Design of Wide-Area Damping Controller to Damp out the Inter-Area Oscillations

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Abstract- In this paper, design is proposed for a wide-area damping controller 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 oscillations between the two areas..

Keywords- Geometric Approach, Inter-area oscillations, Power System Stabilizer, Wide-area damping Controller.

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 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 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 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 exiting power system network, either adds the new lines with exiting 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 devises, lot of restrictions like environmental factors, cost factors etc. are occurs. Therefore, it is better to design a system with exiting power system network for the improvement of electromagnetic oscillations to achieve the maximum power transfer capability of the exiting 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 inert-area oscillations, because, the design of CPSS used local signals as a input and local signal based controller have not global observation and may does not be effectively damped out the inter-area oscillations [4].

It is observed that the remote signals from different locations of power system are more effective to damp inter area oscillations [5]. 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. 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 have nowbecome easier due to the use of PMU [6].

The PMU can provide wide area measurementsignals. 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. 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 oscillation. The signals obtained from PMUs or remote signals contain information about overall network dynamics whereas local control signals has lack adequate observability with regard to some of the significant inter-area mode.

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 **[7].**

The most important task to design the wide area damping control is to select the most effective wide area signals. The basic criteria for selection of the signal is to have good observability and controllability of the signal for the system's inter area mode. So the signal which allow maximum observability and controllability of system's mode has to be selected as the most effective stabilizing signal for the controllers.

In this paper, the gemetric approache is applied to the Kundur's two area four machines system in order to select the most effective signals to damped out the inter-area oscillations.

This paper is structured as follows: Section II presents the architecture of wide-area damping control system; Section III briefly discusses signals selection approaches. Signal selection and control location site for controller, based on geometric measure of joint controllability /observability approach has been described in Section IV while the Section V describe design of power system stabilizer Section-VI Simulation results and discussions and finally the conclusion is presented in section VII.

II. WIDE-AREA DAMPING CONTROLLER STRUCTURE

Generally speaking, there are two classes of solutions to design damping controllers, the decentralized approach and the centralized approach. The main advantage of the first approach comes from the fact that it is based on local measurements hence additional telecommunication equipments are not needed. But, it is less clear that decentralized/local control alone will suffice to economically and efficiently satisfy the damping needs of the heavily stressed networks of the future[8].

On the hand, centralized wide-area damping control provides a more efficient solution due to the availability of a large amount of system wide dynamic data and better observations of inter-area modes. Wide-area controls include any control that requires some communication link to either gather the input or to send out control signals [9]. It is found that if remote signals are applied to the controller, the system dynamic performance can be enhanced with respect to inter-area oscillations [10], [11].

Even though additional telecommunication equipment is needed for the realization of such a centralized wide-area damping control system, it still turns out to be more cost-effective than installing new control devices. In most power systems, local oscillation modes are often well damped due to the installation of local PSS, while inter-area modes are often lightly damped because the control inputs used by those PSS are local signals and often lack good observations of some significant inter-area modes. This suggests that a wide-area controller, which uses wide-area measurements as its inputs to create control signals supplement to local PSSs, may help to improve the damping of inter-area oscillations.

A centralized control system structure is thus proposed and shown in Fig.1. In the proposed wide-area damping control system, selected stabilizing signals are measured by PMUs and sent to the controller through dedicated communication links. The wide-area damping controller calculates modulation signals and sends them to the selected generator exciters. This control scheme is a centralized architecture because every measurement is fed back through central controller to every controller/control device.

