Time Latency Compensation in Signal Delay for PSS in Multi-Machine Power System

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Abstract - **The wide area signal for PSS introduce a time delay in the control signal, witch reduce the system performance. In this paper, analyzed the effect of signal time delay and designed the GPSS which reduce the inter-area oscillations and also compensate the effect of signal delay. The parameters of PSS are optimized by GA. Some simulations results for two area four machine system, shown the effectiveness of proposed controller under different condition of signal delay.**

***Index Terms*— PSS, Signal delay, GA, Inter-area oscillation**

INTRODUCTION

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 China and 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 optimize the economic dispatch of power and get 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. Power system stability is the ability of an electric power system to regain operating equilibrium after being subjected to a physical disturbance. Power system stability is the most important issue in achieving secure and reliable operation [1-2].

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. Oscillations in the power system may affect the stability of entire power systems. If the oscillations are not damped successfully, then power outages may occur and millions of people can be affected. The Western US/Canada power outage that occurred on 10 August 1996 is an example [3].

The outages were due to the excessive power flow through the US/Canada interconnection and the sequence of small disturbances. Oscillations in synchronous generators are the core phenomena behind the collapse of power systems [4-6].

Analyzing the some past in the world history, the incidents that have affected daily living is necessary to understand the effect of power system oscillations. For an overview, a list of the major power outages that have occurred globally are listed in Table – 1 along with the tentative number of affected people [7-8].

Table-1: Major power outage caused by power system instability

Year	**Date**	**Affected Country**	**Affected people(millions)**
1965	9 November	United states, Canada	30
1978	18 March	Thailand	40
1999	11 March	Brazil	97
2001	2 January	India	230
2003	28 September	Italy, Switzerland, Austria, Slovenia and Croatia	55
2005	18 August	Indonesia	100
2009	10-11 November	Brazil and Paraguay	87
2012	30-31 July	India	620
2014	1 November	Bangladesh	150
2015	26 January	Pakistan	140
2016	7 June	Kenya	10

The nature of power system oscillations is complex. In view of fundamental analysis, understanding the various modes of oscillation occurring in the system is important. In general, power oscillations are classified into two types [3], namely:

- Local area modes of oscillation and
- Inter-area modes of oscillation.

Local area modes of oscillation oscillate the nearby generators or the generators in the same region. Thus, the local area modes of oscillation affect the generators in the same region or nearby regions. By contrast, the inter-area modes of oscillation are the oscillations in the coherent generators of different regions connected through long tie lines.

The inter-area oscillations produce serious damages on the stable and efficient operation of power system especially in large interconnected grids. If inter-area oscillations have weak or negative damping ratio then it easily leads to interconnected grids and as a result cascading failures and finally black out could be happen. Thus, to ensure the stable and efficient operation of interconnected grids system the damping strategies should be performed to prevent or eliminate such inter-area oscillations.

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 [9].

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 [10]. 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 [11].

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 [12-14], 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 -2 [15] :

Table-2 : 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 [16], 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, WPSS 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 [14-15]. Therefore, the influence of time delay must be fully taken into consideration in the controller design. Pade approximation [17]-[20] is the effective approach to deal with this kind of constant time delay problem.

The wide area signals or the global signals are nothing but the remote stabilizing signals or the global signals. For the local mode of oscillations the most controllable and observable signals are the local signals such as generator speed deviation. But for inter-area modes the local signals may not have maximum observability to damp these modes. Rather this can be effectively damped by the use of remote signals from a distant location or combination of several locations. Another important advantage of use of wide area signals is that it needs very small gain for the controller compared to the local controllers in order to achieve the same amount of damping.

The main contribution of this research work is to design the wide area damping controller which compensate the delay in controller signal.

The structure of paper is as follows: Section II presents the modal analysis and selection of control signal for PSS; Section III represent the design structure of GPSS. Simulation results and discussion are presented in section IV and finally the conclusion is presented in section V.

Modal Analysis and Selection of Wide-area Signals

Let us consider the identified linear model of network given by equation (1)

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

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

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.

An eigen value analysis of matrix A produces the distinct eigenvalues $\lambda_i (i = 1,2,3, \dots \dots n)$ and corresponding matrices of right and left eigenvectors ϕ and ψ, respectively.

