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Impact of Time- Delay on Wide-Area PSS for Stability Enhancement of Interconnected Power System

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ABSTRACT: The usage of wide area signals obtained from a Phasor Measurement Unit (PMU) introduces a time delays to a Wide-area Power System Stabilizer (WPSS), which would degrade system stability. These conditions introduce inter-area oscillations [0.1 Hz-1.0 Hz] in the power system and which may cause a brownout or blackout of the whole power system. In this paper, analyze the impact of time delay on robust control of power system. The controlled signal obtained by geometric approach is used as a control input for the proposed damping controller to damp out the inter-area oscillations. Some simulations results on Kundur Two-Area Four Machine system show that the proposed controller effectively damp-out the inter-area oscillations and also compensated the effect of time-delay.

Keywords: Signal Delay, Geometric Approach, Inter-area oscillations, Power System Stabilizer.

I. INTRODUCTION

Recently, with the increasing of electric power demand, either existing power system network should be interconnected or we add new lines in existing network. The main reason for interconnection of power system network is that it can efficiently utilize various power resources distributed in different areas and achieve the optimal allocation of energy resources. This also optimizes the economic dispatch of power and gets relatively cheaper power, which implies that decrease of system installed capacity and the investment. Moreover, in case of fault or disturbance in operating condition, it can provide additional supporting power of each area of interconnected grids which can increase the reliability of generation, transmission and distribution system.

But, with the growing electricity demand, nowadays power systems are operating close to their maximum transmission capacity and stability limit. In the past few decades, the angular instability, caused by small signal oscillations, has been observed in the power systems under certain system conditions, such as during the transmission of a large amount of power over long distance through relatively weak tie lines and under use of high gain exciters. These conditions introduce inter-area oscillations [0.1 Hz-1.0 Hz] in the power system and which may cause a brownout or blackout of the whole power system.

The inter area oscillations inherent to the large inter connected grid becomes more dangerous to the system's security and the quality of the supply during transient situation. Hence it can be said that the low frequency oscillations put limitations on operation of the power system and network's control security. The increased interconnected network of power system carries out heavy inter change of electrical energy which invokes such poorly damped low frequency oscillation that the system stability becomes major concern.

Some examples of power system black-outs due to inter-area oscillations are as follows [1]:

(a) Detroit Edison (DE-Ontaro Hydro (OH)- Hydro Quebec (HQ) (1960s, 1985)

(b) Finland-Sweden-Norway-Denmark (1960s)

(c) Saskatchewan-Monitoba Hydro_western Ontarioo (1966).

(d) Italy-Yugoslavia-Austria (1971-1974).

(e) In 1982 and 1983, the State Energy Commission of Western Australia (SECWA) experienced lightly damped system oscillations in the frequency range of 0.2-0.3 Hz.

(f) Western Australia (1982-83).

(g) On August 10, 1996, the Pacific AC Inter-tie (PACI) in WECC experienced unstable low frequency inter-area oscillations following the outage of four 400 kV lines.
(h) India-2012 with a frequency range of 0.35-0.71 Hz [20].

For the flow of heavy power through existing power system network, either adds the new lines with existing power system network or need high voltage compensation such as series compensation, to damp out the low frequency inter area oscillations. But with the expansion of new power system network or installation of compensation devices, lot of restrictions like environmental factors, cost factors etc. occurs. Therefore, it is better to design a system with existing power system network for the improvement of electromagnetic oscillations to achieve the maximum power transfer capability of the existing power system networks.

For this, the traditional approach to damp out the inter-area oscillations by using Conventional Power System Stabilizer (CPSS). The basic function of PSS is to add damping to the generator rotor oscillation by controlling its excitation using auxiliary stabilizing signal. These controllers use local signals as an input signal and it may not always be able to damp out inter-area oscillations, because, the design of CPSS used local signals as input and local signal based controller do not have global observation and may does not be effectively damps out the inter-area oscillations [3].

