Detecting Low Frequency Oscillations Through PMU-Based Measurements for Indian National Grid

Subrata Mukhopadhyay, *Senior Member, IEEE*
EEE/ECE Department
Guru Tegh Bahadur Institute of Technology
(Guru Gobind Singh Indra Prastha University)
G-8 Area, Rajouri Garden
New Delhi – 110064, India
subrata@ieee.org
Vinod K. Agrawal, *Senior Member, IEEE*
Energy Management Department
ReGen Powertech Private Ltd., Chennai, India
agrawal.vk@regenpowertech.com

Sushil K. Soonee, *Senior Member, IEEE*
P. K. Agarwal, *Member, IEEE*
Rajkumar Anumasula
Chandan Kumar, *Member, IEEE*
Power System Operation Corporation Limited
(Powergrid Corporation of India Limited)
B-9 Qutub Institutional Area
New Delhi-110016, India
sksoonee@posoco.in, pkagarwal@posoco.in,
rajkumar@posoco.in,
chandan8240000@gmail.com

***Abstract*— Indian National Grid formed with the connection of Southern Grid to the rest of India in the last phase on December 31, 2013 ushered in having improved frequency regime of operation as well as large inter-regional power transfer for optimal operation. But problems of Low Frequency Oscillations continued to be observed in several parts. Wide-Area Monitoring System with large-scale deployment of Phasor Measurement Units, made it possible to detect such oscillations at specific locations and evolve remedial measures to be undertaken. Under long-term strategy investment-oriented strengthening of transmission system is the choice. But to deal with such problems for day-to-day operation, tuning or re-tuning of Power System Stabilizers, controllers associated with Flexible AC Transmission Systems and HVDC Systems, etc. are considered as the best option. Commensurate Regulatory Framework too is expected to be made for handling such issues from the point of view of Plant-Grid Interaction.**

***Index Terms*-- Flexible AC Transmission Systems, HVDC Systems, Indian National Grid, Low Frequency Oscillations, Phasor Measurement Units, Plant-Grid Interaction, Power System Stabilizers, Regulatory Framework, Small Signal Stability, Synchrophasors, Wide-Area Monitoring System.**

I. INTRODUCTION

The issue of Small Signal Stability (SSS) on account of Low Frequency Oscillations (LFO) is known since long. Other than Transient Stability due to large disturbances and Voltage Stability on account reactive power mismatch, this type of stability has been bothering power system engineers in grid operation. Pioneering work done earlier gave an insight to the effect on the system in terms of synchronizing and damping torque and associated power [1]. Subsequent works made it possible to develop Power System Stabilizer (PSS) to work in conjunction with the excitation system of generators to mitigate the effect of LFO. The latter is in fact broadly categorized to intra-plant, inter-plant, intra-area, and inter-area oscillations with ranges respectively 1.5 – 3.0 Hz, 1.0 – 2.0 Hz, 0.4 – 1.0 Hz, and 0.05 – 0.30 Hz. Subsequent development and usage of HVDC Systems and Flexible AC Transmission Systems (FACTS) also lead to implementation of controllers along with them, like, Power Oscillation Damping (POD) Controllers, etc. These devices help in taking care of particularly intra-area as well as inter-area oscillations depending upon their locations. The root causes of such oscillations require thorough study from long-term transmission planning perspectives, regulatory requirement for interconnection of new plant with the grid as well as its enforcement while in operation with remedial measures in place, like, tuning of PSS, POD Controllers, etc.

This paper provides a brief overview of the problem of LFO as observed earlier in regional systems in the Indian grid. Those observed specifically in wide-scale from August 9 to 12, 2014 at various locations have been detailed. It also explains the measurement based analysis of the low frequency oscillation observed in the systems. Subsequently a picture showing details of what have been observed and measurement-based analysis performed at Regional Load Dispatch Centers (RLDC) and National Load Dispatch Center (NLDC) with synchrophasor data available over there has been depicted. Lastly action plan for additional measures in the Control Centers for the real-time detection and possible mitigation of oscillations have been talked about.