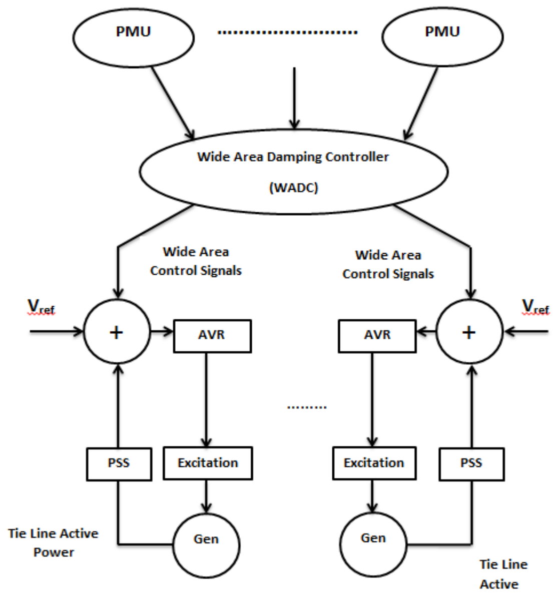

Fig.-1 General structure of wide area damping controller

In practice, there are two ways to implement the proposed wide-area damping controller. The first way is to install a centralized controller in the control center. The controller collects all measurements, calculates the control signals and sends them to control locations. Another way is to install one controller at each globally controlled generator. Thus, a completely peer-to-peer architecture can be applied to achieve the same function. In this design, all local PSSs are still conventional controllers designed by classical methods. They are modeled in the open loop state-state representation, on which the design of the WADC is based. The whole damping system includes two levels. The first level is fully decentralized and consists of conventional local PSSs. The second level is centralized and provides supplemental damping actions in addition to the first level forlightlydampedinter-areaoscillations

III. SIGNALS SELECTION

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 shortcoming, the method used in [15] geometric measures of modal controllability/observability.

After linearization around a given opearating condition and elimination of algebric variabes, the stateispcae model of studied system can be written as

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

$$y = Cx \tag{1}$$

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 critcal inter-area mode with the help of geometric measures of modal controllability/observability.

Geometric Approach

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

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

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

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 $\theta\left(\phi_k, c_j^T\right)$ geometric angle between the output vector j and k^{th} right eigenvector.The joint controllability and observability index of geometric approach is defined by:

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

In the geometric approach it can prove that the higher the value of joint controllability and observability index more the stability of signal selected.

IV. SIGNAL SELECTION AND CONTROL LOCATION SITE

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-I in bold latter.

Table-I Dominant Oscillation 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

The compass plot of rotor angle state of mode - 15 is obtained from participation factor analysis and shown in Fig - 2. For mode -15, in Fig-2, 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 consider for further analysis of feedback signal selection and control device location.

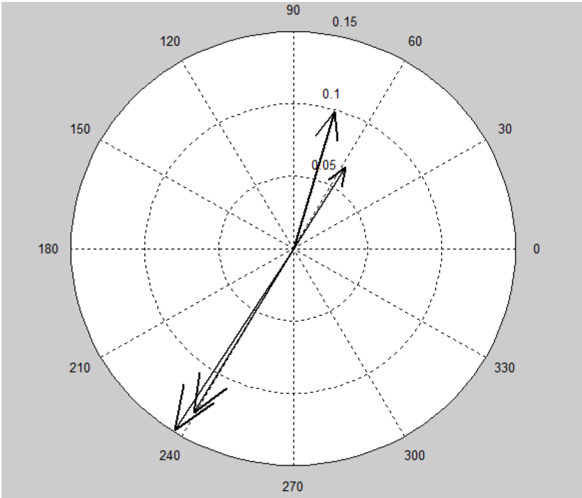

Fig - 2 Compass plots for Coherent Group Identification for Mode-15

The most stabilizing feedback signal selection was evaluated by geometric measure of controllability/observability approach as explained in Section-III. The candidate signals that are considered for the selection process are line active power and generator rotor speeds.

Table-II Geometric measure of controllability/observability approach for signal selection for moode-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
$P_{3\text{-}20}$	0.2726	0.3588	0.2890	0.3871
$P_{3\text{-}101}$	0.7042	0.9269	0.7466	1
$P_{13\text{-}101}$	0.6988	0.9198	0.7409	0.9923
$P_{13\text{-}120}$	0.3629	0.4777	0.3847	0.5153

In Table-II, The highest joint controllability/observability indices are indicated in bold and highest joint controllability/observability indices shown in Table-II 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. 7 to 8. Hence from geometric approach of signal selection the most stabilizing feedback signal is real tie-line power $P_{3\text{-}101}$ and most effective generators for damping the inter area mode are Gen-2 and Gen-4.

V. DESIGN OF PHASE COMPENSATION PART

In this paper researcher has been taken Kundur two area four machine system as a multi-machine system. To achieve the damping of one oscillation mode, the eigenvalue corresponding to that mode must be placed at the left-half of the complex plane. The block diagram of the CPSS is shown in the Fig-3.The stabilizer gain K_{STB} determine 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-leg 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 V_{STAB} input of the excitation system block used to control the terminal voltage of the synchronous machine.

