# Synchrophasor Based Validation of Power System Stabilizer - A Case Study

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***Abstract*—The Indian electricity grid is one of the largest grid and complex networks in the world. Such complex networked power systems experience small signal stability problems in the form of low frequency oscillations. These oscillatory modes if undamped (growing oscillations) can disrupt the system operations. Thus monitoring of undamped oscillations is necessary for reliable operation of the system. These growing oscillations if not damped can even lead to complete blackout. There are various techniques used to estimate the modal content of the power system: model based techniques and measurement based techniques. In the model based technique the nonlinear differential equations governing the system are linearized about an operating point & further the modes are obtained via Eigen value analysis, whereas in measurement based techniques direct measurements from PMU estimate the linear model. Some of the popular measurement based techniques for estimating modes are Prony analysis, Matrix Pencil, Hilbert transform, wavelet transform.**

**The Indian power grid has deployed the technology of Phasor Measurement Units (PMU) which help in the identification of low frequency oscillations present in the system. This paper discusses a case study of an event occurred in the Indian grid which validates the operation of power system stabilizer used to damp oscillations in the power system. The measurement based technique: Prony analysis has been used for estimating the modal contents. The measurements from PMU have been utilized for performing the validation study.**

***Keywords—Phasor measurement unit, low frequency oscillations, Prony, power system stabilizer, model validation***

## I. INTRODUCTION

Low frequency oscillations (LFO) are inherent phenomenon in power systems commonly experienced over the globe, and are a growing concern due to increasing complexity of the grid. The oscillations are initiated by the normal small changes in the system load and disturbances such as generator or line trips [1]. Oscillations are characteristics of a power system need to be carefully monitored and controlled, as the lightly or negatively damped oscillations can grow which can potentially lead to unstable system operation with major consequences like grid breakup, system blackout [2]. A well-known example of this is the August 10, 1996 blackout [3].

With the technological advent, Phasor measurement unit (PMU), the measurements of voltage and current phasors along with frequency and rate of change of frequency (ROCOF) synchronized with Global Positioning System (GPS) satellite are available [4]. With these PMU measurements it is possible to monitor the real time low frequency oscillations power system [5]. Various applications of PMU with benefits are explained in [6] [7]. The applications like fault location identification, classification of faults, oscillatory mode source identification are discussed in [8] [9]. The modern signal processing techniques like Discrete Fourier Transform (DFT) [10] [11] [12], Prony Analysis (PA) [13] [14], Matrix Pencil (MP) [15][16][17], Kalman Filter (KF) [18], Hilbert Transform [19], wavelet transformation technique[20], [21], are being applied to the measurements available from synchrophasor to detect and track the oscillations. Thus helping in developing tools for advanced monitoring and visualization of the grid.

The low frequency oscillations that are identified to be lightly/ poorly damped (negative damping), need to be controlled to avoid the consequences as experienced in the past. There are some devices present in the power system to counteract negative damping which include power system stabilizer (PSS) in excitation system of generator & controls of FACTS devices. Also the real time actions by system operator include generation re-despatch, load shedding, circuit switching etc. are carried out to relieve the stress in the system.

This paper deals with the analysis of synchrophasor measurements to detect the presence of oscillations in the grid. Further this paper demonstrates the operation of Power system stabilizer to add damping to the lightly damped oscillations verified via PMU measurements. An outline of this paper is as follows: Section II reviews the theoretical background on low frequency oscillations (LFO) & power system stabilizer (PSS). Section III focusses on the case study with detailed description of identification of LFOs in the grid and operation of PSS. Section IV concludes the paper.

## II. BACKGROUND

This section provides a brief description of the low frequency oscillations in the power system and the basic model of the power system stabilizer.

### *A. Low frequency Oscillations*

Small signal disturbances occurring due to several reasonsmay disrupt the power system operation. The ability of powersystem to operate in steady state due to such disturbances iscalled small signal stability. Transient stability is associatedwith the ability of power system to maintain synchronism whensubjected to large disturbances like line faults, bus fault, generatortrip etc. During these disturbances the electromagnetic& mechanical torques of each synchronous machine need tobe maintained. The electromechanical torque of synchronousmachine can be resolved into two components: synchronizing torque component($K_s$) & damping torque component($K_d$)asshown in (1).