II. BRIEF OVERVIEW OF LOW FREQUENCY OSCILLATION AND ITS ORIGIN

Small Signal Stability (SSS), one of the two types of Rotor Angle Stability [1], is basically the ability of power system to be in steady-state after a small disturbance. In this case instability that may occur can be attributed to insufficient damping in the system. It may lead to Low Frequency

(Electro-mechanical) Oscillations in the system as observed in parameters, like, rotor velocity and rotor angle, voltage, current, power flow, etc. As a result inadvertent operation of protection may lead to cascade tripping. Hence it is necessary to detect such modes and take up timely corrective action. Linearized system with eigen-value analysis based on simulation or measurement [2] can give an insight to the issue in terms of detecting intra-plant, inter-plant, intra-area, and inter-area modes of oscillations. These are basically in terms of whether one generator oscillates against another in a plant or a neighboring plant (local mode) or a group of generators oscillates against another group of generators in the same area due to weak interconnection (intra-area mode) or group of generators in an area oscillates with respect to those in other area (inter-area mode). While simulation based study can provide observability and clue to controllability, measurement based study shows observability of such nodes. It is to be complemented by simulation for designing the controllers. Data from Phasor Measurement Units (PMU) help in carrying out measurement-based such studies. Usually these are in terms of mode shape (phase-shifting with respect to each other), mode amplitude (peak value), and energy content of mode (given by area under curve when mode is separated from the original signal). Energy content is high when amplitude is high and / or damping is low.

According to Power Systems Engineering Research Center (PSERC) report on Avoiding and Suppressing Oscillations [3], the Low Frequency Oscillations can be classified as forced and spontaneous according to their origin. Any system having N generators will have N-1 number of such LFO modes. However most of these modes are positively damped and not observable in the system. Damping of any such LFO depends on the system condition and the damping torque available in the system. Oscillations may also get excited due to disturbance caused by outage of line or generator which reduces the damping of mode. Forced oscillations may crop up due to incomplete islanding or pulsating load incident on generators. Such type of oscillations is very specific in nature and it is interesting to know how they can originate in a system. The spontaneous oscillations are very dangerous in nature. These are observed when due to system condition two modes come closer to each other on account of changes in their damping and interaction. Such interaction leads to modal resonance. In such cases one mode will have high positive damping while the other high negative damping. To analyze such phenomenon offline and online various computational methods can be used, such as, Matrix Pencil Method, Prony Analysis Method, etc. as shown in the Appendix.

Also a classification may stand in the form of normal or positively damped, sustained or un-damped, and negatively damped. As the names suggest wear and tear as well as vulnerability increases with the second type, while the last one is extremely dangerous. Quantitatively modes having damping of more than 3-5 % are called positively damped while modes within 0-3 % are called poorly or zero damped. Any mode having less than 0% damping is called negatively damped mode. In the studied case of Indian grid the same classification has been followed. Further it has been observed that any mode can become negatively damped from sustained or positive damping depending on the system condition or its excitation by any stimuli. Various such cases have been observed in Indian Grid as elaborated later.

As the system started growing in terms of integrated networks and additional generation to meet more and more load, thus requiring haulage of power over large distance, LFO were being observed. This in turn required simulation of each component of system accurately. Means of mitigation were developed in terms of introduction of PSS in very fast-acting excitation system. Subsequently POD was introduced with HVDC and FACTS devices with the requirement of tuning of associated controllers [4]. Wide-area Damping Controller was adopted in China. Similarly modulating HVDC power flow for damping of oscillations in the system and accordingly allowing variation in loading parallel ac network under different loading conditions was also attempted.

III. OSCILLATION IN INDIAN GRID

As mentioned earlier, Indian grid was not an exception in experiencing LFO. Prior to 2003, in Western Regional Grid LFO used to occur. However with the synchronization of Eastern and Western Regional Grid in 2003 with links having TCSC (Thyristor-Controlled Series Capacitor), it was possible to damp LFO. Similar was the case while synchronizing Central Grid (Synchronized Northeastern, Eastern and Western grid) with the Northern, again through the use of TCSC to damp out the inter-area oscillations. While earlier SCADA data were used for studies, they were not so accurate due to low resolution. But with the advent of technology of late when Phasor Measurement Units (PMU) are in use, it is possible to visualize such oscillations accurately and with time stamp. Detection of LFO and their history are helping in planning and implementation of damping controllers for HVDC, FACTS, etc. It is due to accurate tracking of source of LFO as a result of complete observability of system through large-scale deployment of PMUs. Some of the observations and root causes are detailed in Table I.

All these phenomena along with other observations of LFO as detected have been brought out through two reports in June 2012 and December 2013 [5]. After the formation of Indian National Grid experience on LFO has been narrated through operational feedback in April and July 2014. In the past in fact it has been observed that mainly 3 sub-systems have experienced large number of oscillations cases. These are Karcham Complex in North, CESC (Calcutta Electric Supply Company) System in East, and Palatana in North-East. The case related to one of them, oscillations at Karcham Complex, is explained with reasons. As analyzed, there in fact local oscillations might have aggravated during global oscillations. It may be due to weak links and / or un-tuned PSS. These oscillations were often mitigated by reducing generation (though not desirable due to low pondage with hydro-plants) and in turn line loading or modulating HVDC power flow. Depending on the frequency of LFO, the decision for improving their damping is taken. In general it has been observed that LFO originates in any system with weak interconnection between the generators and the load Centers.