The effective damping mechanism is that the damping torque of synchronous generator is enhanced through proper field excitation. The application of remote signal for damping controller has become successful due to the recent development of Phasor Measurement Units (PMUs). PMUs have very useful contribution in newly developed Wide Area Measurement System (WAMS) technology. The initial development of PMU based WAMS was introduced by Electric Power Research of Institute (EPRI) in 1990. It is found that if remote signals comes from one or more distant location of power system are used as a controller input then, the system dynamics performance can be improved in terms of better damping of inter-area oscillations [4]. The signals obtained from PMUs or remote signals contain information about overall network dynamics whereas local control signals lack adequate observability with regard to some of the significant inter-area mode. The real time information of synchronous phasor and sending the control signal to major control device (e.g. PSSs, HVDC controllers, FACTS based controllers) at high speed has now become easier due to the use of PMU [5].

The PMU can provide wide area measurement signals. The signals can be used to enhance the wide area damping characteristics of a power system. The global signals or wide area measurement signal are then sent to the controllers through communication channel. Thus, network time delay is unavoidable. Such kind of delay varies from tens to several hundred milliseconds. Several experiments, reported in [6–8], have been carried out to measure the time delay.

The total time-delays for different communication links, from the instant of data measured by PMUs to the instant that control signals arrive at control locations, are shown in Table 1 [9].

Table 1: Time-delay for different communication links.

Communication link	Associated delay (ms)
Fiber-optic cables	~ 100-150
Microwave links	~ 100-150
Power line (PLC)	~ 150-350
Telephone lines	~ 200-300
Satellite link	~ 500-700

As even a very small delay can result in loss of power system stability [10], input delay cannot be neglected in controller design. For wide-area damping control, once the control location and feedback signal are selected, the path and mode of signal transmission are also fixed. Usually, this transmission path will not change in the short-term, so that Wide-area Power System Stabilizer (WPSS) input delay becomes stable. Thus, the delay can be modeled as a constant delay in controller design. Although, wide-area PSS provides a great potential to improve the damping inter-area oscillation, the delay caused by the transmission of remote signals will degrade the damping performance or may even cause instability of the closed loop system [8,9]. Therefore, the influence of time delay must be fully taken into consideration in the controller design. Pade approximation [17-19] is the effective approach to deal with this kind of constant time delay problem.

The major contribution of this paper is to design a wide area damping controller for inter-area oscillations damping and different (fixed value) latency compensation. At first, modal analysis of the linear model of power system excluding Wide-area is applied to find out the low-frequency oscillation modes and then identify the critical inter-area modes. Secondly, geometric approach have been used to select the most efficient wide-area signal.

Then the controller gain is determined based on the Integral of Time Error (ITE) criterion and optimized by Genetic Algorithm. This paper is structured as follows: Section II presents the modal analysis and selection of wide-area signals; Section III describes design of WPSS. Simulation results and discussions are in section IV and finally the conclusion is presented in section V.

II. MODAL ANALYSIS AND SELECTION OF WIDE-AREA SIGNALS

The nonlinear dynamic model power system is usually described by a set of differential-algebraic equation. The whole power system excluding the local PSS and wide-area damping controller can be linearized at an equilibrium point.

After linearization around a given operating condition and elimination of algebric variables, the state space model of studied system can be written as:

After linearization around a given operating condition and elimination of algebric variables, the state space model of studied system can be written as:

$$\dot{x} = Ax + Bu \qquad Y = Cx \tag{1}$$

where $x \in R^{n\times n}$, $u \in R^{n\times m}$ and $y \in R^{p\times n}$ are the state, inputs and output vectors respectively. $A \in R^{n\times n}$, $B \in R^{n\times m}$ and $C \in R^{p\times n}$ are state, input and output matrices, respectively.

Modal analysis of linear model (1) is applied to find out the low-frequency oscillation modes and then identify the critical inter-area mode with the help of geometric measures of modal controllability/observability.

For the designing of WADC, selection of stabilizing signals and location of control sites is an important factor. Wide-area control is desirable for inter-area oscillations damping mainly because it provides better controllability and observability thus better damping effects of those modes because remote stabilizing signals have more information about system dynamics. In the selection of stabilizing signals and control locations, it is desirable to use as few measurements and control devices as possible to achieve satisfactory damping effects. The most often used method to select locations and stabilizing signals for PSSs devices is controllability/observability analysis [11-12]. This method is derived from modal control theory of linear time-invariant system and calculates residue-based measures of modal controllability/observability.