$$\Delta T_e = K_s \Delta\delta + K_d \Delta\omega = T_s + T_d \qquad (1)$$

Where:
$K_s$: Synchronizing torque coefficient
$\Delta\delta$: Rotor angle perturbation
$\Delta\omega$: Speed variation
$K_d$: Damping torque coefficient
$T_s$: Synchronizing torque
$T_d$ : Damping torque

The damping torque ($T_d$) changes with the change indamping torque coefficient ($K_d$) & variation in speed ($\Delta\omega$).Reduced damping torque ($T_d$) gives rise to low frequencyoscillations[1]. Undamped oscillations can increase in magnitude& lead to instability and are therefore an object ofstudy by various researchers. These oscillations are classifiedinto four major types inter-area modes (0.1 Hz - 1 Hz), intraplantmodes (1 Hz - 2.5 Hz), torsional modes (10 Hz-40 Hz)& control modes. The inter-area modes are associated withswinging of groups of generators in one area of the systemagainst generators in other area. They usually occur becauseof weak interconnecting network. The intra-plant modes occurdue to the swinging of units of generating station with respectto each other. The torsional modes are associated with turbinegeneratorshaft system and associated rotational components.The control modes are present in the system because ofpoor design of controllers of AVR, HVDC, SVC, AGC etc.The identification of modes is carried out using analyticaltechniques.

### *B. Power System Stabiliser*

The power system stabilizers (PSS) were developed to aidin damping the oscillations by modulation of excitation systemand by this supplement stability to the system [1]. The basicoperation of PSS is to apply a signal to the excitation systemthat creates damping torque which is in phase with the rotoroscillations. The block diagram for PSS is as shown in Fig. 1.The PSS is represented by phase compensation block, signalwashout block and the gain block. The significance of eachblock is as follows:

1) Phase compensation block: provides the appropriatephase lead to compensate for the lag between the exciterinput and the generator electrical torque. The frequencyrange of interest is 0.1 Hz to 2 Hz, and the phase leadnetwork should provide compensation over the entirefrequency range. Fig 1 shows the single first ordercompensation block whereas in practice two or morefirst order blocks may be used to achieve desired phasecompensation.
2) Signal washout block: serves as a high pass filter, withtime constant high enough to allow signals associatedwith oscillations in rotor speed to pass unchanged.Without this block the steady changes in speed wouldmodify the terminal voltage.
3) Gain block: determines the amount of damping introducedby PSS. Ideally the gain should be set to a valuecorresponding to maximum damping.

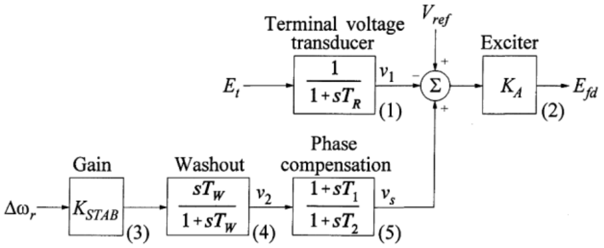

Fig. 1. Block diagram PSS

## III. EVENT DESCRIPTION

This section first describes the operation of PSS for a two area test network as discussed in [1]. Further the real events are discussed that are considered for validating the PSS operation in the power system network using the PMU measurements.

### *A. Two area test network*

The two area four machine system used for the studymimics the behavior of the actual power system operations and has been extensively used in various power system studies[22][23]. It consists of two fully symmetrical areas linkedtogether by two 230 kV lines of 220 km length each as shown in Fig. 2. This system was specifically designed in[24][25][26] to study low frequency electromechanical oscillations inlarge interconnected power systems. Each area consists of twoidentical generators rated 20kV/900MVA. The synchronousmachines have identical parameters [25] [26], except for inertiaswhich are H=6.5s in area 1 and H = 6.175s in area2. This network is simulated for small changes in the systemwithout operation of PSS and with the operation of PSS.

