Power System Stability Enhancement Through Wide Area Measurements

Irfan Ahmed Khan, *KFUPM, Saudi Arabia*, and M. A. Abido, *KFUPM, Saudi Arabia.*

***Abstract*-- Low frequency inter-area oscillations is one of the main concerns for power system operation and control therefore damping of inter-area oscillations is necessary for secure and reliable system operation. However, to enhance damping of the inter-area modes remote signal need to be measured and feedback to the power system stabilizers. This can be done by wide area measurements, through phasor measurement units (PMUs). The power system stabilizers in conjunction with PMUs provide adequate stability. Remote signals through PMUs are of great interest to damp out inter area oscillations. In this paper enhancing the damping of the inter-area modes using wide area measurements has been addressed. The power system stabilizers has been be designed, tested and validated on real time digital simulator (RTDS). The experimental results show the effectiveness of the proposed approach to damp out the low frequency inter-area oscillations**

***Index Terms*-- Inter area oscillations, Phasor Measurement unit, Power system stabilizers and RTDS.**

I. Introduction

The power transmission systems are nowadays operated on the edge of their technical limits and thus became more vulnerable to instabilities and cascading failures than before. The expansion of the transmission grids, on the other hand, is very little due to environmental and cost restrictions. The result is that the existent transmission and generation facilities are fully utilized for bulk power interchanges through tie lines. The tie lines operate near their maximum limits, particularly those connected to the heavily loaded regions. Stressed operating conditions are responsible for inter-area oscillations which may cause breakup of the whole system.

Weakly damped low frequency electromechanical oscillations (0.2 - 0.8Hz) are not only dangerous for the performance and reliability of system but also for the quality of the energy supplied. The increasing yearly power system outages worldwide shows that the need of better monitoring concepts and tools fitted to the actual and future situation of power systems became urgent [1]. Such systems will support the system operators by the online assessment of the system current situations and control the power system by providing extra stability with fore sighting of Overall system. In this context, the use of synchronized phasor measurements is becoming an important for the surveillance of the power systems, which is provided by phasor measurements units (PMUs). They provided the required information needed by the grid operator on the actual system state and are combined with relevant data of the given system with the aim to early detect the instability.

Phasor is the modern measurement technology for the real-time wide area monitoring of the power system, especially for monitoring wide-area disturbances and low frequency electromechanical oscillations. With the development of wide area measurement technology, real time feedback control based on PMU becomes increasingly feasible than ever [2], which is a promising solution for dynamics performance improvement, such as inter area oscillations damping, in a large scale interconnected power system. Due to a lack of global observability, traditional damping controllers like PSSs, cannot always deal with inter-area oscillations effectively. Continuous wide-area controls offer observability and controllability benefits where conventional local continuous controls cannot.

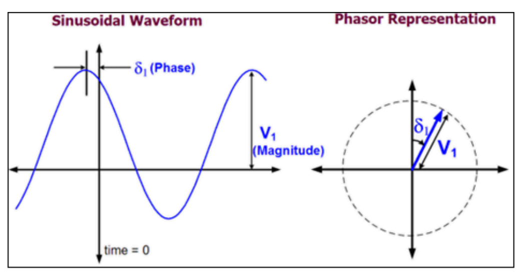

Fig. 1. Phasor representation of a sinusoidal waveform [3]

Its unique ability is to sample analog voltage and current waveform data in synchronism with a GPS-clock and compute the corresponding 60 Hz phasor component from widely dispersed locations. Fig. 1, represents a synchronized sampling process of the different waveforms on a common reference for the phasor calculations [3].

In this paper, we investigate the stability enhancement of the wide area power system using real-time GPS synchronized monitoring with the Phasor Measurement Units (PMUs).

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Once the overall system actual states are available online then the wide area system stability can be improved greatly. IEE2ST multi-input PSS, is integrated with PMUs for the enhancement of wide area power system stability. It is the first time that this type of stabilizer in combination with PMUs are used to damp the inter area oscillations. The controller parameters are optimized using differential evolution method, which are then implemented to the Real time Digital Simulator (RTDS). The system is built and tested on RTDS.

