Detection of LFO and Evaluation of Damping Improvement Using Synchrophasor Measurement

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Abstract— **Synchrophasor has evolved as an effective tool for detection of low frequency oscillation (LFO) inherent to a power system. This paper presents case studies to illustrate utilization of Synchrophasors for post-mortem analysis of oscillations to identify the root cause and evaluate the effectiveness of the remedial measures like Power System Stabilizer (PSS) and System Protection Schemes (SPS) for improving damping in the system. Authors suggest installation of Phasor Measurement Unit (PMU) at suitable locations for performance evaluation of other controllers installed in the system for power oscillation damping (POD).**

Keywords— **Indian Grid, Low Frequency Oscillation, Phasor Measurement Unit, Power System Stabilizer.**

I. INTRODUCTION

Oscillatory modes are inherent to a power system. The oscillations include electromechanical oscillations, control modes and subsynchronous oscillation [1-6]. Such oscillations are not of concern to the system operator as long as they have adequate positive damping. Poorly or negatively damped LFOs pose a serious threat to the system reliability. Low frequency modes could be observed in the rotor velocity, rotor angle, voltage, currents, power flow etc. Abnormal variations in these parameters can result in tripping of the machines, transmission lines, damage to equipment or a large scale blackout [7]. Hence, it is essential to monitor the LFO and their damping in the real-time operation.

Tracking of LFOs is difficult in the conventional Supervisory Control and Data Acquisition (SCADA) system having low sample rate, lack of time synchronization and skewed data. However, Synchrophasors have emerged as an effective tool for detection, visualization, monitoring and analysis of LFO in the power system [1, 2 and 10]. Various algorithms are now available for analyzing the characteristics of LFO, their observability in various parameters, magnitude, damping and mode shape in the entire grid and the coherency observed for the generating plants. Presently system operators across the globe are utilizing it for LFO analysis and mitigation measures. [1-2 and 8-9]. However, it is equally important to evaluate the effectiveness of the mitigation measures- such as tuning of Power system stabilizer (PSS) in generators and tuning of POD controller of Flexible AC Transmission System (FACTS) devices in improving the system damping.

Synchrophasors are being used for detection of LFO in the Indian power system since 2010 [1-2, 11-12 and 18]. The present paper discusses the further advance usage of PMUs for evaluation of damping improvement by PSS and SPS. Section-II of this paper highlights the primary reasons for LFOs in the Indian Grid and the reliability concerns arising from them. While the section-III highlight the Oscillation Monitoring System available in the Western Regional Load Despatch Centre at Mumbai. In section-IV, three case studies have been presented to demonstrate the utilization of synchrophasor data together with conventional SCADA data in identifying the root cause of Low Frequency Oscillations and for analyzing the effectiveness of the mitigation measures taken. In the last section of the paper, overall finding and its summary along with the future scope of work have been presented.

II. LOW FREQUENCY OSCILLATION IN THE INDIAN GRID

The Indian Grid is among the largest interconnected synchronous grid in the world having an installed capacity of 330 GW with more than 1700 generators. Several PMUs were installed under a pilot project in 2010. Analysis of synchrophasor measurements has been used to detect LFO and identify their root cause. The reasons behind the excitation of LFOs observed so far in Indian grid are deliberated in detail in the two POSOCO reports published in Sep 2014 and Mar 2016 [1, 2]. Extracts are quoted below:

1. Weak AC interconnections between control areas.
2. Operation of generating plant with high angular separation from the adjacent node.
3. Malfunction of Unit Control system software and governor system.
4. Unit Test like governor testing, Ramp test, Performance and Guarantee (PG test)
5. Malfunction during unit synchronization or desynchronization
6. Switching of transmission elements causing large reactive power change where fault level is low.
7. Severe fault and delay in fault clearance causing a large voltage dip.
8. Out of service or improperly tuned PSS in generating units.
9. Valve malfunction in the turbine for thermal and nuclear Units.
10. HVDC controller malfunction

The reliability concerns arising from LFOs are listed below:

1. Tripping of transmission elements / Generating units
2. Reduction of Total Transfer Capability (TTC) between control areas
3. Wide area blackout
4. Wear and tear of generator rotor shaft
5. Wear and tear of consumer rotating loads
6. Poor power quality
7. Reduction in generation from the power plant

The next section briefly describes how LFO is monitored on real-time in Indian power system. Further, it also explains how the Synchrophasors complement SCADA/Energy Management System (EMS) in locating the source of the oscillations.