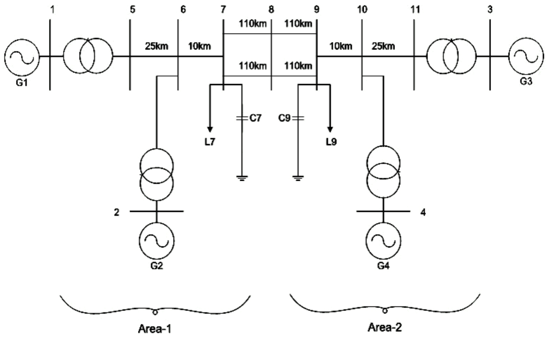

Fig. 2. Two area test network

The modal analysis of the acceleration power of the machinesin the network without PSS detects the presence ofdominant modes with frequencies of 0.64 Hz and 1.12 Hz withdamping of -0.023 and 0.025 respectively as shown in TABLE. I. Further simulation was carried out by adding PSS into thenetwork and the modal analysis of the acceleration powersindicated that the modes with frequencies of 0.6 Hz and 1.12Hz were highly damped. The 0.6 Hz mode was identified tohave damping of -2.3 % during open loop operation while afterinclusion of PSS the damping increased to 29 %.

TABLE I. RESULTS OF MODAL TWO AREA TEST NETWORK

| Sr.No | Frequency (F) | Damping (D) | Amplitude (A) |
|---|---|---|---|
| Without PSS | | | |
| 1. | 1.13 | 0.025 | 0.027 |
| 2. | 0.63 | -0.023 | 0.010 |
| With PSS | | | |
| 1. | 1.23 | 0.25 | 2.36 |
| 2. | 0.62 | 0.29 | 0.48 |

### B. *Oscillatory modes in Northern Region*

Oscillations are always present in the system even undernormal operating conditions but highly damped. This sectiondeals with the identification of critical oscillatory modes inKarcham located in the northern region of the Indian grid. Todo so the measurements of PMU placed at Karcham Wangtooare used for the analysis.

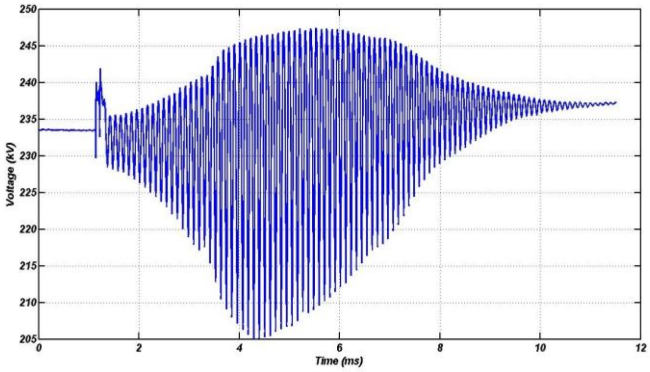

Fig. 3. Oscillations Observed

The phase voltage measurement by PMU located at Karchamis shown in Fig. 3 recorded on 23rd August 2012.The measurements indicate presence of oscillations with largeamplitudes and need to be damped in-order to avoid futurecascading blackouts. Further these measurements are processedin-order to extract the constructive information from the signal.The tool used for analyzing the data discussed in the paper isProny analysis. Other tools likes FFT, matrix pencil,wavelettransformation technique have also been verified. Results ofthe processed data are tabulated in TABLE. II.

TABLE II. RESULTS OF MODAL ANALYSIS IN NR

| **Sr.No.** | **Frequency** | **Damping** | **Amplitude** |
|---|---|---|---|
| 1. | 0.93 | 0.0077 | 25.84 |
| 2. | 0.97 | -0.0013 | 1.002 |
| 3. | 1.84 | 0.004 | 3.38 |
| 4. | 1.95 | -0.0002 | 0.076 |

The oscillations identified in the phase voltage measurementat Karcham are with frequencies of 0.93 Hz, 0.97 Hz withlow damping and high amplitude designated as the dominantmodes. Also modes with frequencies of 1.86 Hz and 1.95Hz with lower amplitudes were detected. The modes with1.86 Hz and 1.95 Hz are the 2$^{nd}$ harmonic components of0.93 Hz and 0.97 Hz. The mode shapes for 0.93 Hz, 0.97Hz, 1.86 Hz and 1.95 Hz are shown in Fig. 4 and Fig. 5respectively. Thus it can be quantified from the analysis thatthe inter-plant and intra-plant modes were observed in the grid.