II. Power System Modeling

A. Power System Stabilizers

Power system stability can be improved by connecting suitably tuned Power System Stabilizers (PSS) on selected generators to damp the oscillatory modes. PSS introduces a component of electrical torque in phase with generator rotor speed deviations resulting in damping of low frequency power oscillations in which the generators are participating [4]. Input signal of stabilizer may be local or a remote signal, such as rotor speed, rotor frequency and accelerating power. Lead-Lag blocks are used to compensate the phase with a proper gain that results in damping of rotor oscillations and thereby enhance power transmission and generation capabilities.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{e}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{1}{K_3 T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta e'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} U_{PSS}$$

As shown in the block diagram, Fig. 2, Philips-Heffron linearized model, the PSS output signal U_{PSS} is applied through the T_A , T'_{do} , and K_2 blocks to obtain the extra damping torque ΔT_E. Where T_A is regulator time constant; T'_{do} is time constant of excitation circuit; T_W washout time; K_A regulator gain; Now from Fig. 2, we can write state space equations as follows:

$$\dot{X} = AX + BU_{PSS} \tag{1}$$

Where,

δ rotor angle;
ω rotor speed;
e'_q internal voltage;
E_{fd} equivalent excitation;

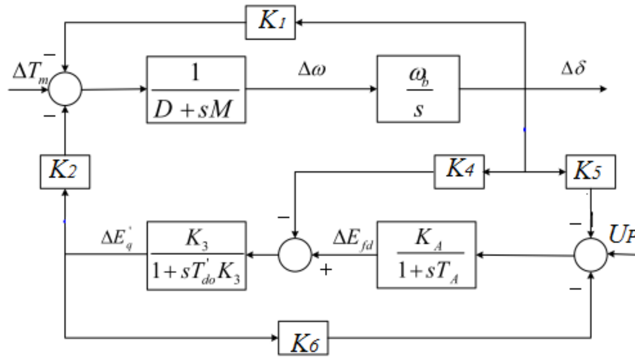

Fig. 2. Philips-Heffron linearized model

The eigenvalues of the matrix A gives the open-loop eigenvalues. If there is a PSS with the following simple structure as shown in Fig. 3, Where, T_1 and T_2 are time constant of lead-lag block while U_{PSS} is PSS output signal, x_5 is the state between two blocks.

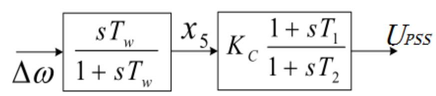

Fig. 3. Block diagram of PSS

Here, two more states have to be added as follows.

$$\Delta\dot{x}_5 = \Delta\dot{\omega} - \frac{x_5}{T_W} \tag{3}$$

Substitute $\Delta\dot{\omega}$ from state space model,

$$\Delta\dot{x}_5 = -\frac{K_1\Delta\delta}{M} - \frac{K_2\Delta e'_q}{M} - \frac{D\Delta\omega}{M} - \frac{x_5}{T_W} \tag{4}$$

$$\dot{U}_{PSS} = \frac{x_5 K_C}{T_2} - \frac{U_{PSS}}{T_2} + \frac{K_C T_1 \Delta\dot{x}_5}{T_2} \tag{5}$$

Substitute the value of $\Delta\dot{x}_5$ from (4)

$$\dot{U}_{PSS} = -\frac{K_1 K_C T_1}{T_2 M}\Delta\delta - \frac{D K_C T_1}{T_2 M}\Delta\omega - \frac{K_C K_2 T_1}{T_2 M}\Delta e'_q - \frac{K_C x_5}{T_2}\left(1 - \frac{T_1}{T_W}\right) - \frac{U_{PSS}}{T_2} \tag{6}$$

Therefore, the system equation with PSS can be written as

$\dot{Z} = A_C Z$, where $Z = \left[\Delta\delta \ \Delta\omega \ \Delta e'_q \ \Delta E_{fd} \ x_5 \ U_{PSS}\right]^T$

Now the control matrix using (2), (4) and (6) is given as,

$$A_C = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & 0 & 0 \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{1}{K_3 T'_{do}} & \frac{1}{T'_{do}} & 0 & 0 \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & 0 & \frac{K_A}{T_A} \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{1}{T_W} & 0 \\ -\frac{K_1 K_C T_1}{T_2 M} & -\frac{D K_C T_1}{T_2 M} & -\frac{K_C K_2 T_1}{T_2 M} & 0 & \frac{K_C}{T_2}\left(1-\frac{T_1}{T_W}\right) & -\frac{1}{T_2} \end{bmatrix}$$

To enhance the system stability it is required to shift the eigenvalues to the left hand side of s-plane. The time constants T_W , T_2 and T_4 are usually prespecified. The stabilizer gain K and time constants T_1 and T_3 are remained to optimize.