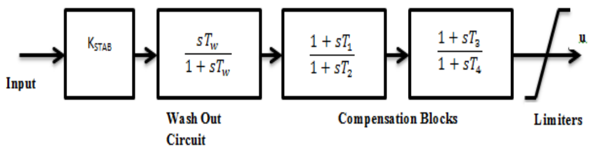

Fig-3 Conventional Power System Stabilizer

The different parameters for the CPSS in this papers are tabulated in Table-IV, based on Genetic Algorithm.

Table-IV Optimized Parameter for WADC

Param-eters	K_{WADC}	T_W	T_1	T_2	T_3	T_4	Limits
Value	0.1	10	0.1	0.02	0.05	0.01	-0.15(Lower) 0.15(Upper)

Each selected generators are employed with a local PSS (LPSS) taking local control signal as input to the controller. The local controllers are fed by change in speed deviation as input to the LPSS. Local controllers are assumed to be employed with selected generator in order to damp local mode oscillations. There is a supplementary PSS fed by wide area signal, usually referred to as Global PSS (GPSS). The sum of both the signal is given to the input of AVR. The global area control scheme is given Fig-4.

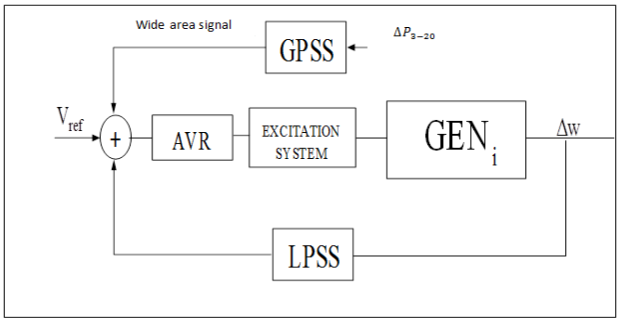

Fig-4 Global area control scheme.

VI. SIMULATION RESULTS AND COMPARISON

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.

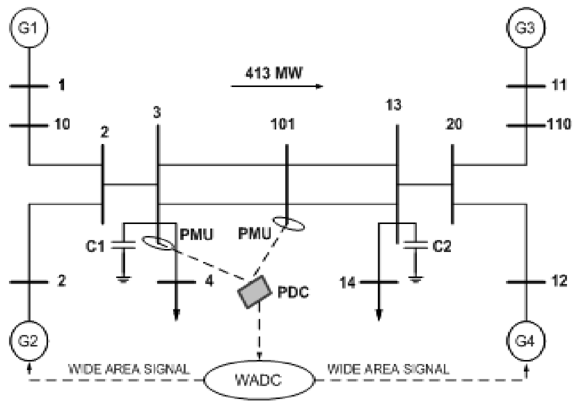

Fig-5 Kundur's Two Area Four Machine System

The simulation time was of 20 seconds. Then the response of tie-line active power flow from area-1 to area-2, rotor speed deviation , positive sequence voltage of Bus-3 and Bus-13 are examined in Fig-6, Fig-7 & Fig-8 respectively by considering the test system with GPSS and LPSS under the presence of selected feedback signals by geometric approach.

