Low Frequency Oscillations in Indian Grid

P. Pentayya, A.Gartia, Pushpa Seshadri, Rajkumar A and Chandan Kumar

Abstract—**Small signal stability is of prime concern in operation of a large grid like India. Instability related to small signal results in low frequency oscillations which are of prime concern while operating a synchronized grid having four regions connected to Southern grid via asynchronous HVDC links in India. Small signal stability problems have been observed in NEW grid under stressed conditions or during disturbances. On certain occasions, growing oscillations were observed due to inadequate damping in the system for certain modes. Low damping may lead to oscillation of electrical parameters like voltage, current and power which can lead to mal-operation of protection instruments. This paper describes the LFO observed in the Indian System by analyzing Synchrophasor data using Matrix Pencil method. One disturbance each in Northern region and in Western region are considered as case studies and analyzed in detail to identify the modes of oscillation. Modes having negative damping and high amplitude which get excited during these disturbances have been analyzed and discussed. Also the measures employed and further requirement in the system to damp out these oscillations are discussed in brief.**

***Index Terms*— *Low Frequency Oscillations, Small Signal Stability, Wide Area Measurement System,Phasor Measurement Unit, Matrix Pencil*.**

I. INTRODUCTION

The Indian electricity grid is one of the largest Power grids in the world with an installed capacity of 225.7 GW [1] comprising five regional grids namely Northern, Eastern, North Eastern, Western and Southern grid. Among these the first four are operating synchronously with each other and known as NEW grid, while Southern grid is connected asynchronously with the NEW grid. It is planned to synchronize Southern grid with NEW grid by 2014. At present system operator is facing many challenges as the complexity in the grid is increasing day by day. Also there is a rapid increase in the network expansion with addition of large generators, long EHV and Multi- terminal HVDC lines. Even though, operating regional grids in synchronism provides better reliability and security, increased interregional transactions under deregulated market environment has witnessed small signal stability problems during stressed conditions, which has become one of the major concern to grid operators. Low frequency oscillation detection and its damping is very important for grid operation. This paper discusses two case studies of the low frequency oscillations in Indian grid through utilization of WAMS (Wide Area Monitoring System) technology.

II. LOW FREQUENCY OSCILLATION

Power system is a typical case of a large nonlinear system with lots of oscillation modes. These include eletromechanical oscillations, Control modes and Sub Synchronous Resonance (SSR) etc. [2]. In this paper only the eletromechanical oscillations have been considered. The root cause of electrical power oscillations is the unbalance between power demand and available power at a particular operating point. The change in the eletromechanical torque of a synchronous machine following a perturbation can be split into two components as shown in eq. (1).

$$\Delta T_e = K_s .\Delta\delta + K_d .\Delta\omega = T_s + T_d \tag{1}$$

The component $K_s .\Delta\delta$ is called the synchronizing torque T_s and determines the torque change in phase with rotor angle perturbation $\Delta\delta$. The component $K_d .\Delta\omega$ is called damping torque T_d and determines the torque change in phase with speed variation. K_s and K_d are called synchronizing torque coefficient and damping torque coefficient respectively [3, 4]. Rotor angle stability depends on both components of torque. Lack of synchronizing torque causes non-oscillatory instability or monotonic instability in the system and lack of damping torque result in oscillatory instability in the system.

Rotor angle stability is of two types which are small signal stability (small disturbance in the power system) and transient stability (large disturbance in the power system). Small signal stability is the ability of power system to be in steady state after a small disturbance. The instability due to this is mainly attributed to insufficient damping torque. While transient stability is associated with the ability of power system to maintain synchronism when subjected to large disturbances like line fault, bus fault, generator outage etc.. The instability arising due to this is result of insufficient synchronizing torque.

Small signal instability is due to insufficient damping torque leading to low frequency eletromechanical oscillations in system which is oscillatory in nature. If there are N generators in a system, then total number of such LFO modes would be N-1. During Low Frequency oscillations, mechanical kinetic energy is exchanged between synchronous generators of the inter-connected system through tie lines. Most of these oscillatory modes in normal power system state are well damped. However, they get excited during any small disturbance in the system and lead to oscillation in power system parameters like rotor velocity, rotor angle, voltage, currents power flow etc.. Due to oscillation in parameters, protection equipment may undesirably operate leading to cascade tripping in power system. Therefore, it is necessary to

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detect such modes and initiate corrective actions to ensure system reliability and security. Among these parameters the rotor velocity of the generators and the power flow in the network are most important. The rotor velocity variation causes fatigue to the mechanical parts of turbine-generator system. The power flow oscillations may amount to the entire rating of a power line, when they are superimposed on the stationary line flow and would limit the transfer capability by requiring increased safety margins.