B. *Optimization Problem Formulation*

To increase the system damping to electromechanical modes, the following eigenvalue based objective function is considered.

$$J = min \left\{ \zeta_1 : \zeta_i \in \zeta s \text{ of electromechanical modes} \right\} \qquad (7)$$

where ζ_1 is the damping ratio of the i^{th} electromechanical mode eigen value respectively. In the optimization process, it is aimed to Maximize J in order to increase the damping of electromechanical modes. The problem constraints are the optimized parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Maximize J Subject to

$$\begin{aligned} K_i^{\min} &\le K_i \le K_i^{\max} \\ T_{1i}^{\min} &\le T_{1i} \le T_{1i}^{\max} \\ T_{2i}^{\min} &\le T_{2i} \le T_{2i}^{\max} \\ T_{3i}^{\min} &\le T_{3i} \le T_{3i}^{\max} \\ T_{4i}^{\min} &\le T_{4i} \le T_{4i}^{\max} \end{aligned} \qquad (8)$$

Typical ranges of the optimized parameters are [0.001-50] for K_i , [0.06-1.5] for T_{1i} and T_{3i} , and [0.01-0.1] for T_{2i} and T_{4i} . The time constant T_W is set as 5sec. Considering the objective functions given in (7), the proposed approach employs DE algorithm to solve this optimization problem and search for optimal set of PSS parameters, { $K_i , T_{1i} , T_{2i} , T_{3i} , T_{4i}$, i=1,2,…, n_{PSS} }.

C. *Differential Evolution*

The Differential Evolution (DE), is a population based optimization technique and is characterized by its simplicity, robustness, few control variables and fast convergence. Being an evolutionary algorithm, the DE technique is suited for solving non-linear and non-differentiable optimization problems. The controller parameter, gains and time constant are optimized by using DE. A separate Matlab program is built for this purpose which is then feedback to the RSCAD. The flow chart of DE is shown in Fig. 4. More details can be found in [5]-[6].

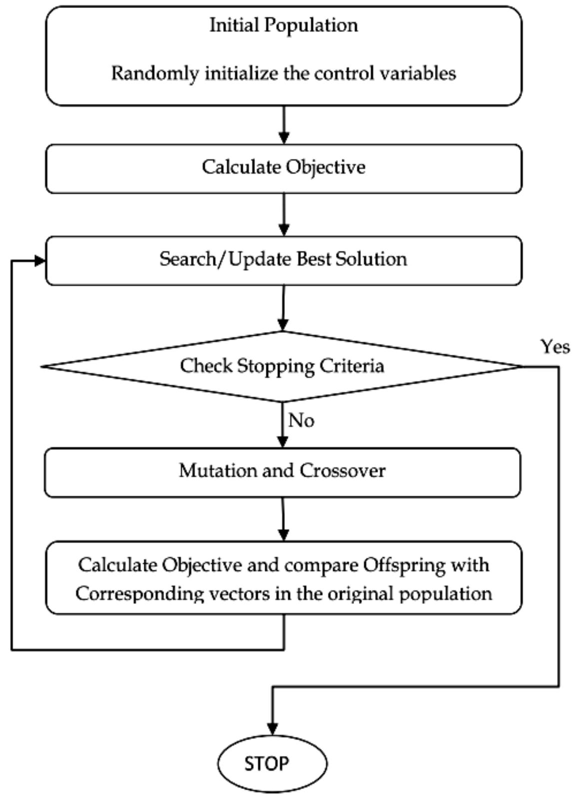

Fig. 4. Flowchart of Differential Evolution optimization

III. EXPERIMENTAL SETUP

A. *Real Time Digital Simulator*

Real time digital simulator (RTDS) is a combination of specialized computer hardware and software designed specifically for electromagnetic transient simulations in real time [7]. An extensive power system component library together with a friendly graphical user interface, facilitate the assembly and study of a wide variety of ac, dc and integrated ac/dc power systems. The system is used for high speed simulations, closed-loop testing of protecting and control equipment and hardware in the loop (HIL) applications. A proper RTDS lab is built under Power and Energy Group in Electrical Engineering Department of King Fahd University of Petroleum and Minerals, Saudi Arabia. Where one rack of RTDS equipped with 2 GPC cards are installed with all accessories. Research is carried on testing different current relays, smart grid applications, Power system stability enhancements, Renewable energy such as PV-systems and wind energy power generation.

