area mode 2 by considering time delay uncertainty in its remote input signal is:

$$\mathbf{C}_{22\mathrm{ud}}(s)=\left[6.250\frac{(1+s\,0.5073)(1+s\,0.1534)}{(1+s\,0.1428)(1+s\,0.9385)} \;\middle|\; 16.17\frac{(1+s\,2.61)(1+s\,0.73)}{(1+s\,0.1428)(1+s\,0.9385)}\right]$$

Table IV provides the profile of two least weakly damped inter-area modes of the test system with the controllers designed for inter-area modes 1 and 2, by considering time delay uncertainty in their remote input signals and with delay of 1s in their remote input signals.

2) Second Sequential Design

Second sequential design involves the 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 the already designed PSS controller for inter-area mode 2 located at generator G4 in the test system.

Table V provides the profile of two least weakly damped inter-area modes of the test system with the controllers designed for inter-area modes 1 and 2, by considering time delay uncertainty in their remote input signals and with delay of 1s in their remote input signals.

TABLE V
WEAKLY DAMPED INTER-AREA MODES IN TEST SYSTEM

With, controllers designed for modes 1 and 2 with considering time delay uncertainty in their remote signals, and 1s delay added in designed controllers' remote input signals during simulation		
Inter-area Modes	**ξ (%)**	**Freq. (Hz)**
-1.5241+4.4652	39.62	0.72
-1.6458+5.2431	40.31	0.84

Comparison of results for the first and second sequential designs indicates that the damping of inter-area modes 1 and 2 has increased in the second sequential design compared to the first. Therefore, it is concluded that second sequential design is better than the first.

C. Time Domain Simulation Results

In order to simulate the system behavior under large disturbance conditions, a balanced three-phase fault of 100 ms duration is applied at bus A2 in the test system. The variation of real power delivered by generator G3 ($\Delta P_{G3}(t)$) with the PSS controllers designed for the inter-area modes 1 and 2 is shown in Fig. 6 for the following alternative scenarios:

- without considering the delay in remote input signals and no delay in remote input signals,
- without considering the delay in the remote input signals and with 1s delay in the remote input signals,
- with considering the delay uncertainty in the remote input signals and with 1s delay in remote input signals

This figure indicates that the response of deviation of $\Delta P_{G3}(t)$, with PSS controllers designed for inter-area modes 1 and 2 without considering time delay is better damped when no delay is included in the remote input signals of the controllers during the simulation but becomes oscillatory when a constant delay of 1s is included in the remote input signals during the simulation. Fig. 6 also indicates that for a constant delay of 1s included in the remote input signals during the simulation, the response of deviation $\Delta P_{G3}(t)$, with H_∞-based PSS controller redesigned considering uncertainty in delay is better damped as compared to that with H_∞-based PSS controller designed without considering delay.

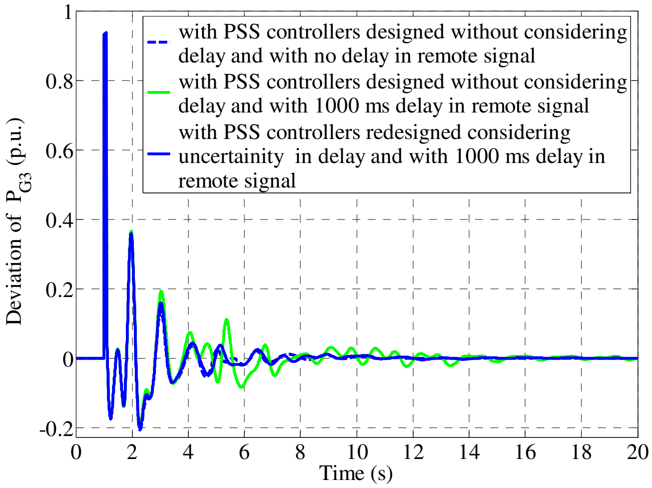

Fig. 6. Deviation of $P_{G3}(t)$ following a 3-phase fault at bus A2.

D. Robustness of Controller Regarding Time Delay

To further assess effectiveness of the proposed approach regarding robustness, transient performance indices are computed for different time delays. Transient performance index for electrical power output of the generator, following a three-phase short-circuit of 100 ms duration at bus A2 in Fig. 5, is computed using the following equation

$$I = \int_0^t \left| P_e(t) - P_{e0}(t) \right| \; dt \qquad (6)$$

For comparison purpose, this index is normalized on the base of the index for the mean value of delay range considered in the delay uncertainty case:

$$\mathrm{I_N} = \frac{\mathrm{I_{DD}}}{\mathrm{I_{MD}}} \qquad (7)$$

where I_{DD} is the transient performance index for different time delays and I_{MD} is the transient performance index for the mean value of delay range considered.

The normalized transient performance indices for the electrical power output of the generator for the time delays ranging from 0 to 1s and with the proposed H_∞-based PSS controller are shown in Fig. 7. The controllers are designed on the one hand considering uncertainty in time delay in its remote input signal and without considering time delay on the other. It can be seen from the Fig. 7 that the normalized transient performance indices for the proposed PSS controller, are nearer to unity for the range of time delays for which the controller is designed as compared to those for the PSS controller designed without considering time delay in its remote input signal. This clearly indicates that for different time delays the transient responses of the generator with the proposed PSS controller, designed considering time delay uncertainty, are well damped as compared to those with the PSS controller, designed without considering time delay. This indicates that, the system behavior exhibits robustness with the proposed controller for the range of time delays for which the controller is designed. This shows that the proposed PSS controller, designed considering time delay uncertainty, is more robust regarding time delay uncertainty as compared to the H_∞-based PSS controller, designed without considering time delay.

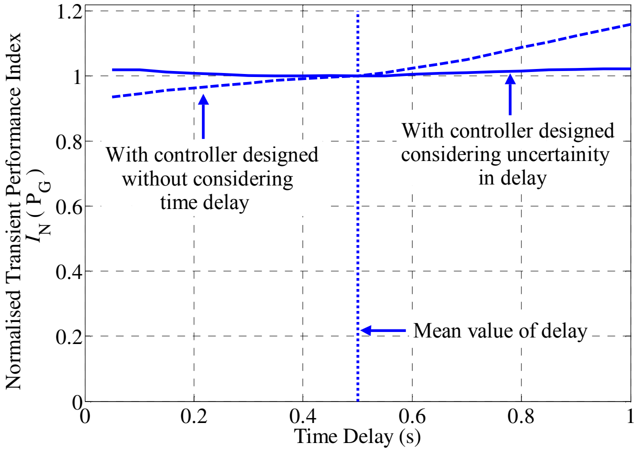

Fig.7. Normalized transient performance index I_N for generated power

V. CONCLUSION

In this paper an approach for the design of local decentralized control for separate damping of inter-area modes of interest, considering uncertainty in time delay in the remote PMU signals, including application examples on a three-machine, three-area test power system, has been presented. Two local decentralized robust H_∞-based PSS controllers have been designed for the two least damped inter-area modes present in the test power system. PSS controller for an assigned single inter-area mode is designed first without and then with considering uncertainty in time delay in its remote input signal by keeping the other control loop open. PSS controller for the other assigned single inter-area mode is then designed with and without considering uncertainty in time delay in its remote input signal 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. 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 controllers, using remote PMU signals and taking into account uncertainty in time delay, contribute significantly to the damping of inter-area oscillations and the enhancement of small-signal stability in the presence of wide range of variations in time delay in the remote input signal of controllers.

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