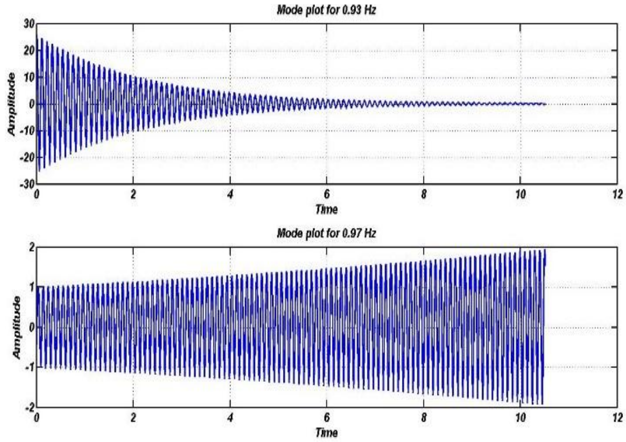

Fig. 4. Mode shapes for 0.93 Hz & 0.97 Hz

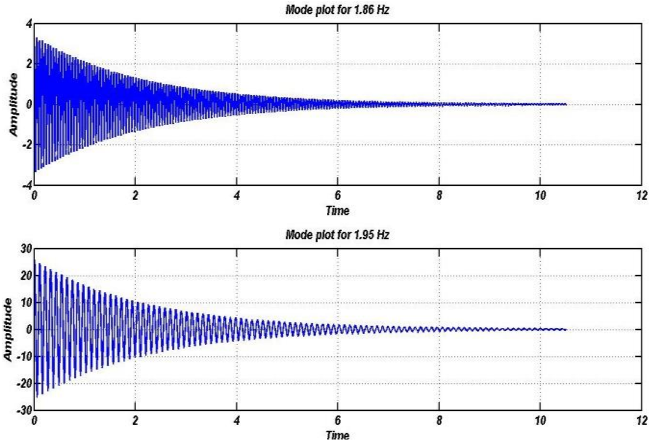

Fig. 5. Mode shapes for 1.86 Hz & 1.95 Hz

The mode with frequency of 0.93 Hz can be designatedas inter-plant mode which was observed due to interaction ofKarcham Wangtoo hydro plant with rest of the grid, while1.84 Hz mode is produced by one of the generators oscillatingwith respect to other generators in the plant. Also 0.97 Hz,an inter-plant mode is observed to have negative dampingalong with 1.95 Hz (second harmonic component of 0.97 Hz)mode with further reduced damping. These oscillatory modeswith low damping & high amplitude may lead to unstablesystem operation, thus some actions need to be taken in-orderto avoid occurrence of such conditions.

The results of modal analysis can be interpreted as follows,the generation of the Baspa-Karcham-Jhakri complex was3000 MW (Jhakri: 1600 MW, Wangtoo: 1100 MW and Baspa:300 MW). Considering them as three generators, we will have2 Modes (because, if there are N generators, we have N-1modes in the system). So the Intra-plant modes 1.84 Hz and1.93 Hz modes were due to these three generators interactingwith each other (As the plants are located close-by, theycan be assumed as three generators located nearby). Thesemodes can be due to Jhakri-Karcham interaction and Jhakri -(Karcham+Baspa) interaction based on the fact that Baspa isonly connected with Karcham only. While these generatorsare also connected with the rest of the generators of gridwhich led to inter-plant mode of oscillation with frequency0.93 and 0.97 Hz, interaction with grid led to their highamplitude.

### *C. Operation of power system stabilizer*

This section discusses a case that validates the operationof PSS using PMU measurements. On 12th April 2013, a testwas conducted by switching off the PSS of generator unitat Karcham. The measurements from PMU were recordedwhen PSS switched off & switched on as well. The plotfor Karcham Wangtoo bus voltage captured by PMU withPSS switched OFF & ON are shown in Fig. 6. This figureclearly indicates that when PSS is switched ON (plot n blue)number of oscillations observed in the voltage profile are lessas compared to the oscillations observed with PSS switchedOFF (plot in red).

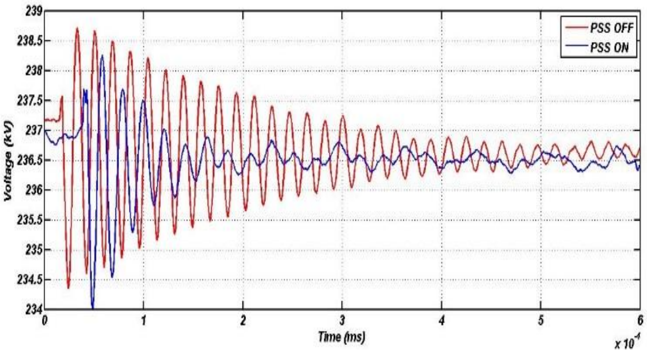

Fig. 6. Wangtoo bus voltage recorded by PMU

The modal analysis of the plots in Fig. 6 were performedin order to identify modes of oscillations in the system. Theresults of modal analysis using MP method are tabulated in TABLE. III for cases when was PSS switched OFF & ON.