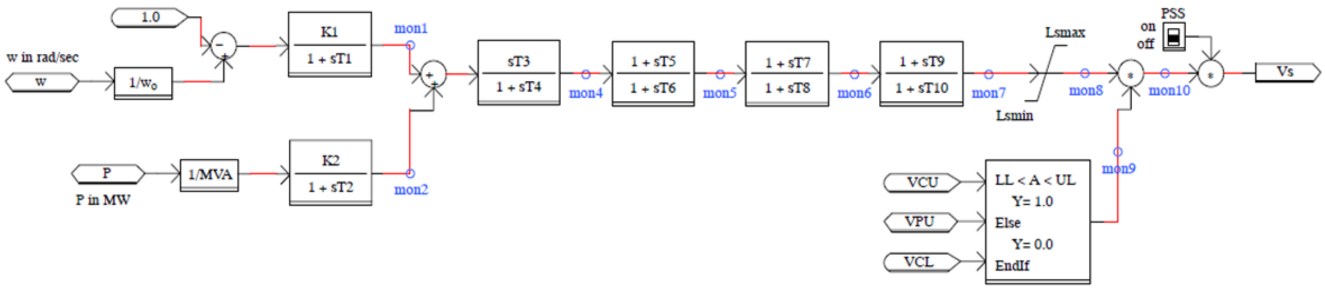

Fig. 5. Block diagram of IEE2ST type power system stabilizer

B. RTDS Model

The power system test model is built on RSCAD, the graphical user interface, having a vast library of all modern components of power system. The test model is then simulated on high speed real time digital simulator RTDS. The 3-Machine 9-Bus system is built on the simulator as shown in Fig. 6., the complete system data is available in [8]. First the test system is simulated for the case when no PSS connected to the system, and all the critical states are monitored in real time. Then the IEESET type PSS is used to damp out the oscillations. After that the PMU is installed to collect the remote signal from distant generator in synchronism with the GPS signal. After that, this remote signal is sent to the IEE2ST type multi input PSS. Studies shows that PSS equipped with both local and remote signals, effectively damp out the inter area oscillations.

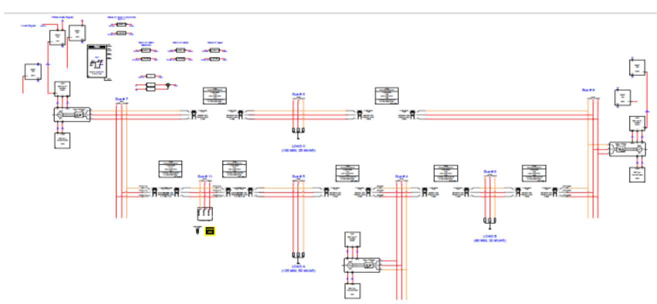

Fig. 6. Test system built on RSCAD

IV. Simulation And Results

3-Machine 9-Bus system [8] as shown in Fig. 7, is used to test the system response on three different cases for inter area oscillations. First, when no PSS is connected to the test system. Second, when the system is connected with IEEES type PSS, Fig. 5, Third, when system is connected with a IEE2ST type PSS integrated with PMUs Fig. 8.The system is built on RSCAD and simulated on RTDS. A six cycle three phase fault is applied on bus 7. And system response is noted down for all three cases. Different optimization techniques are used in [9] for the same 3-Machine 9-Bus system for calculating the stabilizer parameters. However, in this paper differential evolution is used to optimize the gains and time constant of the power system stabilizers. Table I, indicates the optimal controller gains and the time constants for case 2 when single input type PSS (IEEEST) is connected to the test system and for case 3 when system is connected with multi-input type PSS (IEE2ST) integrated with PMUs'.