In this paper, three case studies of LFOs are analyzed using synchrophasor data and the remedial actions to be taken for LFOs mitigation are suggested. In addition, the impacts of these remedial actions on LFOs also have been evaluated using Synchrophasors.

III. OSCILLATION DETECTION IN THE INDIAN POWER SYSTEM USING SYNCHROPHASOR MEASUREMENT

Electromechanical oscillations have a frequency range from 0.1 Hz to 3 Hz in general and thus require time synchronized data of more than 10 samples per second. Such granular time synchronized data is presently possible only with the help of PMUs. Oscillation Monitoring System (OMS) based on synchrophasor measurements has been deployed in each Regional as well as National Control Centre [1]. The outputs of OMS are frequency, magnitude, energy level, damping ratio and mode shape of LFO. It also indicates the coherent group of generators along with its geospatial variation and generates alarms during low damping.

Screenshot of the various display of OMS available in the control centre in Western Regional Load Despatch Centre, Mumbai is shown in figure 1, 2, 3 and 4. Figure 1 shows the various modes present in the system, their damping and alert level. The dotted circles in Figure 1 highlight the 0.86 Hz mode and its instability as damping is nearing zero on one occasion, while Figure 2 and Figure 3 show the mode frequency Vs. damping chart and mode shape respectively. Figure 4 shows the geospatial display of the LFO along with its mode shape, which is essential as it helps in identifying which part of the system is oscillating. It may be inferred from Figure 4 that the 0.86 Hz mode is present only in the Eastern part of the Western regional grid of India power system.

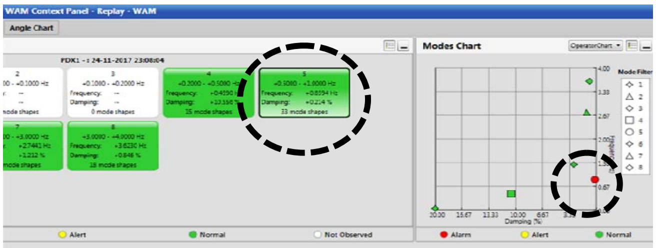
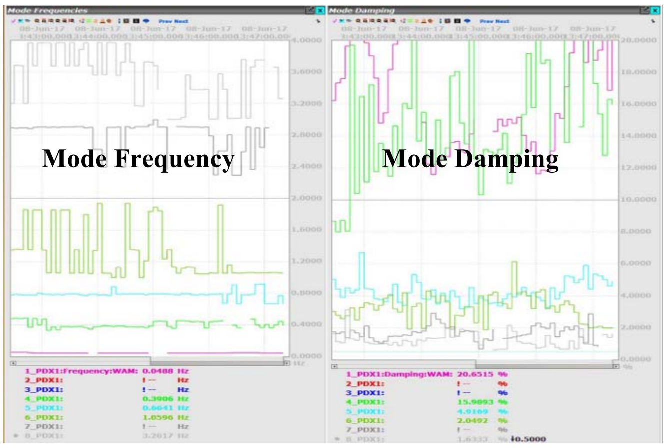


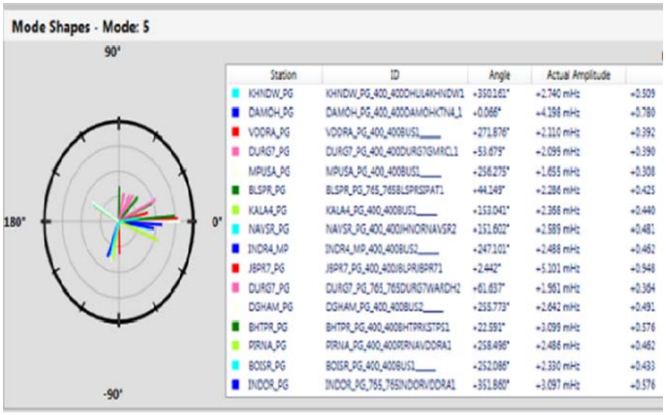
Figure 1. Snapshot of OMS display showing oscillation modes and their damping along with alarms at Western Regional Load Despatch Centre



1_PDX1:Frequency:WAM: 0.0488 Hz
2_PDX1: !— Hz
3_PDX1: !— Hz
4_PDX1: 0.3906 Hz
5_PDX1: 0.6641 Hz
6_PDX1: 1.0596 Hz
7_PDX1: !— Hz
8_PDX1: 3.2617 Hz

1_PDX1:Damping:WAM: 20.6515 %
2_PDX1: !— %
3_PDX1: !— %
4_PDX1: 15.9893 %
5_PDX1: 4.9169 %
6_PDX1: 2.0492 %
7_PDX1: !— %
8_PDX1: 1.6333 %

Figure 2. Frequency and Damping Chart for all the observable mode of Western Regional Grid of India.



