Delay-Dependent Wide-Area PSS For Stability Enhancement of Interconnected Power System

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Abstract - The usage of remote signals obtained from a wide-area measurement system (WAMS) introduces time delays to a wide-area Power System Stabilizer (PSS), which would degrade system damping and even cause instability. In this paper, design a delay-dependent Wide-area Power System Stabilizer (WPSS) to damp-out the inter-area oscillations in a large scale power system. The controlled signal obtained by geometric approach is used as a control input for the proposed damping controller to damped 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.

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

I. INTRODUCTION

The current installed capacity of electricity generation in India is 304.761 GW as of the end July 2016, [1]. Nowadays, the continuous inter-connection of regional electric grid is the developing trend of modern power system all over the world, such as interconnection of national grids of India, Europe network, the Japan power grids, the national grids of Chinaand North American power grids. The main reason for interconnection of electric grids 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.

With the growing electricity demand and the aging utility infrastructure, the present-day 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 black out 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.[2][3]:

In early 1960's, oscillations were observed when the Detroit Edison (DE), Ontario Hydro (OH) and Hydro-Québec (HQ) systems were inter-connected.

In 1969, oscillations were observed under several operating conditions in the Finland-Sweden (and Norway)-Denmark interconnected system.

In 1971 and 1972, over 70 incidents of unstable inter-area oscillations occurred in the Mid-Continent Area Power Pool (MAAP) system in North America.

In 1975, unstable oscillations of 0.6 Hz were encountered on the interconnected power system of New South Wales and Victoria.

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.

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.

India-2012 with a frequency range of 0.35-0.71 Hz. [CERC, 2012]

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[4].

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 [5]. 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[6].

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 [7]–[9], 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-I [10]

Table-I Time-delay for different communication links

Communication link	Associated delay (milliseconds)
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 [11], 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 [9, 10]. Therefore, the influence of time delay must be fully taken into consideration in the controller design.Pade approximation [18-20] 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 selectthe most efficient wide-area signal. Then the controller gain is determined based on theIntegral 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 variabes, the state space model of studied system can be written as:

$$\dot{x} = Ax + Bu$$

$$y = Cx \qquad (1)$$

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 critcal 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 [12], [13].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.) [14]. To overcome this short coming, the method used in [15] 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]:

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

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

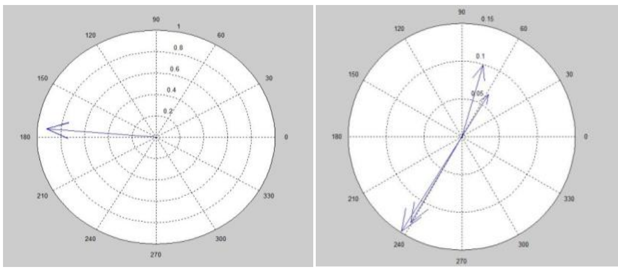
In (2) and (3), b_i is the i^{th} column of matrix B corresponding to i^{th} input, c_j is the j^{th} row of output matrix C corresponding to j^{th} output. $|z| and \|z\|$ is the modulus and Euclidean norm of z respectively. $\alpha(\psi_k, b_i)$ is geometrical angle between input vector i and k^{th} 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:

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

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-II in bold letters.

Table-II 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.	$\mathbf{0.05 \pm 4.1i}$	-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

The compass plot of rotor angle state of mode - 5 and mode - 15 is obtained from participation factor analysis and shown in Fig -1. 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.

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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-III Geometric measure of controllability/observability approach for signal selection for mode-15 ($\mathbf{0.05 \pm 4.1}\boldsymbol{i}$)

Signals	Generators			
	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
P3-20	0.2726	0.3588	0.2890	0.3871
P3-101	0.7042	0.9269	0.7466	1
P13-101	0.6988	0.9198	0.7409	0.9923
P13-120	0.3629	0.4777	0.3847	0.5153

III. THE DESIGN 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 ith generator, and the overall structure of a Wide-area PSS designed for multi-area interconnected power system is illustrated in Fig.-2.

As shown in Fig.2, 'd 'is the signal transmission delays between measurement location and wide-area PSS. The transfer function of wide-area PSS is:

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

Where TW is the washout constant and usually chosen as 5- 10s, T1 and T2 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 KW determines the amount of damping introduced by the PSS. The signal washout block is a high pass filter, with time constant TW, 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.

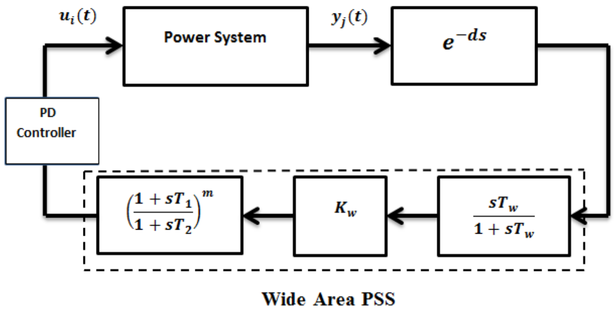

Fig-2 The proposed structure of wide-area PSS

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.