TABLE III. RESULTS OF MODAL ANALYSIS FOR VALIDATION

| With PSS OFF | | | With PSS ON | | |
|---|---|---|---|---|---|
| *Frequency* | *Damping* | *Amplitude* | *Frequency* | *Damping* | *Amplitude* |
| - | - | - | 0.186 | 0.0903 | 0.19 |
| - | - | - | 0.54 | 0.06 | 2.54 |
| 0.62 | 0.20 | 2.19 | - | - | - |
| 0.65 | 0.015 | 1.4 | - | - | - |
| - | - | - | 0.84 | 0.14 | 4.43 |
| 1.2 | 0.04 | 0.19 | 1.1 | 0.116 | 2.26 |

Results in TABLE. III indicate that when PSS of generator at Karcham was switched off, modes with frequencies of 0.62Hz, 0.65 Hz, 1.2 Hz were identified to have damping lessthan 5 %. The mode shapes for the same are shown in Fig. 7. An inter-area mode of 0.65 Hz was observed to have highamplitude and low damping.

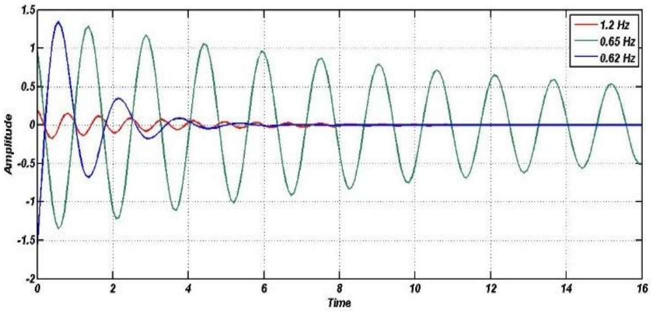

Fig. 7. Mode shapes with PSS OFF

The results for modal analysis of phase voltagemeasurement at Karcham are tabulated in TABLE. III.The modes with frequencies of 0.18 Hz, 0.54 Hz, 0.84 Hz and 1.1 Hz were identified all with damping greater than5%. The mode shapes for modal parameters identified withPSS switched on in the system are shown in Fig. 8. Thus after switching ON PSS the modes detected have sufficientdamping. This clearly signifies the job of adding damping tothe mode with insufficient damping.

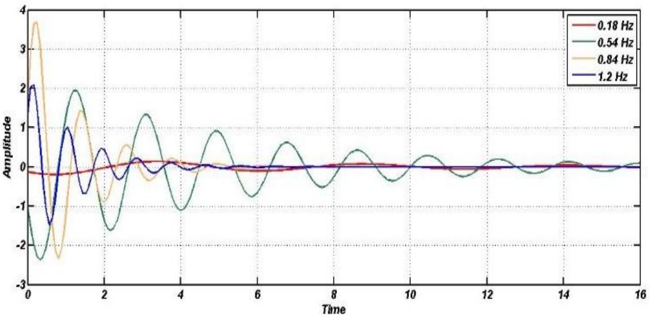

Fig. 8. Mode Shapes with PSS ON

## IV. CONCLUSION

With the advancements in communication and information technology and the ever increasingly important need of wide-area visibility for power grids, PMUs are extensively deployed in the Indian power grid network. The measurements available from PMU give the near to real time grid visualization and applications like model validation, control strategies, wide area protection schemes etc. can be developed.

A PSS model validation has been carried out using the system measurements available from PMU. The approach is demonstrated for PMU data recorded at Karcham in the NR of Indian electricity grid. Prony analysis was used to estimate the damping of the oscillatory modes in the system. It was observed that an inter-area mode with frequency of 0.65 Hz had reduced damping before the operation of PSS. With switching on the PSS, this mode of 0.65 Hz was damped, also rest other modes had enough damping. This study helps to validate the operation of PSS in adding damping the growing oscillatory modes. With techniques on identifying the source of oscillations using PMU measurements and tune the PSS to damp the undesired modes in system will help in healthy system operation.

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