	Station	ID	Angle	Actual Amplitude	
🟦	KHNDW_PG	KHNDW_PG_400_400DHUL4KHNDW1	+350.161°	+2.740 mHz	+0.509
🟦	DAMOH_PG	DAMOH_PG_400_400DAMOHKTN4_1	+0.066°	+4.198 mHz	+0.780
🟥	VDDRA_PG	VDDRA_PG_400_400BUS1____	+271.876°	+2.110 mHz	+0.392
🟥	DURG7_PG	DURG7_PG_400_400DURG7GMRCL1	+53.679°	+2.095 mHz	+0.390
	MPUSA_PG	MPUSA_PG_400_400BUS1____	+256.275°	+1.655 mHz	+0.308
🟩	BLSPR_PG	BLSPR_PG_765_765BLSPRSIPAT1	+44.149°	+2.286 mHz	+0.425
🟩	KALA4_PG	KALA4_PG_400_400BUS1____	+153.041°	+2.368 mHz	+0.440
🟦	NAVSR_PG	NAVSR_PG_400_400JHNORNAVSR2	+151.602°	+2.589 mHz	+0.481
🟦	INDR4_MP	INDR4_MP_400_400BUS2____	+247.101°	+2.486 mHz	+0.462
🟥	J8PR7_PG	J8PR7_PG_400_400J8LPRJ8PR71	-2.442°	-5.101 mHz	-0.948
🟥	DURG7_PG	DURG7_PG_765_765DURG7WARDH2	+61.637°	+1.961 mHz	+0.364
	DGHAM_PG	DGHAM_PG_400_400BUS2____	+255.773°	+2.642 mHz	+0.491
🟩	BHTPR_PG	BHTPR_PG_400_400BHTPRKSTPS1	+22.591°	+3.099 mHz	+0.576
🟩	PIRNA_PG	PIRNA_PG_400_400PIRNAVDDRA1	+258.496°	+2.486 mHz	+0.462
🟦	BOISR_PG	BOISR_PG_400_400BUS1____	+252.086°	+2.330 mHz	+0.433
🟦	INDOR_PG	INDOR_PG_765_765INDORVDDRA1	-351.860°	-3.097 mHz	-0.576

Figure 3. Mode Shape of Low Frequency Oscillation for one of the mode observed having 0.86 Hz frequency in Western Regional Grid of India.

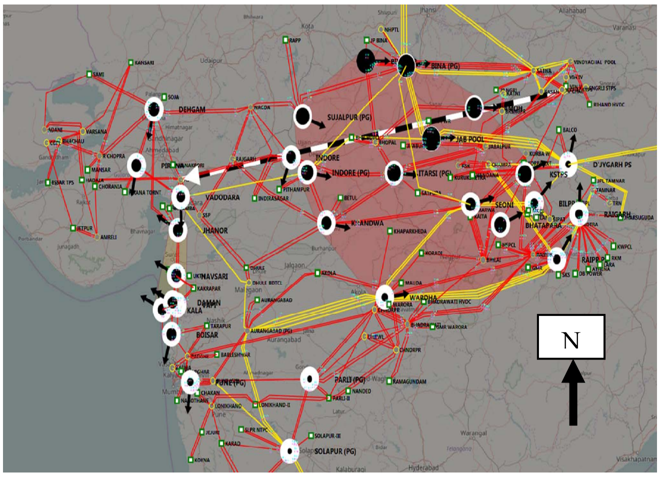


Figure 4. Geospatial display of Low Frequency Oscillation along with mode shape for a typical case in the Western Regional Grid of India

The observability of low frequency oscillation was poor with the conventional SCADA system due to its inherent data latency and skewness. However, SCADA data is helpful in finding the source of forced oscillation due to any power plant by measuring the variation in real and reactive power for all the units in the grid [10, 16].