Low frequency oscillations can be classified as four major types as indicated below: [2]:

1. Inter-Area Mode (0.1-1Hz): Inter-area modes are associated with swinging of a group of generators in one part of the system with group of generators in other parts due to weak interconnecting lines between two power systems.
2. Intra-Plant Mode (1 Hz -2.5 Hz): It is due to the swinging of units in a generating station with respect to each other.
3. Control Mode: These are in system due to poor design of controllers of AVR, HVDC, SVC, AGC etc.
4. Torsional Mode (10-40 Hz): These modes are associated with the turbine-generator shaft system and associated rotational components.

III. DETECTION OF LOW FREQUENCY OSCILLATIONS USING SYNCHROPHASOR MEASUREMENTS

With the current SCADA system, power system operators are not able to identify LFOs in the system due to inherent slow updating rates i.e. once in every 4 -15 Seconds (analog values). The oscillation at generator level i.e. intra-plant or local mode was assumed as it appeared as hunting in the generators while the inter-area modes were not visible to system operators by any means apart from simulation studies. The SCADA data reporting rate is comparatively slow which are not useful in detecting the oscillation or the changes going in the system in sub-seconds.

With advent in the technology, faster data processing and time synchronized phasor measurements availability at a reporting rate of 25-50 frames/second from Phasor measurement unit (PMU), now operator is able to visualize such oscillations in the system [5]. Tools and techniques are also in development to detect the source of such oscillation and to analyze them in real time and take corrective action before they create further complexities in the system. The detection of LFOs and their history is of great help in planning and implementation of damping controllers of HVDC, TCSC etc. At present PMUs have enabled the operator to visualize such LFOs whose source can be tracked with placement of optimum number of PMUs giving complete observability of system.

IV. CASE STUDIES

In India, PMUs have been installed at various locations and their details are enlisted in [5]. The data from these PMUs have been analyzed for identification of low frequency oscillations in the Indian grid using Matrix Pencil method in offline mode [6]. Matrix Pencil is a linearization based computational method for detection of LFO modes, damping ratio, amplitude and energy of the modes.

Matrix pencil method is an efficient approach to fit measured data set with sum of exponentials. This method is just a one step process of finding signal poles directly from the eigenvalues of the matrix constructed. It directly estimates the parameters for the exponential terms in eq. 2 to an observed measurement [7].

$$\mathbf{y}(t) = \sum_{i=1}^{n} A_i \exp^{\sigma_i t} \cos(\omega_i t + \Phi_i) \tag{2}$$

Where:

A_i : Amplitude of the i^{th} frequency component

σ_i : Damping coefficient of the i^{th} frequency component

ω_i : Angular frequency of the i^{th} frequency component

φ_i : Phase shift of the i^{th} frequency component

Data matrix [Y] is formed using input data shown in eq. 3.

$$\begin{bmatrix} y(0) & y(1) & \dots & y(L) \\ y(1) & y(2) & \dots & y(L+1) \\ \vdots & \vdots & \vdots & \vdots \\ y(N-L-1) & y(N-L) & \dots & y(N-1) \end{bmatrix}_{(N-L)X(L+1)} \tag{3}$$

Where N is number of measured samples, L is pencil parameter. Next SVD of matrix [Y] is calculated which gives:

$$[Y] = [U][\Sigma][V^T] \tag{4}$$

Here [U] & [V] are unitary matrices composed of eigenvectors of $[\mathrm{Y}]^T[Y]$ & $[Y][\mathrm{Y}]^T$ respectively, and [Σ] is diagonal matrix consisting of singular values of [Y]. Next consider the filtered matrix$[V']$, it contains 'n' dominant right singular vector of [V].Thus

$$[Y_1] = [U][\Sigma'][V_1']^T \tag{5}$$

$$[Y_2] = [U][\Sigma'][V_2']^T \tag{6}$$

The poles of the signal are given by non-zero Eigen values of

$$\{[V_1']^T\}^+[V_2']^T \tag{7}$$

Once n & poles (σ_i) are known residues are solved using least square sense.

$$\begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_n \\ \vdots & \vdots & \vdots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \dots & z_n^{N-1} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} \tag{8}$$

Following case studies have been considered for the detection of LFO in Indian grid:

1. Tehri Koteshwar plant tripping on 10th Sept, 2012.
2. Sipat Generating plant tripping on 14th Sept,2012

A. Tehri Koteshwar generating plant Tripping on 10th Sept, 2012

On 10th Sept 2012, 1350 MW generation loss was there due to tripping of Tehri and Koteshwar plant in Northern grid of India [5]. During the tripping frequency fell from 49.80 Hz to 49.46 Hz in the NEW grid. The oscillation can be clearly seen from fig. 1 in the Real Power (MW) flow recorded by PMU at Karcham which is located nearest to the Tehri and Koteshwar plant.