The limit of residue-based measures is that they are only valid for the signals of the same type. This approach suffers a scaling problem when comparing the strength of signals of a widely differing physical significance, such as power flow in a tie-line (MW), bus frequency (Hz), shaft speed (rad/s), and angle shift (deg.) [13]. To overcome this shortcoming, the method used in [14] is geometric measures of modal controllability/observability.

a) Geometric Approach

The geometric measure of controllability gm_{ci} (k) and observability gm_{oj} (k) associated with the mode kth are given by[16]:

$$gm_{ci}(k) = \cos\left(\alpha\left(\psi_k, b_i\right)\right) = \frac{|\psi_i b_i|}{\|\psi_k\|\|b_i\|} \tag{2}$$

$$gm_{oj}(k) = \cos\left(\theta\left(\phi_k, c_j^T\right)\right) = \frac{|c_j \phi_k|}{\|\phi_k\|\|c_j\|} \tag{3}$$

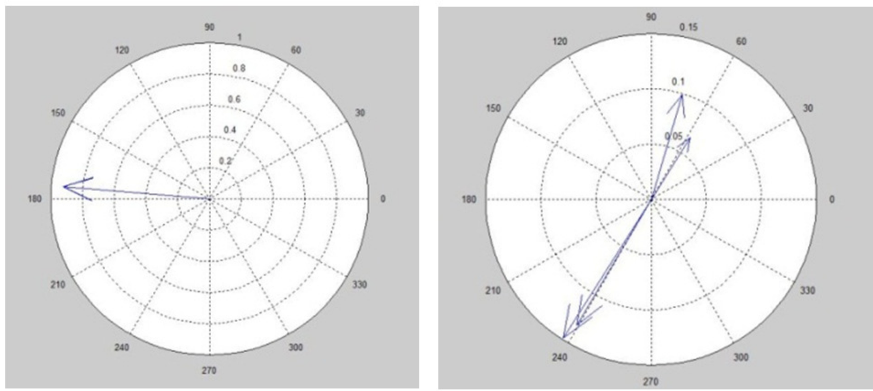
In (2) and (3), b_i is the i^{th} column of matrix *B* corresponding to i^{th} input, c_j is the j^{th} row of output matrix *C* corresponding to j^{th} output. $|z|$and$\|z\|$ is the modulus and Euclidean norm of *z* respectively. $\alpha(\psi_k, b_i)$ is geometrical angle between input vector *i* and k^{th} left eigenvector and $\theta(\phi_k, c_j^T)$ geometric angle between the output vector *j* and k^{th} right eigenvector. The joint controllability and observability index of geometric approach is defined by:

$$C = gm_{ci}(k) * gm_{oj}(k) \tag{4}$$

In the geometric approach it can prove that, higher the value of joint controllability and observability index more the stability of signal selected. In development of WADC model, each generator of proposed model has 11 state variables. Therefore, as per Kundur two area four machines model adapted in this research and the total order of the non-linear system has 44 state variables. After linearizing the non-linear test system about stable operating point of tie line active power whose initial value is 413 MW, the small signal analysis was undertaken using the PST. This resulted in one critical inter-area oscillations mode characterized by their damping ratio and frequency which are tabulated in Table 2 in bold letters. The compass plot of rotor angle state of mode - 5 and mode - 15 is obtained from participation factor analysis and shown in Fig. 1.

Table 2: Dominant Oscillations Modes (Without PSS).

Mode No.	Eigen Value	Damping Ratio	Frequency (Hz)
05.	$-0.25 \pm 0.65i$	0.36	0.10
13.	$-3.59 \pm 0.04i$	1.00	0.01
15.	$0.05 \pm 4.1i$	-0.01	0.65
25.	$-8.2 \pm 9.49i$	0.651	1.51
27.	$-8.12 \pm 9.68i$	0.64	1.54
29.	-5.66 ± 14.81	0.36	2.36
31.	$-4.45 \pm 16.63i$	0.26	2.65



Mode-5 (a) **Mode-15 (b)**

Fig. 1. Compass plots for Coherent Group Identification for Mode-5 & Mode-15.

