Design of PSS for Multi-Machine Power System to Damp the Inter-Area Oscillations

Durga Sharma[1], Dr. S.K. Singh[2]
[1]Department of Electrical Engineering, C V Raman University, Bilaspur, CG
[2]Department of Electrical Engineering, Govt. Polytechnic, Balod, CG

***Abstract*—In this paper, a Global Power System Stabilizer (GPSS) and local PSS have been designed to damp out the inter-area oscillations and local oscillations from the multi-machine power system. On the basis of geometric measure of joint controllability /observability the feedback signal is obtained for the PSS. The parameters of PSS is obtained on Integral of Time Error (ITE) criterion and optimized by Genetic Algorithm. Also, the simulation results confirm that the proposed method effectively damp out the inter-area oscillations from the multi-machine system.**

***Index Terms*—Joint controllability & observability, ITE, PSS, Inter-area oscillations.**

I. 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 I: 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 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[10-12]. 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[13-14].

The major contribution of this dissertation work is to design a wide area damping controller for inter-area oscillations damping. 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 has 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 architecture of wide-area damping control system; Section III briefly discusses signal selection and control location site for controller, based on geometric measure of joint controllability /observability while the Section IV find the parameters for local PSS and wide-area PSS. Section-V discuss the simulation results and comparison and finally the conclusion is presented in section VI.

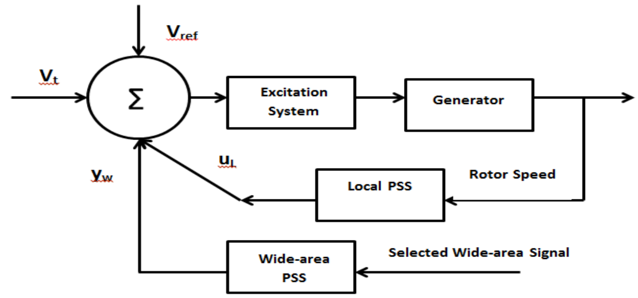
II. WIDE-AREA DAMPING CONTROLLER STRUCTURE

For the analysis of inter-area oscillation, Kundur's two area four machine system has been implemented with proposed WADC.

In this, whole system is divided in two area and each area have two generators with ST1A type of excitation system and governor. Local rotor speed signal based PSS are assumed to be connected with selected generators to damp out the local oscillations in addition with global signal based PSS to damp out the inter-area oscillations at selected generator as shown in figure -1.

Figure -1: Configuration of the generator with PSS

III. SIGNALS SELECTION & CONTROLLER LOCATION



SITE

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

$$\dot{x} = Ax + Bu$$
$$y = Cx \quad (1)$$

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]:

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

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

In (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 $\theta\left(\phi_k, c_j^T\right)$ 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.

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-II.

Table-II: Inter-Area Mode of Oscillation of Two Area Four Machines System

Mode No.	Eigen Value	Damping Ratio	Frequency (Hz)
5	$-0.25 \pm 6.5i$	0.36	0.**1**
15	$0.05 \pm 4.1i$	-0.01	0.65

From Table-II, it is shown that, mode-15 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-III.

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

Signals	Generators			
	G-1	G-2	G-3	G-4
$P_{7\text{-}6}$	0.2726	0.3588	0.2890	0.3871
$P_{7\text{-}8}$	0.7042	0.9269	0.7466	1
$P_{5\text{-}6}$	0.1314	0.1730	0.1394	0.1867
$P_{3\text{-}11}$	0.1878	0.2473	0.1991	0.2667
$P_{4\text{-}10}$	0.1397	0.1839	0.1481	0.1984
$P_{9\text{-}8}$	0.6988	0.9198	0.7409	0.9923
$P_{9\text{-}10}$	0.3629	0.4777	0.3847	0.5153
$P_{11\text{-}10}$	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

IV. PARAMETERS FOR LOCAL PSS AND WIDE-AREA PSS

For the test system, G-2 of area-1 and G-4 of area-2 are equipped with a LPSS and GPSS 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.

The oscillations 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).

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

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.

Subject to : $T_{1i}^{min} \le T_{1i} \le T_{1i}^{max}$

$$T_{2i}^{min} \le T_{2i} \le T_{2i}^{max}$$

$$T_{3i}^{min} \le T_{3i} \le T_{3i}^{max}$$

$$T_{4i}^{min} \le T_{4i} \le T_{4i}^{max}$$

Where, T_{ji}^{min} and T_{ji}^{max} are the lower and upper bound of time constant for the controllers. The optimized value of lead-lag compensator and other parameters are tabulated in Table –IV.