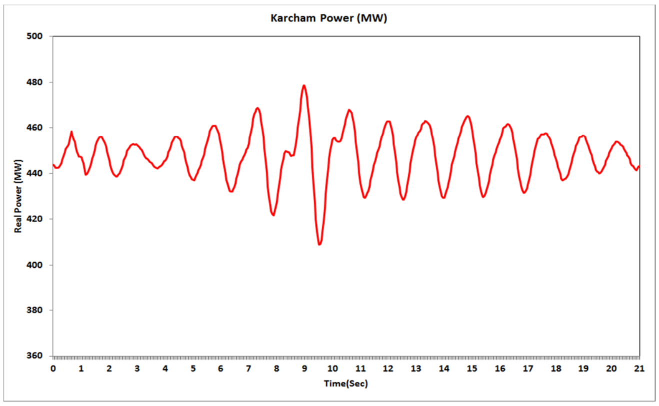

Figure 1. Oscillation observed in PMU data during the tripping of Tehri-Koteshwar generators

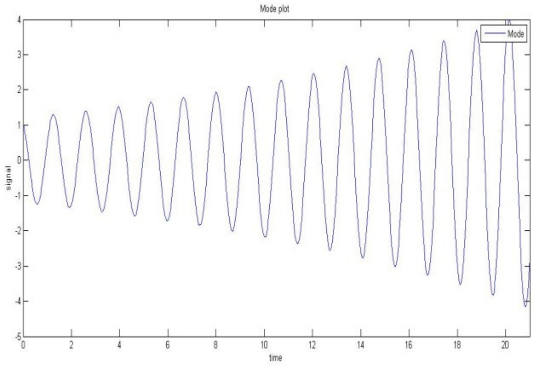

Figure 2. 0.7 Hz having negative damping of 1.2 % and high amplitude during the occureence at tehri koteshwar

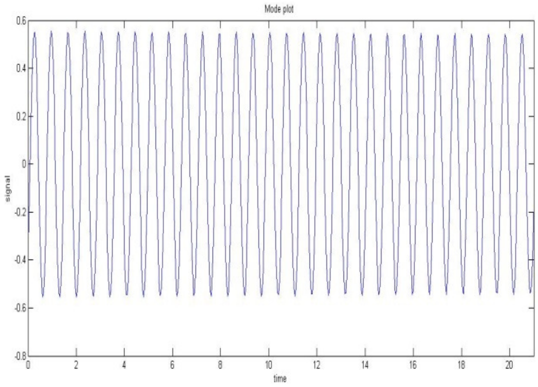

Figure 3. 1.4 Hz having almost zero damping and high amplitude during the occureence at tehri koteshwar

The LFOs observed during the occurrence were 0.7 Hz with negative damping and 1.4 Hz with almost zero damping as shown in figures 2 and figure 3. As given in Table 1, both of these were having high amplitude during the occurrence. Apart from these, other modes were also observed having frequency 1 Hz and 1.9 Hz and these have low amplitude with positive damping.

Table 1: Major LFO Modes, damping ratio and amplitude observed with Matric Pencil Method for Tehri Koteshwar tripping

Frequency	Damping ratio	Amplitude
0.7	-0.01284	1.20061
1	0.01621	2.81553
1.4	0.00013	0.55666
1.9	0.00357	0.06939

B. Sipat generating plant tripping on 14th Sept, 2012

On 14th Sept 2012, Sipat generating plant with capacity of 2980 MW (660 X 3 + 500 X 2) generation along with ACBIL plant having generation capacity of 270 MW (135X2) tripped due to fault in the system [8]. Both these plants are in the Western grid of India. The total generation loss during the disturbance was 2388 MW. During the disturbance four events occurred as shown in fig 4. Severe oscillations are also observed in the system during the occurrence. The first incident i.e. Sipat unit 5 and ACBIL 1 and 2 unit tripping was analyzed using Matrix pencil method. The data window analyzed during the event is shown in figure 5.