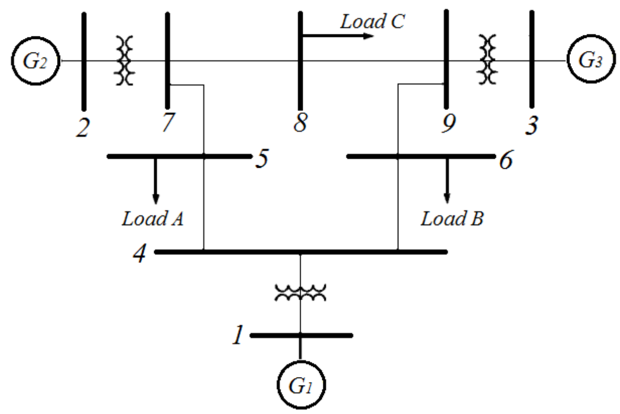

Fig. 7. 3-Machine 9-Bus system test system

TABLE I
CONTROLLER GAINS AND TIME CONSTANTS

Constants	*IEE2ST Type PSS*	*IEEEST Type PSS*
K1	40.127	8.275
K2	0.05	-
T1	0.049	0.201
T2	0.05	0.05
T3	3	0.137
T4	3	0.05
T5	0.698	5
T6	0.001	5
T7	0	-
T8	0.001	-
T9	0.0001	-
T10	0.001	-

In first case, 3-phase 6-cycle fault is applied to the test system with no PSS connected and monitor the system responses. The system is found to be unstable and the oscillations continue for long period of time. In case two, single input type PSS (IEEEST), using *w* as local input signal, installed on Gen2, and a simple PSS on Gen 3. It is observed that the oscillations are damped efficiently. In third case, Gen 2 is equipped with multi-input type PSS (IEE2ST) integrated with PMUs', where *Pe* is used as a local signal and *w* as a remote signal from Gen 3. This remote signal is provided by PMUs in synchronism with GPS clock.

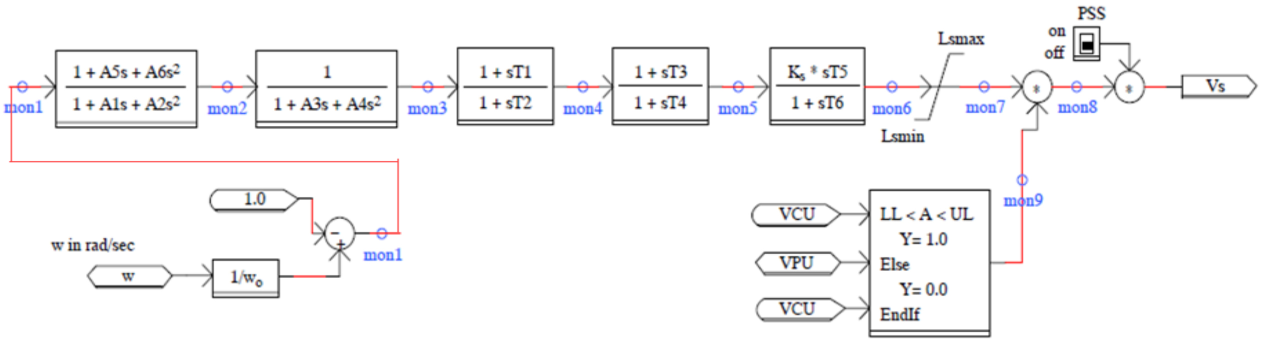

Fig. 8. Block diagram of IEEEST type power system stabilizer

Simulation results shows the performance of each case discussed before, for no PSS, for IEEEST type PSS and for IEE2ST type PSS. Response of generator 1, 2 and 3 for each case is shown in Fig. 9, Fig. 10 and Fig. 11 respectively. From simulation results it is concluded that input signal *w* from remote locations can effectively damp inter area oscillations as compared to local signals as shown in Fig. 12, while the selection of remote signal is based on participation factor.