IV. SIMULATION RESULTS AND DISCUSSION

The structure of the Wide-area PSS is shown in Fig.-3. The Vt and Vref 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.

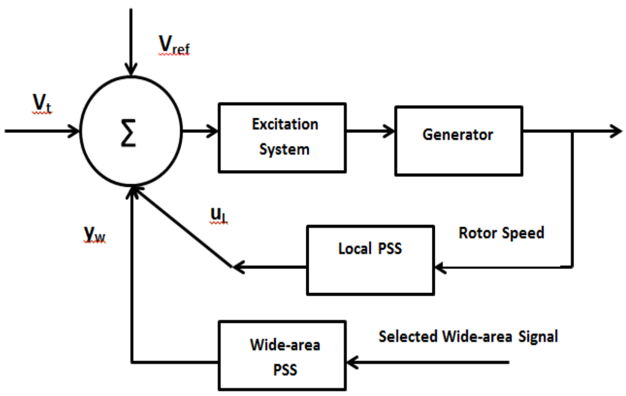

Fig-3 Configuration of the generator with PSS

Table-IV Gain of PSS at different conditions of signal delay

Disturbance	PSS/ Delay	LPSS		WPSS (gain*e-04)	
		G-2	G-4	G-2	G-4
Small	50ms	62.6976	69.1248	4.0748	3.0835
	100ms	61.3458	48.7599	3.3398	7.8815
	150ms	50.4641	58.7675	9.1003	4.8302
Large (3-phase fault)	150ms	42.9863	65.297	4.1649	2.4596

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-IV. Rest of the parameter of LPSS and WPSS as follows at different condition of signal delay tabulated in table-V.

Table-V Different Parameters of LPSS & WPSS

Gen / PSS	G-2,G-4		
	TW(s)	T1 (s), T2 (s)	T3 (s), T4 (s)
LPSS	10	50e-03,20e-03	3,5.4
WPSS	10	0.1, 0.02	0.05,0.01

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 -4, a small pulse with magnitude of 5% as a disturbance was applied to the generator G1 for 12 cycles.

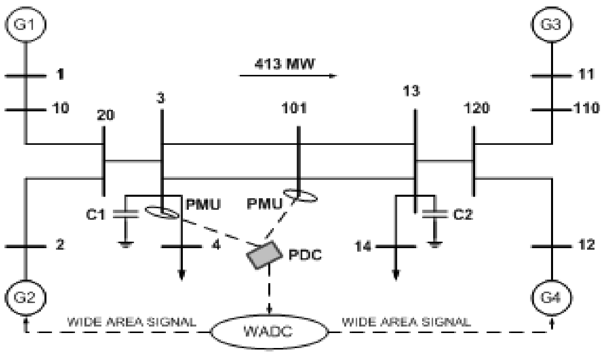

Fig-4 Kundur's Two Area Four Machine System

The simulation time was of 20 seconds. Then the response of tie-line active power flow from area-1 to area-2, rotor speed, rotor speed deviation , 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.