The OMS along with the conventional SCADA data provides sufficient details to identify the root cause of most of the low frequency oscillation observed in the Indian Power system [1, 2, and 13].

IV. CASE STUDY ON LFO DETECTION AND EVALUATION OF REMEDIAL MEASURES FOR DAMPING IMPROVEMENT

In this section, three case studies have been presented to illustrate the process of detection of LFO in real time, for assessment of the reason for low damping and for evaluation of the effectiveness of remedial measures taken for improving damping by tuning the PSS or through System Protection Schemes (SPS) [14-15 and 17-18].

The effectiveness of remedial actions (PSS tuning, SPS) in improving the damping could be done by calculating the ratio of reduction in first and second peak, improvement in damping ratio and reduction in the oscillation period. The security enhancement measures taken were considered effective when after the implementation of the measures the damping ratio improved to more than 10 % and the peak-to-peak ratio reduced to less than 50 % within 5 seconds interval [2].

The input data for the case studies have been taken from Western Regional Load Despatch Centre (WRLDC) of Power System Operation Corporation Limited.

A. Case 1: Oscillation in the Powerplant due to Angular Instability and PSS out of service

2 X 600 MW Thermal power plant G1 is connected with the grid at 400 kV Voltage level through a double circuit line (246 km/circuit) having triple Snowbird ACSR conductor. The network connectivity of the power plant is shown with the help of figure 5.

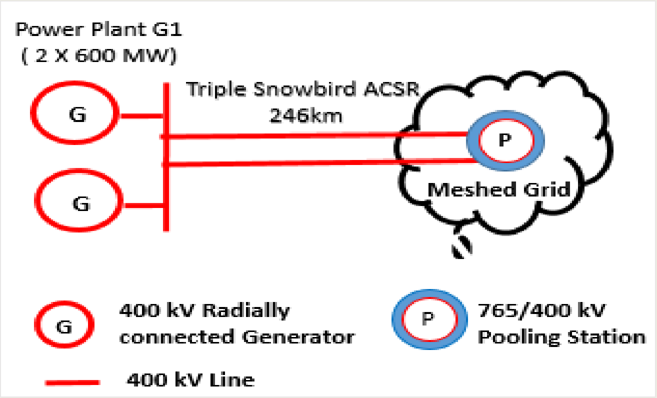


Figure 5. Single line diagram of power plant G1.

During one of the events, the power plant G1 was generating at full capacity and a phase-to-phase fault occurred on one of the evacuation circuits due to jumper snapping. With the correct operation of distance protection, the line tripped and the fault was cleared. Tripping of the line was recorded in the SCADA sequence of event (SOE) list.

However, after the tripping of one circuit, the entire generation started getting evacuated through the remaining single circuit. Followed by this event, LFOs in the grid were captured in the Oscillation Monitoring System at WRLDC. The frequency of oscillation was 0.86 Hz while the damping ratio was below 0.3 % as shown in Figure 1.

Figure 3 and Figure 4 show the mode shape and geospatial presence of this mode in the Western region of Indian grid respectively. The variation of net active power from the power plant G1 monitored through PMU can be seen in Figure 6 where it can be observed that the oscillation magnitude was quite high and it persisted for more than 5 minutes. To mitigate oscillations in real-time, the power plant G1 was advised to back down generation immediately.

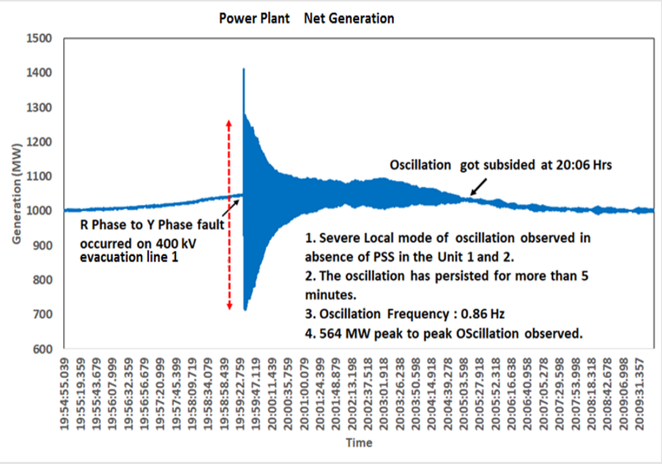


Figure 6. Oscillations at power plant G1 without SPS and PSS tuning

Post-mortem analysis for this event was carried out using synchrophasor measurements and SCADA data. Offline simulations were also done to find out the root cause. The major reasons for the LFO emerged are as follows:

1. **Large Angular separation between the adjacent nodes:** It was observed that under N-1 of one of the 400 kV evacuation lines, the angular separation between power plant bus and next adjacent bus was 27 degrees, which is close to the steady-state limit of 30 degrees.
2. **Absence of PSS:** PSS at the generating plant was kept out of service as it was not tuned. In order to address the above two issues, the power station was advised to implement one SPS for automatic reduction of generation under the N-1 contingency and also to keep the PSS in service after tuning. The same was implemented in the power plant G1.

Subsequently, when an event of similar nature occurred at power plant G1 (Tripping of one of the two 400 kV evacuation lines on single phase to earth fault), PSS acted to damp the oscillations while the SPS acted to back down generation to a safe limit. Figure 7 shows the power plant net injection during this event as measured by the installed PMU. It can be observed that the LFO at the power plant got damped within 10 seconds as compared to 5 minutes in the previous case. The peak to peak amplitude of the oscillation reduced from 564 MW to 278 MW. The damping ratio changed from 0.3 % to more than 10 %. Though the antecedent generation influences the amplitude and duration of an oscillation, however, the improved damping and reduction in oscillation amplitude indicate the effectiveness of 'keeping the PSS in service' and 'automatic generation reduction through SPS'.

Thus, the above case study illustrates the detection of LFO in case of N-1 contingency at the radially connected power plant, remedial action requirements and evaluation of remedial measures using synchrophasor measurements for the securable operation of the grid.

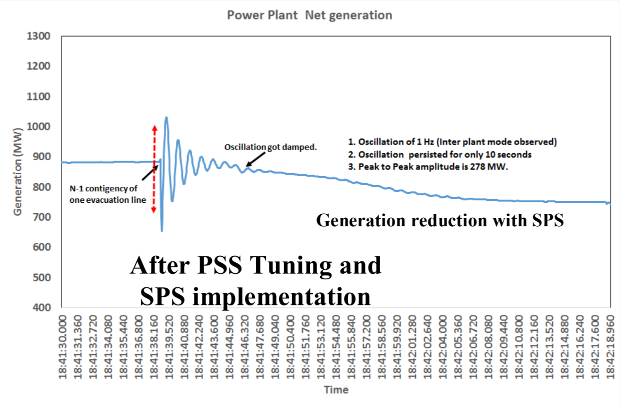


Figure 7. Oscillations at power plant G1 after SPS implementation and PSS tuning.

B. Case 2: Detection of the Local mode of Oscillations and PSS Re-tuning Evaluation

Four power plants (Plant A: 6 X 660 MW, Plant B: 2 X 500 MW, Plant C: 2 X 500 MW, Plant D: 2 X 660 MW) having a cumulative installed capacity of 7280 MW are located in the North-Eastern part of Western Regional Grid. Connectivity of this large generating complex with the grid is illustrated in Figure 8. It may be seen that power plant A, power plant B, power plant C and power plant D are evacuated through common pooling station Q.