Geometric Approach

The geometric measure of controllability $gm_{ci}(k)$ and observability $gm_{oj}(k)$ associated with the mode k^{th} are given by [11, 15]:

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

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

In (3) and (4), 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 the higher the value of joint controllability and observability index more the stability of signal selected.

To design the wide area damping controller, each generator have eleven state variables and the whole Kundur multi-machine system were designed in PST software. To find the electro-mechanical mode of oscillations, linearized the proposed multi-machine model about an initial operating point 413 MW tie-line active power flow with a small disturbance at V_{ref} of G-1. This resulted in two critical inter-area oscillations modes characterized by its frequency with positive and negative damping ratio which are tabulated in Table-3.

Table-3: Electromechanical Mode of Oscillation of Two Area Four Machines System

Mode No.	Eigen Value	Damping Ratio	Frequency (Hz)
5,6	$-0.25 \pm 6.5i$	0.36	0.1
13,14	$-3.59 \pm 0.04i$	1	0.01
15,16	$0.05 \pm 4.1i$	−0.01	0.65
17,18	$-0.54 \pm 7.38i$	0.072	1.17
19,20	$-0.53 \pm 7.58i$	0.07	1.21
25,26	$-8.2 \pm 9.49i$	0.65	1.51
27,28	$-8.12 \pm 9.68i$	0.64	1.54
29,30	$-5.66 \pm 14.81i$	0.36	2.36
31,32	$-4.45 \pm 16.63i$	0.26	2.65

From Table-3, it is shown that, mode-15 and mode-16 have negative damping ratio, a small disturbance in the system, excited the state variables towards instability and make the system unstable.

The most suitable feedback signal for wide area PSS was evaluated based on joint controllability and observability method. The test signals for signal selection which are consider are: generator rotor speeds, bus voltage angle and tie-line active power as given in Table-4.

Table - 4: Geometric measure of controllability/observability approach for signal selection

Signals	Generators			
	G-1	G-2	G-3	G-4
P_{7-6}	0.2726	0.3588	0.2890	0.3871
P_{7-8}	0.7042	0.9269	0.7466	1
P_{5-6}	0.1314	0.1730	0.1394	0.1867
P_{3-11}	0.1878	0.2473	0.1991	0.2667
P_{4-10}	0.1397	0.1839	0.1481	0.1984
P_{9-8}	0.6988	0.9198	0.7409	0.9923
P_{9-10}	0.3629	0.4777	0.3847	0.5153
P_{11-10}	0.1878	0.2473	0.1991	0.2667
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
θ_7	0.3454	0.4565	0.3677	0.4925
θ_9	0.4684	0.6166	0.4966	0.6652
θ_8	0.1255	0.1653	0.1331	0.1783

DESIGN OF GPSS

a) Structure of PSS

The general structure of GPSS with control signal delay to damp out the inter-area oscillations corresponding to i^{th} –mode is shown in figure-1.

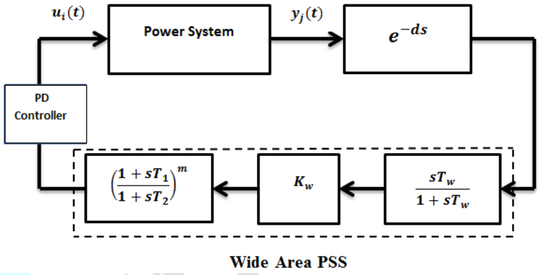

Figure-1: Structure of GPSS

As shown in figure-1,‘d’ is the signal transmission delays between measurement location and GPSS. The transfer function of GPSS is:

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

The value of T_1 and T_2, are calculated as follows:

$$\phi = 180^0 - arg(R_i) \tag{6}$$

$$\alpha = \frac{T_1}{T_2} = \frac{1-sin(\Phi/m)}{1+sin(\Phi/m)} \tag{7}$$

$$T_2 = \frac{1}{\omega_i\sqrt{\alpha}};\ T_1 = \alpha T_2 \tag{8}$$

In equation (5), T_W is the washout constant and T_1, T_2 are phase-compensation parameters, K_W is the positive constant gain, ‘m’ is the number of lead-lag compensation stages.