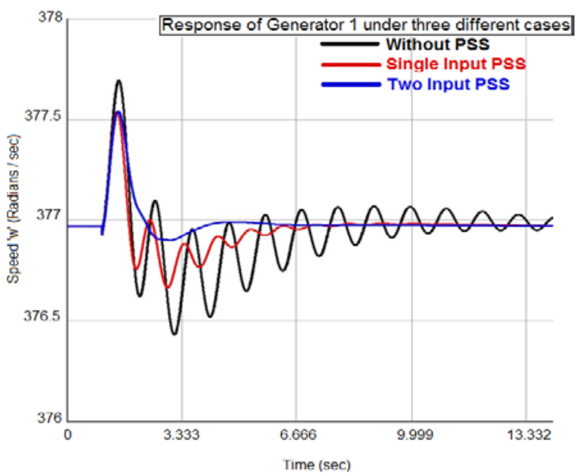

Fig. 9. Response of Generator 1 under three different cases

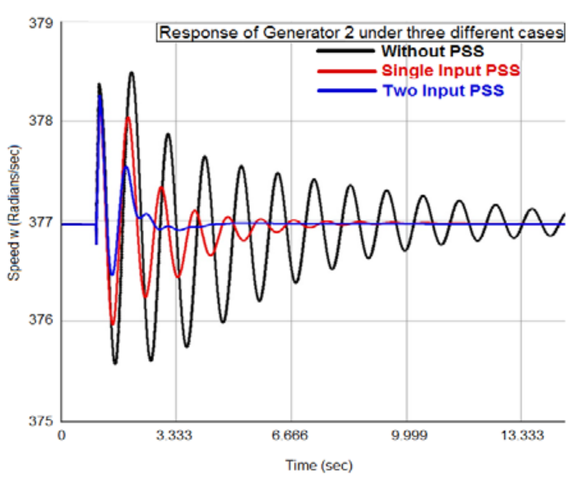

Fig. 10. Response of Generator 2 under three different cases

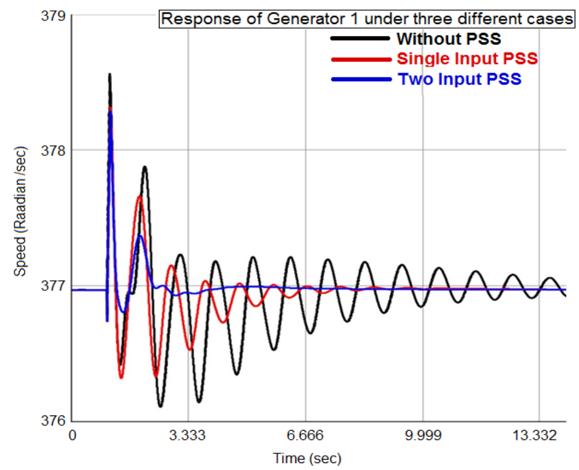

Fig. 11. Response of Generator 3 under three different cases

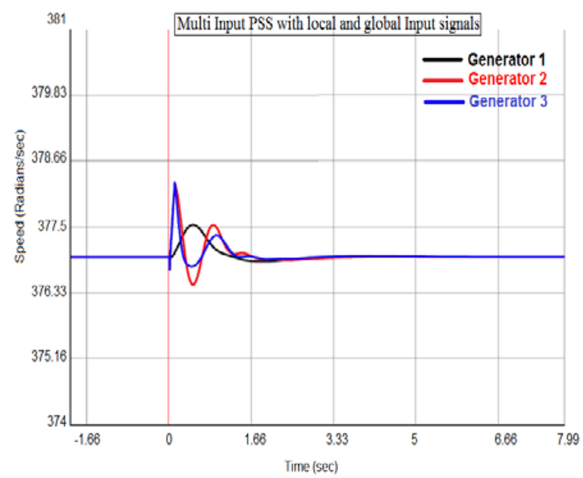

Fig. 12. Multi-input PSS integrated with PMUs

V. Conclusion

In this paper, power system stability enhancement through wide area measurements is presented. System stability can be enhanced by using modern type of PSS controllers integrated with PMUs. IEE2ST PSS controller is used in combination with PMUs to damp out inter area modes. The simulation results show that remote signal from dispersed locations can efficiently damp out the inter area oscillations.

VI. Acknowledgment

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VIII. Biographies

Irfan Ahmed Khan was born in Karachi in Pakistan, on June 8, 1986. He graduated from the Sir Syed University of Engineering and Technology. He is currently working as a Research Assistant and also doing his masters from Electrical Engineering Department, King Fahd University of Petroleum and Minerals. His research interests are power system planning, power system stability enhancements, wide area measurements and renewable energy resources.

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