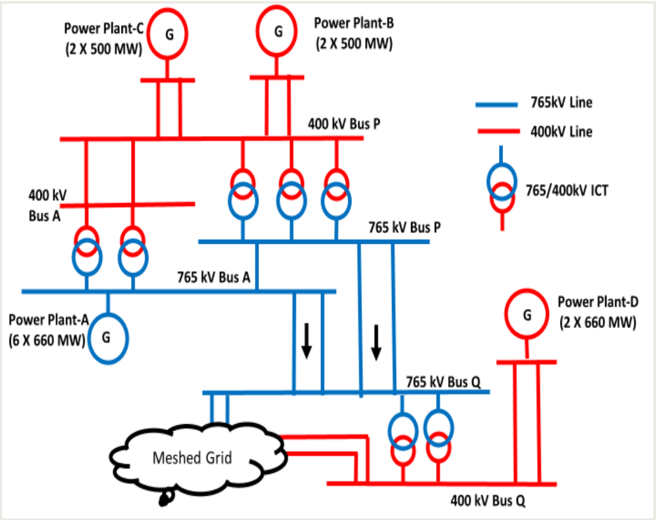


Figure 8. Schematic Diagram of power plant complex for case study 2

There was a transient fault on one of the 765 kV evacuation lines in the complex after which oscillation of 0.78 Hz was observed in these four power plants. Figures 9, 10, 11 and 12 show oscillations in the net generation output from the power plants A, B, C and D respectively. It may be seen that peak-to-peak amplitude of oscillation in the net generation at Plant A, Plant B and Plant C was 823 MW, 323 MW and 292 MW respectively. The oscillations got damped after 18 seconds. However, the amplitude of oscillations at Plant D (which was closer to the fault) was only 39 MW and it damped within 12 seconds.

Detailed analysis using Synchrophasor measurements and SCADA data along with other inputs from power plants revealed that the PSS in the generating units of power plants A, B and C have either not tuned with the change in the network topology or kept out of service unlike the PSS in the units of power plant D which was tuned with consideration of the current network. Therefore power plants A, B and C were pursued to tune their PSS and take them in service.

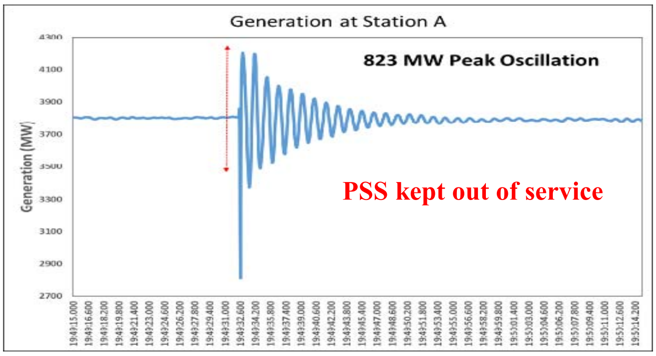


Figure 9. LFO observed at power plant A.

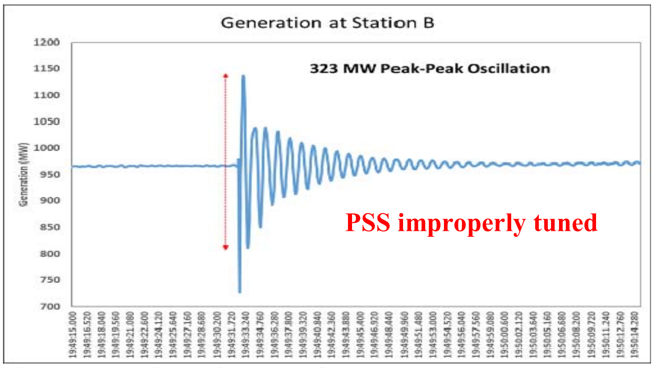


Figure 10. LFO observed at power plant B.

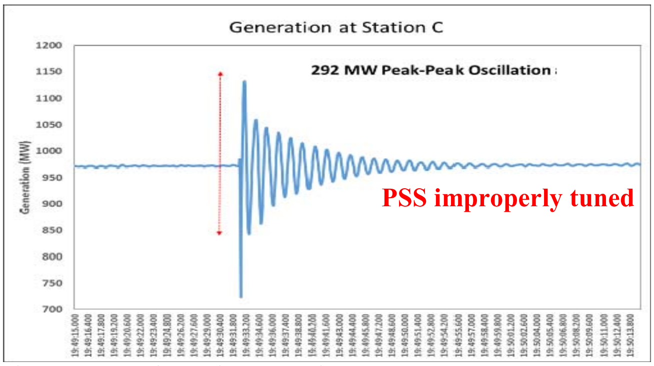


Figure 11. LFO observed at power plant C.

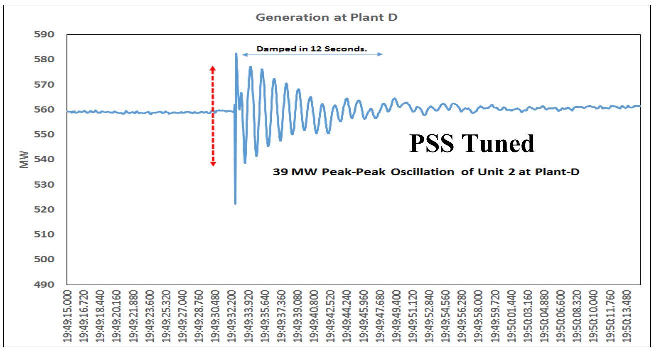


Figure 12. LFO observed at power plant D.