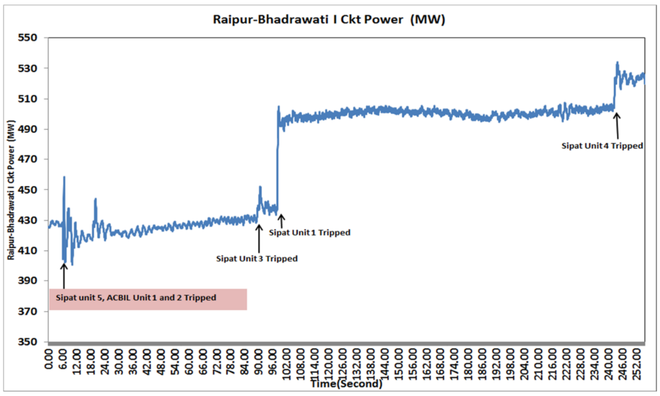

Figure 4. Oscillation observed in PMU data during the tripping of Sipat and ACBIL generating station.

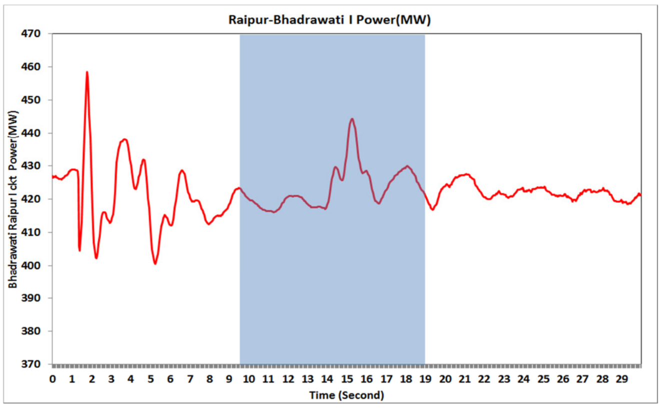

Figure 5. Extended view of real power duri the first event during which Sipat unit 5 and ACBIl unit 1 & 2 tripped. Shaded portion indicate the analysis window for Matrix pencil.

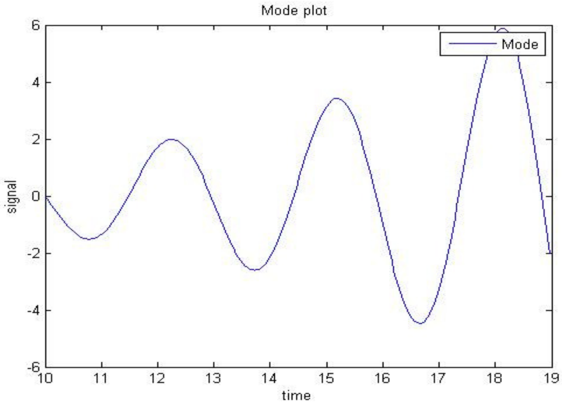

Figure 6. 0.35 Hz having negative damping of 8.6 % and high amplitude during the occureence.

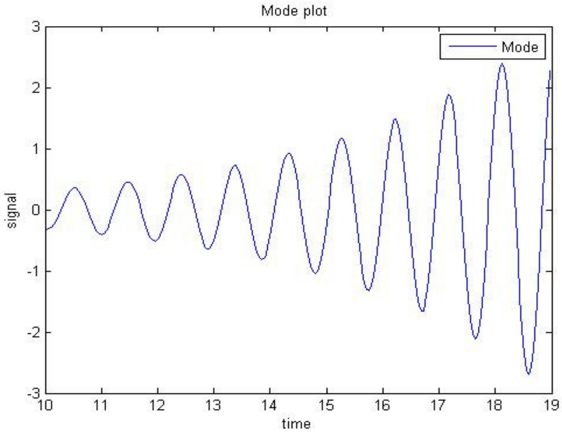

Figure 7. 1 Hz having negative damping of 3.7 % and high amplitude during the occureence.

Based on the analysis with MP method, it was found that 0.35 Hz and 1 Hz are having negative damping with high amplitude and they got excited during the system occurrence as shown in the figures 6 and figure 7. Before the event, these modes were having positive damping and low amplitude. But with the weakness in network configuration due to tripping of units and lines, grid was stressed which led to poor damping of above modes. Other modes were also observed with negative damping and low amplitudes as shown in table 2.