For mode –5, Fig 1 (a) shows a single arrow, but actually there are four arrows of representing four generators with the same magnitude and direction superimposed one over the other, so they form only one area. For mode -15, Fig. 1 (b) Gen-1 and Gen-2 form area-1 and Gen-3 and Gen-4 form area-2 and they are oscillating with respect to each other. So, mode -15 is considered for further analysis of feedback signal selection and control device location.

The most stabilizing feedback signal selection was evaluated by geometric measure of controllability/observability approach. The candidate signals that are considered for the selection process are line active power and generator rotor speeds. In Table-III, The highest joint controllability/observability indices are indicated in bold and highest joint controllability/observability indices shown in Table-III suggest that the given inter area mode is efficiently controllable from Gen-2 and Gen-4 and are well observable from line active power flow of the tie-line connecting bus no. 3 to 101. Hence from geometric approach of signal selection the most stabilizing feedback signal is real tie-line power P3-101and most effective generators for damping the inter area mode are Gen-2 and Gen-4.

Table 3: Geometric measure of controllability/observability approach for signal selection for mode-15 (0.05±4.1i).

	Generators			
Signals	**G-1**	**G-2**	**G-3**	**G-4**
ω_1	0.0046	0.0060	0.0049	0.0065
ω_2	0.0031	0.0040	0.0033	0.0044
ω_3	0.0069	0.0091	0.0073	0.0098
ω_4	0.0061	0.0081	0.0065	0.0087
P_{3-20}	0.2726	0.3588	0.2890	0.3871
P_{3-101}	0.7042	0.9269	0.7466	1
P_{13-101}	0.6988	0.9198	0.7409	0.9923
P_{13-120}	0.3629	0.4777	0.3847	0.5153

III. THE DESIGN OF WIDE-AREA PSS

A. Structure of wide-area PSS

The wide-area PSS is designed to damp a critical inter-area oscillation mode-k by providing supplement damping control signal for excitation system of the i^th^ generator, and the overall structure of a Wide-area PSS designed for multi-area interconnected power system is illustrated in Fig. 2.

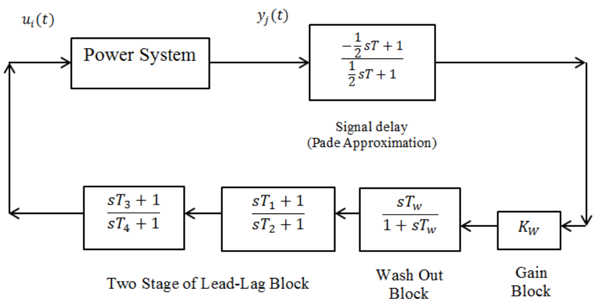


Fig. 2. The proposed structure of wide-area PSS.

As shown in Fig. 2, 'T' is the signal transmission delays between measurement location and wide-area PSS. The transfer function of wide-area PSS is:

$$H_{WADC}(s) = K_W \frac{sT_W}{1 + sT_W}\left(\frac{1 + sT_1}{1 + sT_2}\right)^m \qquad (5)$$

Where TW is the washout constant and usually chosen as 5- 10s, T_1 and T_2 are phase-compensation parameters, KW is the positive constant gain, m is the number of lead-lag compensation stages (usually equal to 2). The stabilizer gain K_W determines the amount of damping introduced by the PSS. The signal washout block is a high pass filter, with time constant T_W, which eliminates the low frequencies that are present in the speed signal and allows the PSS to respond only to speed changes. The phase compensation block is usually a single first order lead-lag transfer function or cascade of two first order transfer function used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine. The output is the stabilization voltage to connect to the input of the excitation system block used to control the terminal voltage of the synchronous machine.