The washout block behave like a high pass filter with time constant T_W and it eliminate the low frequency oscillations i.e. it allow the PSS to responds only when there is a transient present in the control signal. The amount of damping introduced by PSS depends on the value of K_W. Lead-lag compensators are used for compensate the phase lag between electrical torque and excitation voltage of synchronous machine.

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.

In MATLAB, time-delays are expressed in the exponential form (e^{-ds}) in the Laplace domain. It can be replaced by a first-order Pade approximation [20-26, 29, 30]:

$$e^{-ds} \approx \frac{-\frac{1}{2}sd+1}{\frac{1}{2}sd+1} \tag{9}$$

b) Optimized Value Of Controller Parameters

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 parameters of Local PSS and Global PSS (GPSS) optimized based on Integral of Time Error (ITE) criterion by GA considering with any delay in wide-area signal.

Table-5: Gain of PSS at Different Conditions of Signal Delay

Disturbance			50ms	100ms	150ms
Small	LPSS	G-2	62.6976	61.3458	50.4641
		G-4	69.1248	48.1248	58.7675
	GPSS	G-2	4.0748×10^{-4}	3.3398×10^{-4}	9.1003×10^{-4}
		G-4	3.0835×10^{-4}	7.8815×10^{-4}	4.8302×10^{-4}

Simulation Results and Discussion

Dynamic analysis of the closed loop system is performed on Kundur two-area four machine system as shown in figure-2. A small step change of 5% is applied at G-1 V_{ref} for 12 cycle.

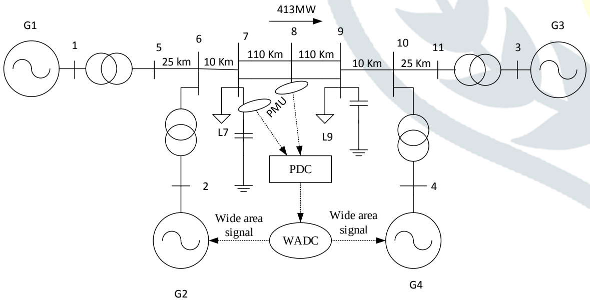

Figure - 2: Two are four machine system

The response of active power flow from area-1 to area-2, rotor speed, bus voltages and rotor mechanical angle are shown in figure from-3 to figure-7 under different condition of signal delays.

a) With local and global PSS not able to handle different signal delay

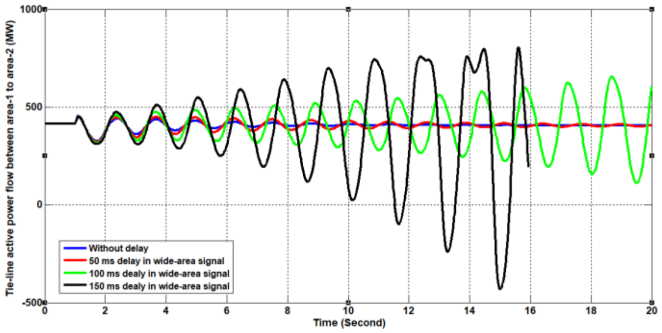

Figure-3: Tie-line active power flow for different delay

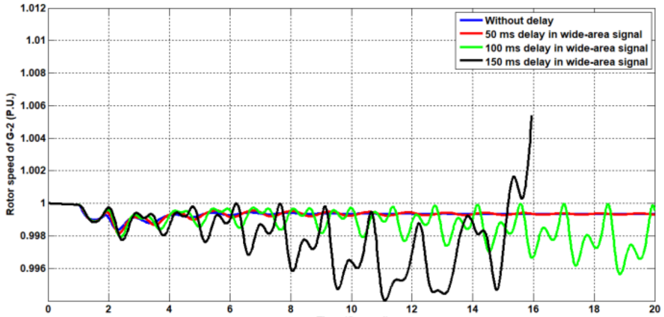

Figure 4: Rotor speed of G-2 for different delay

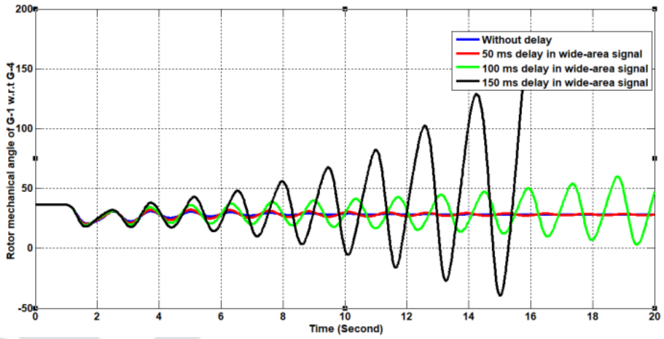

Figure 5: Rotor mechanical angle of G-1 w.r.t. G-4 (degree)

b) With local and global PSS able to handle different signal delay.