A. SMALL SIGNAL STABILITY ASSESSMENT

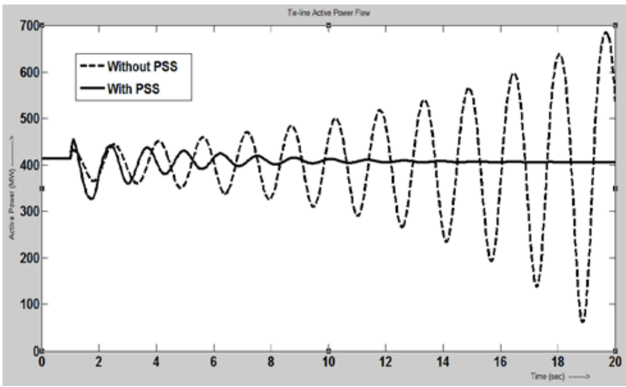

Fig-6 Tie-Line Active Power Flow Deviation

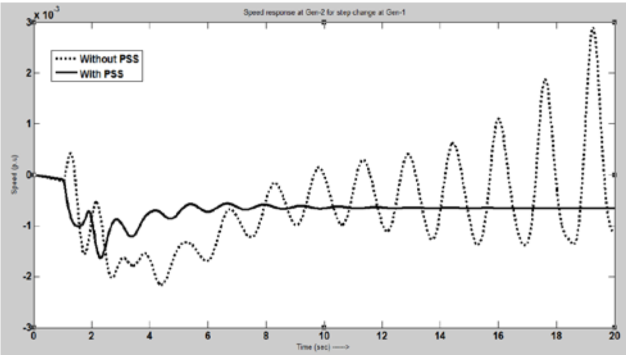

Fig-7 Rotor Speed Deviation of Gen-2

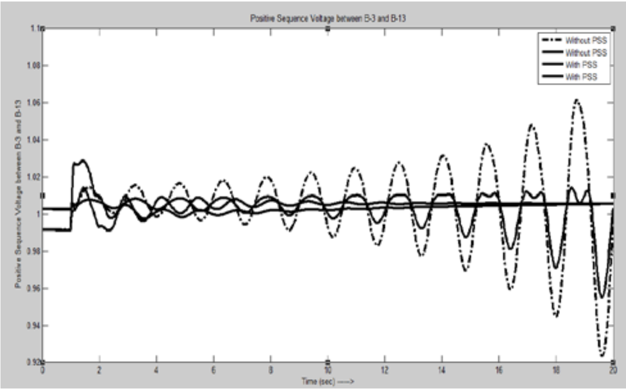

Fig-8 Positive Sequence Votage of B-3 and B-13

B. CONTROLLER ROBUSTNESS

To analyse the controller robustness the performance of the system was observed under large disturbance.

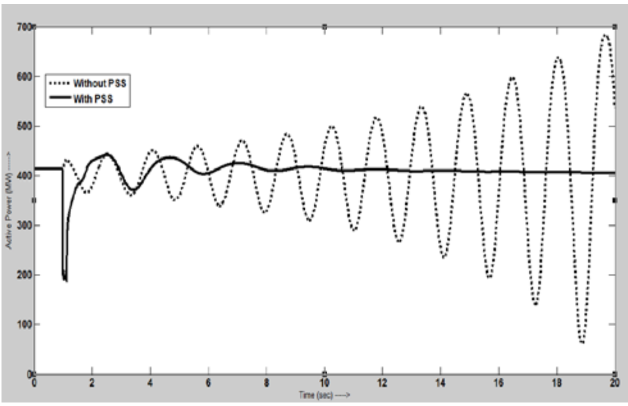

Fig-9 Tie line active power flow deviation after 3-phase fault

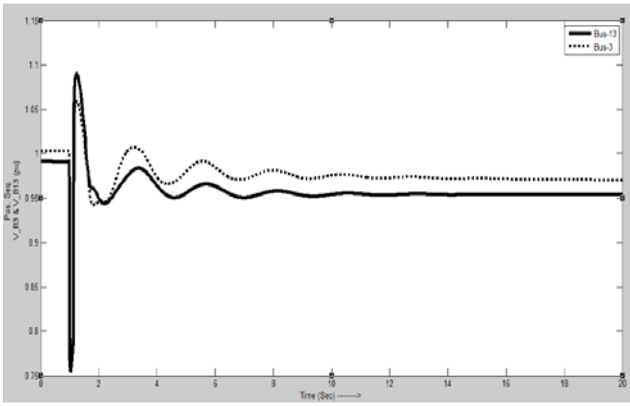

Fig-10 Positive sequence voltage of B-3 and B-13 after 3-phase fault

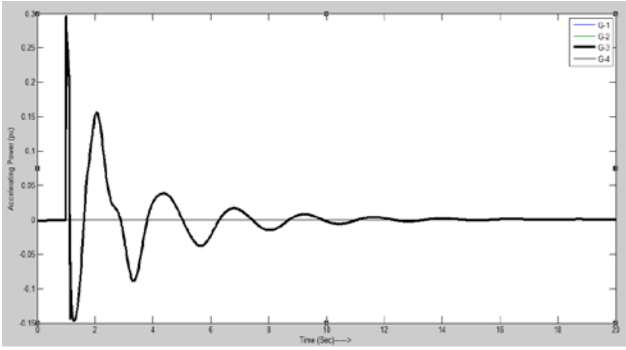

Fig-11 Accelerating power for all four gnenrators after 3-phase fault

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-13, Positive sequence voltage of Bus-3 and Bus -13 and accelerating power for all four generators, for a three phase fault on Bus-101, have been observed for 20s and are shown in Fig-9 and Fig-10 and Fig-11 respectively under the presence of selected feedback signals by geometric approach.

VII. CONCLUSION

In this paper researcher designed a simple wide-area damping controller to damped 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 distubance. From the simulation results, it reveals that the proposed controller damp out the inter-area oscillations effectively under different conditions.

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