B. Pade Approximation

The feedback signal delay of wide-area controller affects the control effect is because the delay will introduce phase deviation at the input signal. Usually, for an oscillation mode with frequency off, the phase lag φ introduced by delay T can be obtained by

$$\varphi = 360fT \qquad (6)$$

For example, when the dominant frequency of a WPSS is 0.5 Hz, a delay of 100 ms will introduce a phase lag of

$$360° \times 0.5 \times 0.05 = 9° \quad \text{(Phase lag)}$$

It can be seen from above that the phase lag introduced by delay is determined by both the delay itself and the oscillation frequency [21]. For the same delay, the corresponding phase lag is larger with the higher frequency, and vice versa. In MATLAB, time-delays are expressed in the exponential form (e^{-sT}) in the Laplace domain. It can be replaced by a first-order Pade Approximation [22]:

$$e^{-sT} \approx \frac{-\frac{1}{2}sT+1}{\frac{1}{2}sT+1} \qquad (7)$$

C. Optimization Method - Genetic Algorithm (GA)

The GA is basically a search algorithm in which the laws of genetics and the law of natural selection are applied. For the solution of any optimization problem (using GA), an initial population is evaluated which comprises a group of chromosomes. Initially, a random population is generated, and then from this population fitness value of each chromosome is calculated. This can be found out by calculating the objective function by the process of encoding. Then a set of chromosomes termed as parents are evaluated which are known as offspring generation, which are generated from the initial population. The current population is replaced by their updated offspring that can be obtained by considering some replacement strategy. Figure-3 shows the flow chart for the Genetic algorithm [23].

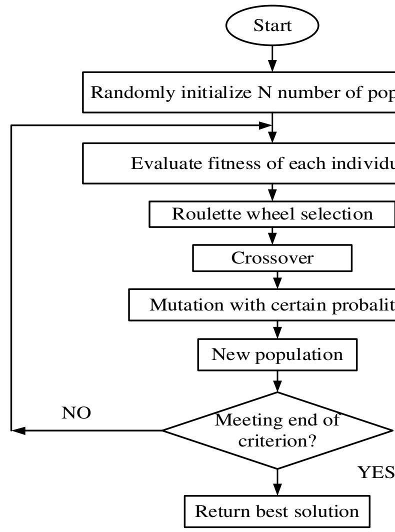


Fig. 3. Flow Chat for GA.

The genetic algorithm begins with a set of solutions (represented by chromosomes) called the population. Solutions from one population are taken and used to form a new population. This is motivated by the possibility that the new population will be better than the old one. Solutions are selected according to their fitness to form new solutions (offspring); more suitable they are more chances they have to reproduce. This is repeated until some condition (e.g. number of populations or improvement of the best solution) is satisfied. The oscillation of a system can be seen through the tie-line active power deviation or speed deviation of rotor. To minimize the oscillation of any deviation is research objective. For Kundur's two area four machines system, integral of time error of speed deviation for G-2 and G-4 taken as a objective function (J)

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| . t . dt \quad (8)$$

where

t_{sim} = simulation time range.

For a stipulated period of time, the time domain simulation of the above power system is worked out and from the simulation the calculation for the objective function is calculated. The prescribed range of the PSS and damping controller are limited in a boundary. Thus the following optimization problem is formulated from the above design approach.

Minimize J

Subject to :

$$40 \le K_{1a1} \le 70$$
$$0.001 \le K_{2a1} \le 0.01$$
$$40 \le K_{3a2} \le 70$$
$$0.001 \le K_{4a2} \le 0.01 \quad (9)$$

Where, K_{1a1}, K_{2a1}, K_{3a2} and K_{4a2} are the gain of LPSS and WPSS of the controllers.

IV. SIMULATION RESULTS AND DISCUSSION

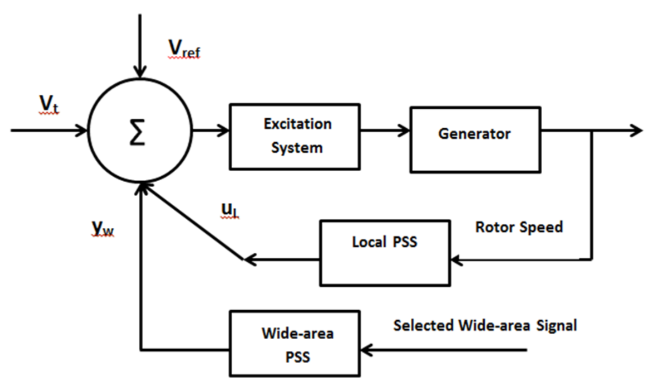


Fig. 4. Configuration of the generator with PSS.