Table 2: Major LFO Modes, damping ratio and amplitude observed with Matric Pencil Method for Sipat tripping

Frequency	Damping Ratio	Amplitude
0.35	-0.08607	0.20716
1.0	-0.03758	0.02628
1.2	-0.01693	0.03051
1.4	-0.0036	0.08059
2.0	-0.01755	0.00138

V. LFO ANALYSIS

The Major oscillations observed in Western and Northern grids during disturbances are entirely different. In Northern grid oscillations are of 0.7 Hz and 1.4 Hz which are inter-area and intra-plant modes respectively, while in the Western grid 0.35 Hz and 1 Hz modes were observed, which are inter-area modes. The presence of inter-area modes in both the regions during ring down can be associated due to weak links and stressed conditions in the grid before the disturbances.

The transmission depletion and lack of immediate frequency response add to factors which results in low damping in the system which might have excited such modes. These modes are not only attributed to the system weakness but also due to dynamic imbalance between the demand and supply in the system on account of loss of generation. Any small perturbation during dynamic situation may trigger cascade trippings in the system as observed in case of several blackouts in the world [2]. Common modes observed in the NEW grid are 1, 1.4 and 2 Hz which are having low damping during disturbances in the system.

The tripping of transmission lines and generating units during any event significantly modifies the characteristics of the grid with power flows taking over alternate long distance routes with consequent higher stability risk and stressed grid operation. The new network configuration may have less damping compared to the original network.

VI. REMEDIAL APPROACH TO DAMP LFO

Damping of local modes or intra-plant modes can be improved by PSS tuning at many generating stations, while inter-area mode damping is more related to network configuration and power flows. Interconnecting two grids improves reliability of the power supply, but also introduces new inter-area modes. If the rating of the tie-line is not sufficient to take care of power flow variations associated with the mode, transmission line protections may operate.

The measures implemented to increase the damping of such inherent modes of the system are by strengthening of transmission network, PSS tuning of generators, tuning damping controllers of HVDC, TCSC and SVC in the system. In western region, the TCSC at Raipur end of Raipur-Raigarh I and II circuit have been tuned for damping oscillation with frequency 0.33 ± 0.05 Hz which has improved the damping of this mode. While in the northern region, PSS tuning of Karcham-Wangtoo and Tehri units was carried out to improve the damping for 0.7 and 1.4 Hz.

VII. CONCLUSION

From the analysis of the events it is observed that during certain disturbances involving generation loss in Northern region, 0.7 Hz is having negative damping and 1.4 Hz is having zero damping, while 1.0 and 2.0 Hz Modes are having positive damping. While during certain system disturbance in Western region, 0.35 Hz is having negative damping with high amplitude while, 1.0, 1.2, 1.4 and 2 Hz modes are having negative damping with low amplitude. It is thought provoking to note that several modes and their harmonics are observed which could be due to nonlinearities of the power system and need further analysis. The coordinated use of FACTS along with HVDC damping controllers and PSS of generators is required for improved damping of LFO in Indian Grid. This will have an important role in safe and reliable transmission of power, to enhance transmission network transfer capabilities, improve system stability, reliability and security of power system.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

[1] Central Electricity Authority, *All India Installed Capacity,* [online]. Available : http : / / cea.nic.in / reports / monthly / executive_rep / installedcap_allindia.pdf

[2] K. Prasertwong, N. Mithulananthan and D. Thakur, "Understanding Low Frequency Oscillation in Power Systems,"in IJEEE, vol. 47, pp 248-262 ,July 2010.

[3] P. Kundur*, Power System Stability and Control*, (McGraw-Hill: New York, 1994).

[4] P. Kundur, J. Paserba, V. AjjaraPu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. VanCutsem and V. Vittal, “Definition and classification of Power system stability IEEE/CIGRE joint task force on stability terms and definitions,” in *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp.1385 -1401 2004

[5] “Synchrophasors Initiative in India,” POSOCO, New Delhi, Tech.Rep.July 2012

[6] T. K. Sarkar and O. Pereira, “Using the matrix pencil method to estimate the parameters of a sum of complex exponentials,” in *IEEE Antennas Propagat. Mag.*, vol. 37, pp. 48-55, Feb. 1995.

[7] Y. Hua ,T. K. Sarkar, “On SVD for estimating generalized eigenvalues of singular matrix pencil in noise,” in *IEEE Trans. Signal Processing*, vol. 39, pp. 892-900, Apr. 1991.

[8] Western Region power Committee (January, 2013), *116th PCM Agenda*, [Online], Available: http: / / www. wrpc. gov. in / pcm / 116 pcm _ agenda1.pdf