Thereafter, during a similar contingency involving tripping of the 765 kV evacuation line from the referred generation complex, it was observed that the amplitude of oscillations observed at power plant A (6 X 660 MW) reduced to 215 MW and the oscillations damped within 5 seconds as shown in Figure 13. While for generating plants B and C the oscillation magnitude reduced to 116 and 105 MW along with the damping time within 4 & 5 seconds as shown in figure 14 and 15 respectively. Power plant D that was already tuned has effectively shown damped response.

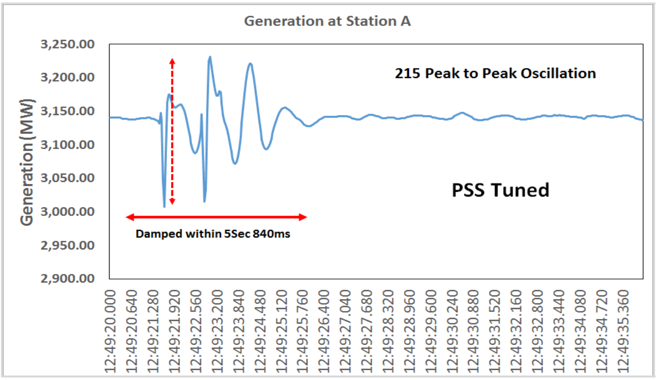


Figure 13. LFO observed at power plant A after PSS was tuned.

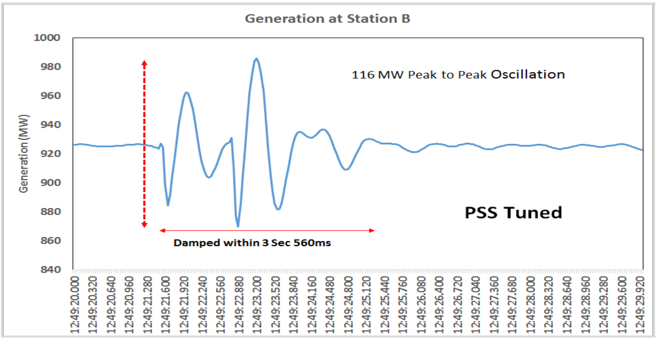


Figure 14. LFO observed at power plant B after PSS was tuned.

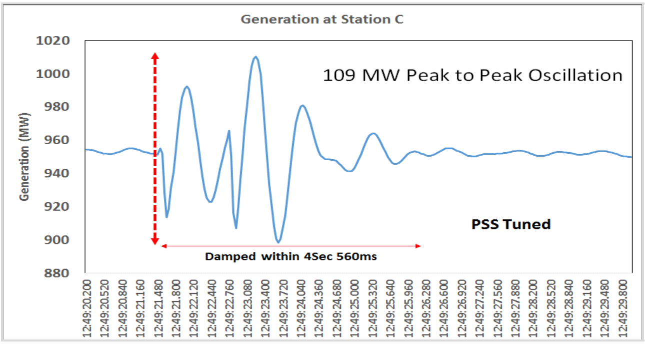


Figure 15. LFO observed at power plant C after PSS was tuned

The improved damping and reduction in oscillation amplitude prove the effectiveness of ‘PSS tuning’. The case also illustrates the utilization of synchrophasor data by the system operators for detecting an improperly tuned PSS or PSS out of service in the grid and in providing a feedback to the power plant to take suitable measures for security enhancement.

C. *Case 3: PSS and System Protection Scheme (SPS) resulting in damping improvement*

One 4 X 660 MW capacity power plant N is connected at 400 kV as well as 765 kV through two different evacuation paths as shown in figure 16. Three Units of the plant are connected at 400 kV level while the fourth unit is connected at 765 kV voltage level. The 400 kV and 765 kV level are connected by a 1500 MVA, 765/400 kV ICT.