Table IV - Different parameters for PSS without any delay

Parameters	LPSS	GPSS
T_W	10	10
T_1	50×10^{-3}	0.1
T_2	20×10^{-3}	0.02
T_3	3	0.05
T_4	5.4	0.01
Gain	11	0.1
Wash-out time constant	10	10

V. SIMULATION RESULTS AND COMPARISON

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.

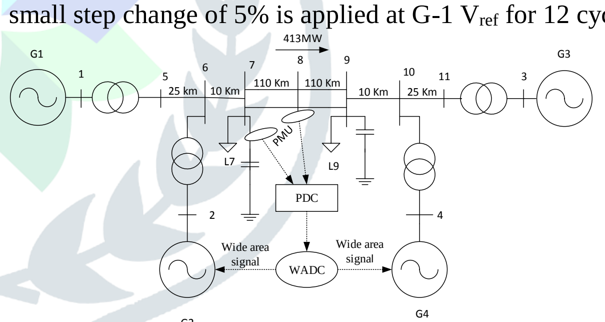


Figure - 2: Two are four machine system

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 with PSS and without PSS.

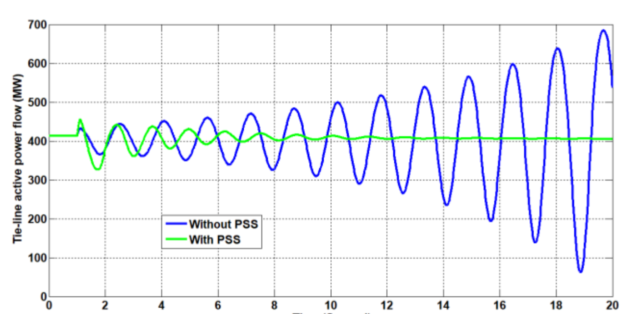


Figure - 3: Tie line active power flow deviation

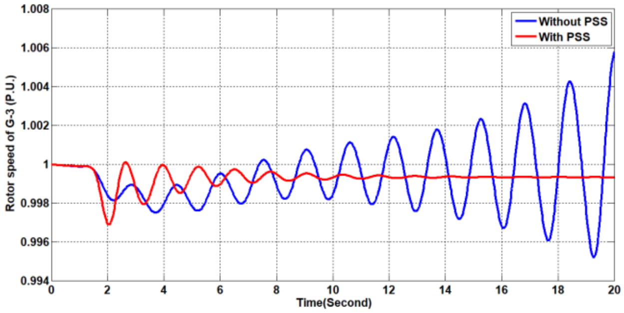


Figure-4: Rotor speed of Gen-3

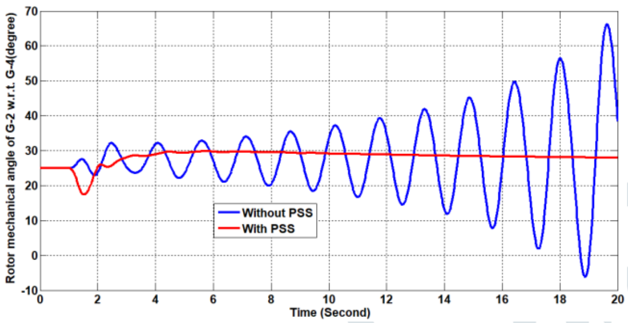


Figure-5: Rotor mechanical angle of G-2 w.r.t. G-4

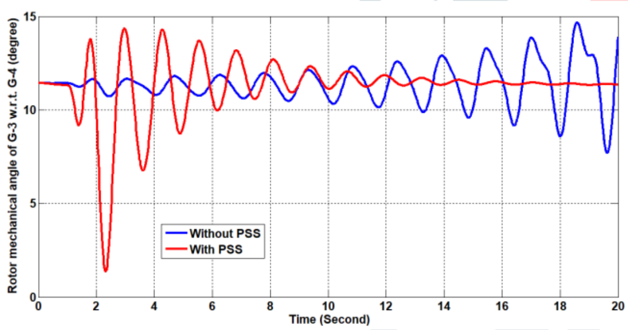


Figure-6: Rotor mechanical angle of G-3 w.r.t. G-4

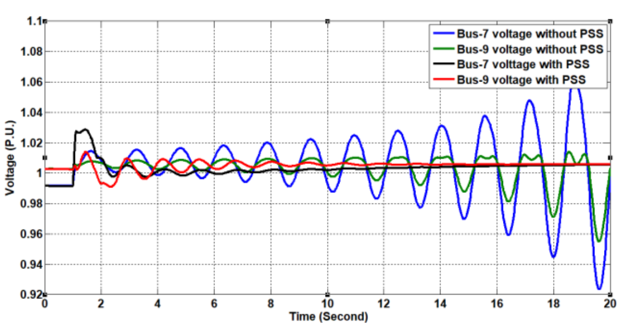


Figure-7: voltage at Bus-7 and Bus-9

VI. CONCLUSION

In this paper, to damp out the inter-area oscillation a GA based PSS is presented. Feedback signal for the PSS have been selected based on joint controllability and observability and tie-line active power is found most suitable signal for PSS. Case study is undertaken based on a four machine two-area power system to demonstrate the design principle and verify the feasibility of the proposed method.

REFERENCES

[1] L. Wang, Q.-S. Vo, and A. V. Prokhorov, ``Stability improvement of a multi-machine power system connected with a large-scale hybrid wind photovoltaic farm using a super capacitor," IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 50_60, Jan. 2018.

[2] D. Remon, A. M. Cantarellas, J. M. Mauricio, and P. Rodriguez, ``Power system stability analysis under increasing penetration of photovoltaic power plants with synchronous power controllers," IET Renew. Power Gener., vol. 11, no. 6, pp. 733_741, May 2017.

[3] G. Rogers, ``Modal analysis for control," in Power System Oscillations. Boston, MA, USA: Springer, 2000, pp. 75_100.

[4] G. Andersson et al., ``Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance," IEEE Trans. Power Syst., vol. 20, no. 4, pp. 1922_1928, Nov. 2005.