The structure of the Wide-area PSS is shown in Fig. 4. The V_t and V_{ref} denote the generator terminal voltage and its reference. The local mode is damped by PSS which uses the rotor speed of local generator as input and its parameter is determined based on phase compensation of local mode frequency. The output of wide-area PSS is added to the excitation system of the selected machine together with the output of the local PSS to provide damping for the inter-area modes.

For the test system, G-2 of area-1and G-4 of area-2 are equipped with a LPSS and WPSS to damp the local mode oscillation as well as inter-area oscillations. For this gain of LPSS and WPSS is optimized based on Integral of Time Error (ITE) criterion based on GA, considering different condition for signal delay and optimized value of gain tabulated in Table 4. Rest of the parameter of LPSS and WPSS as follows at different condition of signal delay tabulated in Table 5.

Table 4: Gain of PSS at different conditions of signal delay.

Disturbance	**Delay (ms)**	**Area-1 (G-2)**		**Area-2 (G-4)**	
		LPSS	**WPSS**	**LPSS**	**WPSS**
Small	50	63.7662	0.0096	57.5580	0.0065
	100	50.1133	0.0050	44.3484	0.0020
	150	68.5843	0.0013	46.7144	0.0053

Table 5: Different Parameters of LPSS & WPSS.

Gen **PSS**	**G-2,G-4** **All are in second**				
	T_W	T_1	T_2	T_3	T_4
LPSS	10	50e-03	20e-03	3	5.4
WPSS	10	0.1	0.02	0.05	0.01

D. Small Signal Stability Assessment

To perform the dynamic analysis of the closed loop test system for Kundur two area four machine system as shown in Fig. 5, a small pulse with magnitude of 5% as a disturbance was applied to the generator G1 for 12 cycles.

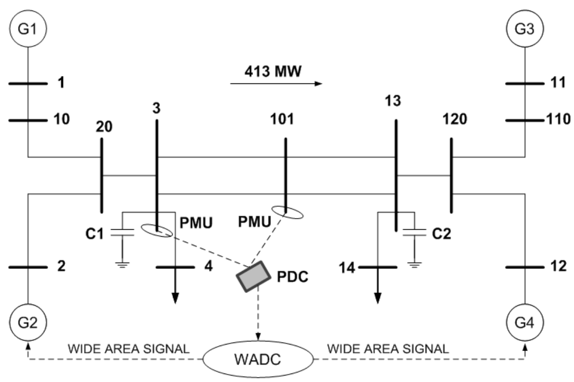


Fig. 5. Kundur's Two Area Four Machine System.

The simulation time was of 20 seconds. Then the response of tie-line active power flow from area-1 to area-2 and rotor angle deviation are examined by considering the test system with WPSS and LPSS under the presence of selected feedback signals by geometric approach and considered the effect of signal delay.

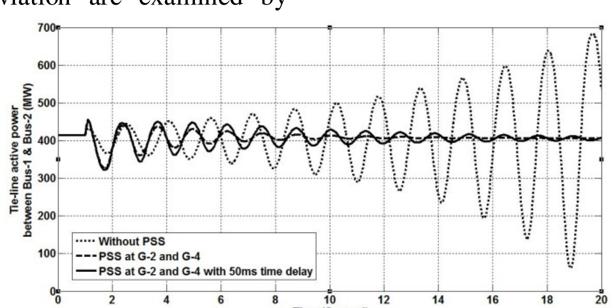


Fig. 6. Tie-Line Active Power Flow.

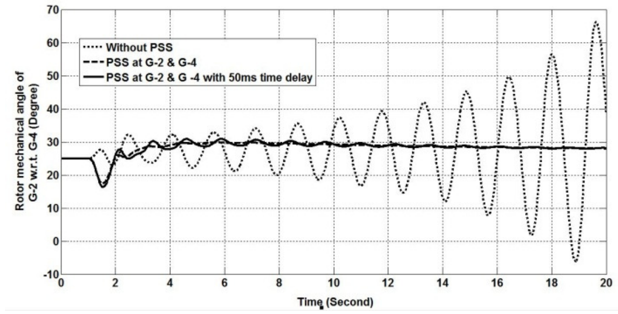


Fig. 7. Rotor Mechanical Angle of G-2 w.r.t. G-4.