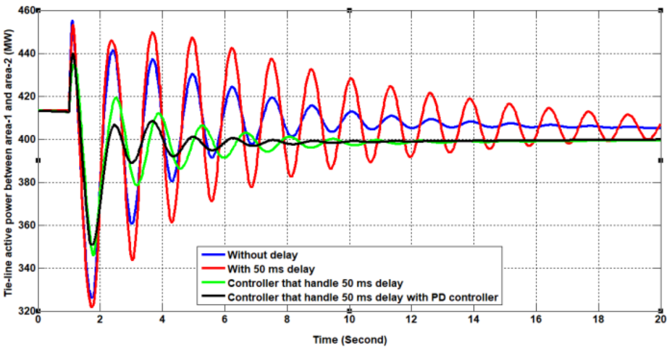

Figure 6: Tie-line active power flow

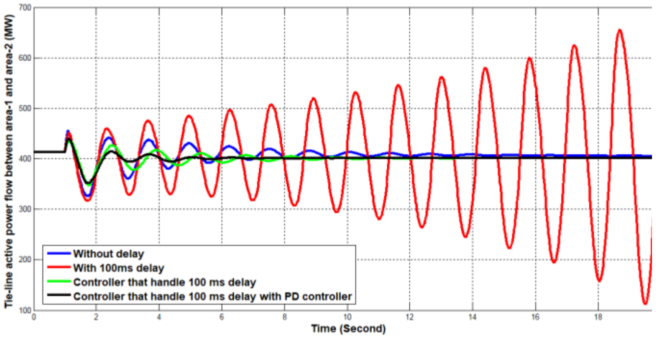

Figure 7: Tie-line active power flow

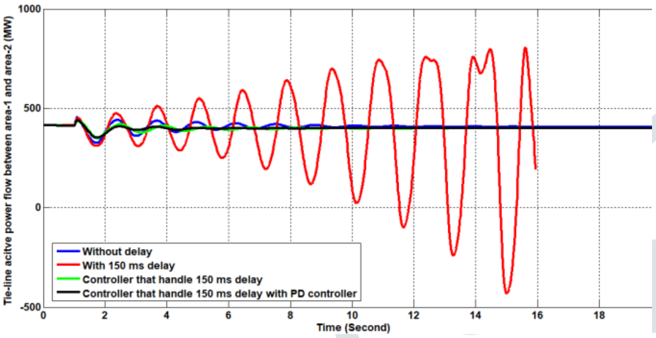

Figure-8: Tie-line power flow

c) Controller robustness

To analyse the controller robustness the performance of the system was observed under large disturbance. A three phase temporary fault has been applied to bus 8 for a duration of 12 cycles.

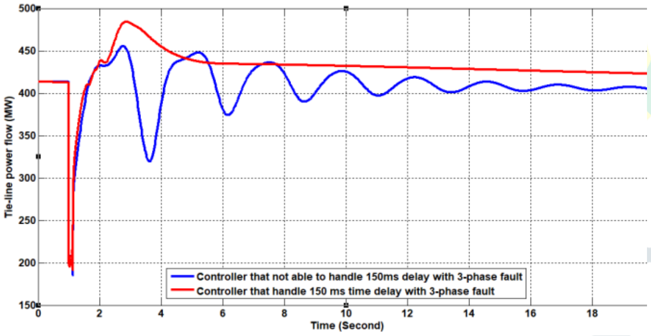

Figure-8: Tie-line power flow

CONCLUSION

In this paper, designed a GPSS which damp out the inter-area oscillations from inter connected power system and also nullify the effect the signal delay in control signal for PSS. The signal selected for GPSS is based on geometric measure of controllability and observability method. 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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