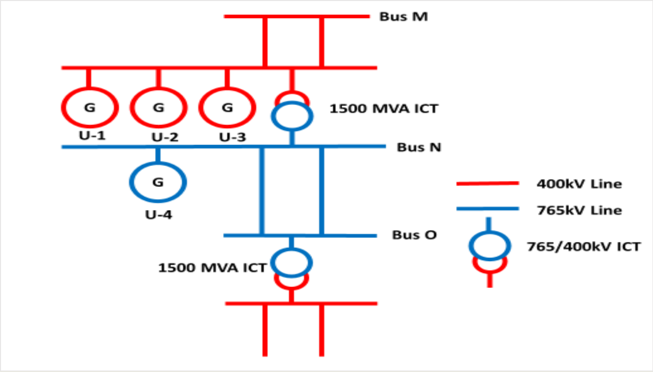


Figure 16. Single line diagram of power plant N for case study 3.

It was observed that during the tripping of one of the 765 kV or 400 kV evacuation lines, severe power swings and low frequency oscillations occurred in the other lines from the power plant and nearby areas. During the event, the other evacuation lines from plant N observed power swings that resulted in tripping of lines on distance protection. Since there were no PMUs installed at the power plant N, the frequency signals captured from PMUs at nearby stations were used for analysis. Inter-plant mode of oscillation of 0.97 Hz frequency (figure 17) was observed.

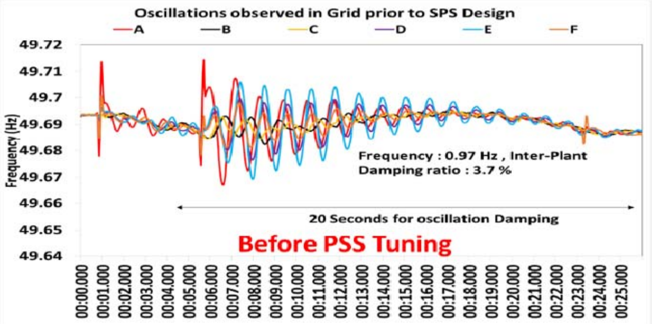


Figure 17. LFO before PSS tuning and implementation of SPS

Offline simulations revealed that the oscillations and power swings were caused due to high angular separation and improperly tuned PSS [14, 17 and 18]. Tuning of PSS in all units for the frequency range of 0.1 Hz – 3 Hz and fast generation reduction after detecting a power swing was recommended. Figure 18 illustrates the oscillations observed for a similar contingency that occurred after the implementation of the recommendations. It can be observed that there is a significant reduction in the amplitude of oscillations. The oscillations damped within 6 seconds instead of 20 seconds as observed in the earlier instance.

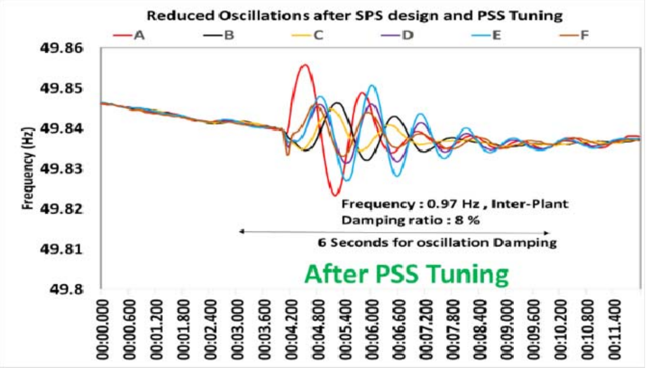


Figure 18. LFO after PSS tuning and implementation of SPS

V. SUMMARY

The paper discusses the utilization of synchrophasor measurements in the detection and analysis of LFOs. It highlights that the effectiveness of the security enhancement measures taken could be evaluated by measurement techniques in addition to the conventional model-based techniques. It has been demonstrated through the case studies presented in the paper that the measures such as ‘tuning the PSS’, ‘keeping the PSS in service’ and/or implementing automatic generation reduction through SPS are effective in improving the damping and reducing the oscillation amplitude post contingency.

The paper also highlights the relevance of PMU placement in the grid. Around thirteen Static Synchronous Compensators (STATCOM) are envisaged to be commissioned in the Indian grid in near future. Based on the learning from the three case studies presented in this paper, it is suggested that PMUs could be installed at suitable locations so as to assist the operators in observing and analyzing the effectiveness of the Power Oscillation Damping Controllers of STATCOMs. Likewise, installation of PMUs on the LV side of the Generator Transformers could also be considered for a better understanding of the generator –turbine system.

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