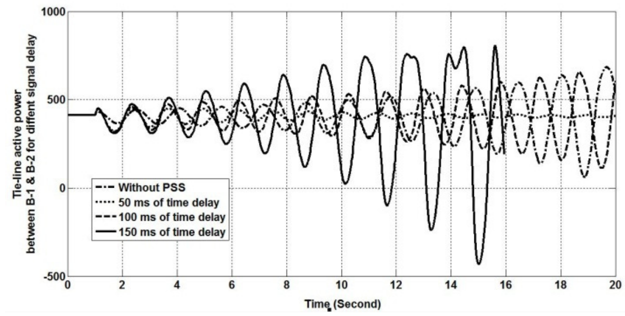


Fig. 8. Tie-line active power for different delay.

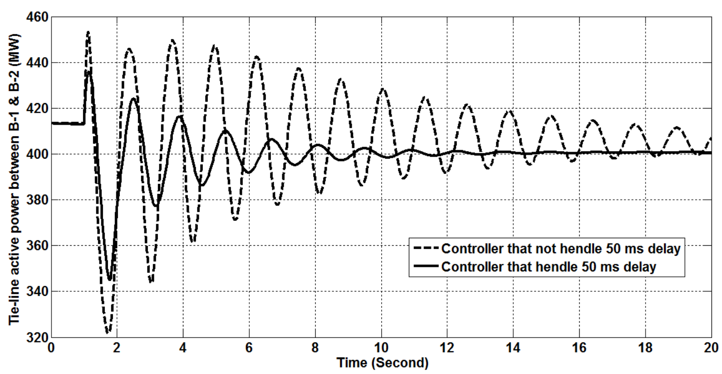


Fig. 9. Tie-Line Active Power Flow with proposed controller, 50 ms delay.

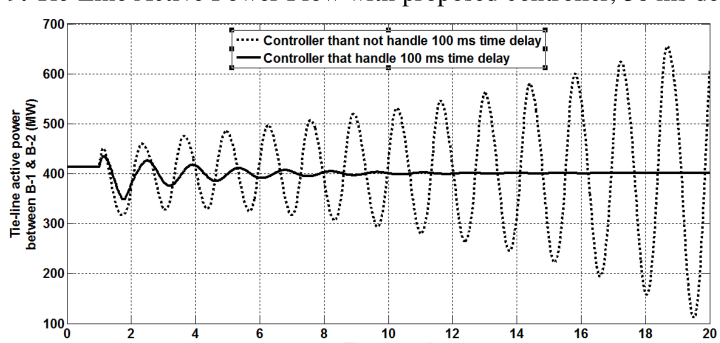


Fig.10. Tie-Line Active Power Flow with proposed controller, 100 ms delay.

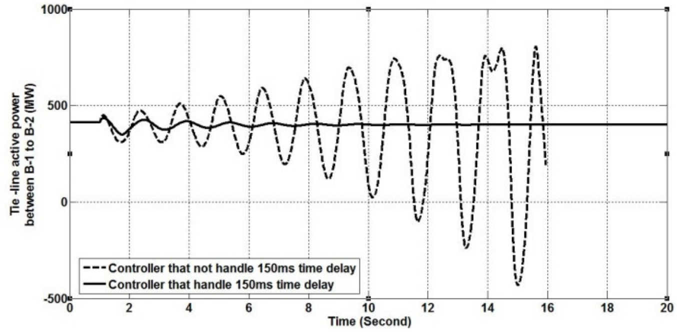


Fig. 11. Tie-Line Active Power Flow with proposed controller, 150 ms delay.

V. CONCLUSION

In this paper researcher designed a delay dependent wide-area damping controller to damp out the inter-area oscillations in a large scale power system. The proposed controller design based on observed signal that can be obtained from the method of geometric measure of controllability and observability associated with the inter-area oscillations mode. Some simulation results are carried out to verify the effectiveness of proposed controller under small disturbance. From the simulation results, it reveals that the proposed controller damps out the inter-area oscillations effectively under different delay conditions.

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