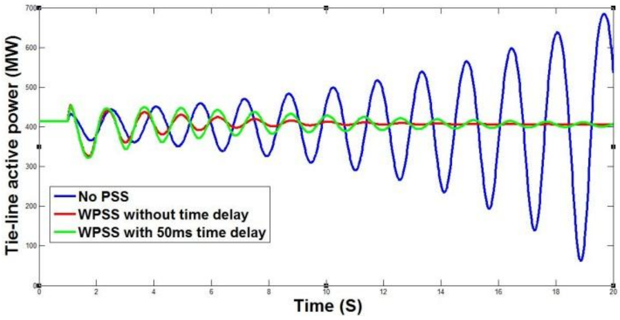

Fig-5 Tie-Line Active Power Flow

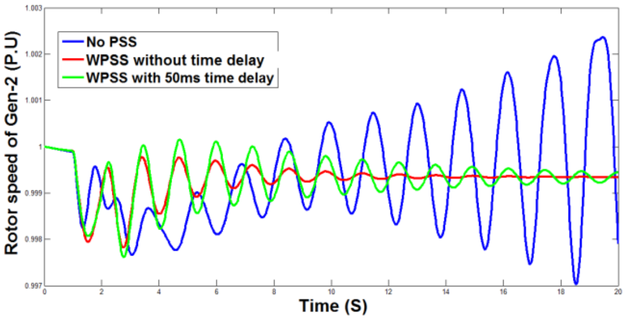

Fig-6 Rotor speed of Gen-2

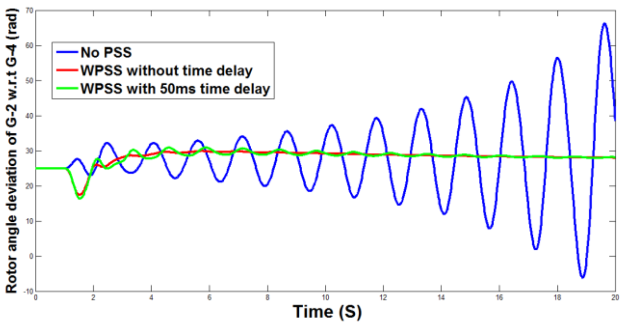

Fig-7 Rotor angle deviation of G-2 w.r.t G-4

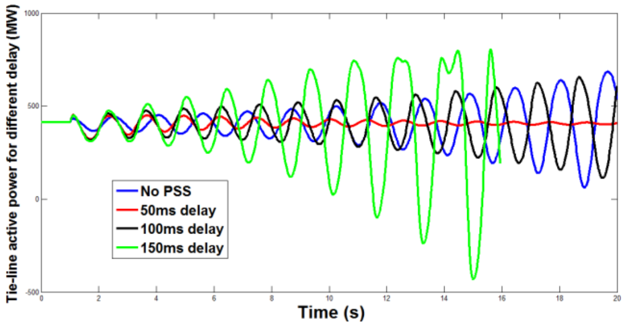

Fig-8 Tie-line active power flow for different delay

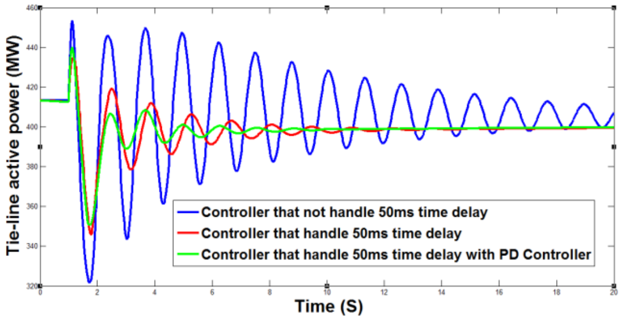

Fig-9 Tie-Line Active Power Flow with proposed controller, 50 ms delay

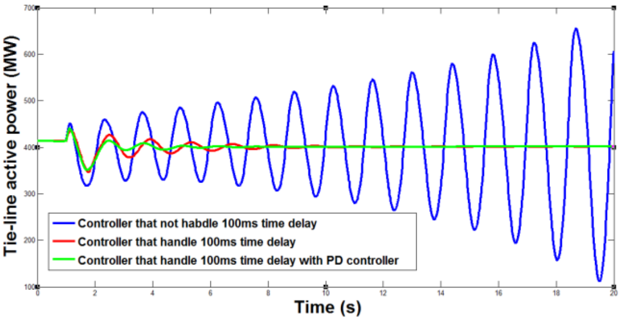

Fig-10 Tie-Line Active Power Flow with proposed controller, 100 ms delay

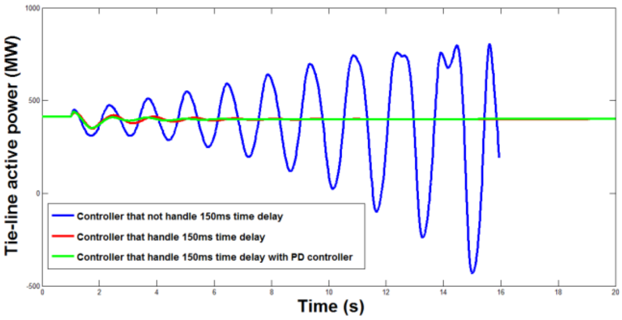

Fig-11 Tie-Line Active Power Flow with proposed controller, 150 ms delay

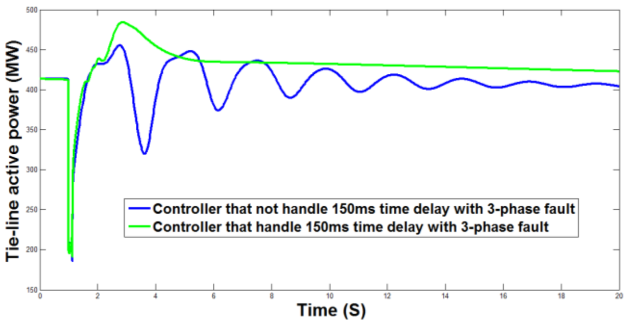

Fig-12 Tie-Line Active Power Flow with proposed controller, 150 ms delay

Controller Robustness

To analyze the controller robustness, the performance of the system was observed under large disturbance. A three phase temporary fault has been applied to Bus-101 for a duration of 12 cycles.The real power of tie-line connecting Bus-3 to Bus-13for a three phase fault on Bus-101, have been observed for 20s and are shown in Fig-12under the presence of selected feedback signalby geometric approach.

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 and large 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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