[5] F. Wang et al., ``Fractal characteristics analysis of blackouts in interconnected power grid," IEEE Trans. Power Syst., vol. 33, no. 1, pp. 1085_1086, Jan. 2018.

[6] Y. Besanger, M. Eremia, and N. Voropai, ``Major grid blackouts: Analysis, classification, and prevention," in Handbook of Electrical Power System Dynamics: Modeling, Stability, and Control. Hoboken, NJ, USA: Wiley, 2013, pp. 789_863.

[7] O. P. Veloza and F. Santamaria, ``Analysis of major blackouts from 2003 to 2015: Classi_cation of incidents and review of main causes," Electr. J., vol. 29, no. 7, pp. 42_49, Sep. 2016.

[8] Z. Bo, O. Shaojie, Z. Jianhua, S. Hui, W. Geng, and Z. Ming, ``An analysis of previous blackouts in the world: Lessons for China's power industry," Renew. Sustain. Energy Rev., vol. 42, pp. 1151_1163, Feb. 2015.

[9] AIEE Subcommittee on Interconnections and Stability Factors, "First Report Of Power System Stability," AIEE Trans., 1926,pp. 51-80.

[10] Breulmann H, Grebe E, Lösing M, Winter W,Witzmann R, Dupuis P, Houry M. P, T., MargotinJ,Zerenyi, Dudzik J,Machowski J, Martin L,Rodriguez J. M, Urretavizcaya E, "Analysis and Damping of Inter-Area Oscillations In The UCTE/CENTREL Power System," CIGRE, Paris, 2000,pp. 38-113.

[11] CIGRE Task Force 38.01.07 on Power System Oscillations, "Analysis and Control of Power System Oscillations," CIGRE Technical Brochure, no. 111, Dec. 1996.

[12] Dominguez-Garcia J. L, Binachi F. D, and Bellmunt O. G, "Control Signal Selection for Damping Oscillations With Wind Power Plants Based On Fundamental Limitations," IEEE Trans. Power Sys., vol. 28, no.4, Nov 2011,pp. 4274-4281.

[13] Dominguez-Garcia J. L, Ugalde-Loo C. E, Binachi F. D, and Bellmunt O. G, "Input–Output Signal Selection for Damping of Power System Oscillations Using Wind Power Plants," Elec. Power Syst. Res., vol. 54, pp. 75-84,Jan 2014.

[14] Erlich I, Hashmani A, Shewarega F, "Selective Damping Of Inter Area Oscillations Using Phasor Measurement Unit (PMU) Signals," Proceeding of IEEE conference Power Tech, Pub: IEEE, Trondheim, 2011, pp. 1-6.

[15] Hamdam, A. M. A.; and Elabdalla, A. M.; 'Geometric Measures of Modal Controllability and Observability of Power System Models' Electric Power Systems Research, Vol. 15, 1988, pp. 1872-1876.