So in case of a local oscillation originating from a generating station (based on various PMUs measurement, frequency gives type of oscillation and amplitude gives locality), the reduction in generation reduces the stress on the system and many a times damps the excited oscillation.

TABLE I. DETECTION OF LFOS AND POSSIBLE REASONS

PMU location	**Date & time**	**Duration (seconds)**	**Dominant Mode (Hz)**	**Type**	**Possible Reason**
All PMUs in NR	11-Apr-13 1:45	8	1.54 – 2.58	Intra-plant	Evacuation of Paricha Units through 220 kV
All PMUs in NEW grid	13-Apr-13 22:02	60	0.53	Inter-area	WR-ER link tripping, generator-load at boundary disconnected for ER & hanging only to WR via 220 kV lines
Karcham	24-July-13 15:36	130	1	Inter-plant	Oscillations in power flow on lines emanating from another plant Jhakri

(NR: Northern Regional Grid, SR: Southern Regional Grid, ER: Eastern Regional Grid, WR: Western Regional Grid, NER: North-Eastern Regional Grid, NEW: Synchronized Northern, Eastern (& North-Eastern), and Western Regional Grid)

In case of inter-area oscillation, the flow of weak tie line is reduced first by using HVDC and then by load-generation change in the system. The lesser flow on tie links reduces the system stress (that refers to operation with large angle difference during high power flow). Determination of the exact amount of reduction in real time operation is difficult. However it is practiced to reduce the generation / increase HVDC power flow, wherever possible, in order to keep the system parameters remaining under normal operating condition as per the specified limit. So, the amount of reduction varies depending on the condition of the system and load-generation pattern in the Indian grid. It is also a fact that subsequent tuning of PSS has helped in resolving the issue to a great extent.

IV. LFO FROM AUGUST 9 TO 12, 2014

During early morning hours of August 9 to 12, 2014 Low Frequency Oscillations were observed in the Indian Grid. These resulted in hunting in several generating plants in Eastern Region (ER), Western Region (WR), and NER (North-Eastern Region). Oscillations in HVDC power order and in power flow through several transmission lines too were observed at quite high level based on SCADA (Supervisory Control And Data Acquisition) System and Synchrophasor Data. Damping observed was less than 2% and in some cases going negative even.

The criteria for negative damping and method have been explained earlier. Basically in real time any oscillation monitoring system uses moving window approach for any of the modal analysis techniques. The negative damping in a system is in general not acceptable for any time duration even if it is small. However, time line of damping itself varies with the frequency. For a low frequency oscillation of 0.2 Hz one cycle of oscillation is completed in 5 seconds. In order to classify whether it is negatively or positive damped, it can be found only if two cycles of oscillation are present, i.e., for 10 seconds. However, for a 2 Hz oscillation, the same time reduces to 1 second. So, time line for negative damping varies. For oscillation, anything below 3 % of damping is not acceptable and all methods to improve damping in system have to be utilized. However based on the survey it is observed that more than 5 % damping criteria for line tripping and more than 3 % damping criteria for faults is acceptable only in case the planners are using field-validated data for modeling of system components. In case of standard modeling, the criteria should be more than 10 % damping under any circumstances; otherwise it should be more than 10 % for all type of oscillations and should reduce its peak-to-peak ratio by 50 % in 5 seconds interval. Further, it should also match with the system response observed in the real time provided as a part of feedback by system operator.

A. *Overview of Day 1 (August 9, 2014)*

CESC (Calcutta Electric Supply Company) reported to ERLDC (Eastern Regional Load Dispatch Center) at 4:30 am about oscillations in power flow in transmission line connecting CESC and West Bengal State System in ER. When reported in turn to NLDC, the latter while verifying found oscillations in ER, WR, and NER as well with higher magnitude compared with NR and SR. Oscillations persisted almost up to 6:00 am. Observations indicated low damping and even negative damping. Based on visual inspection of measured data, it was found oscillations were predominant in ER compared to other two regions, WR and NER. The frequency of the mode was from 0.72 – 0.76 Hz as shown in Figure 1, based on NLDC Wide-Area Monitoring System.

Figure 1. Zoomed view of Oscillation in frequency between 05:40- 05:59Hrs along with online Modal analysis.

The blue dot indicates low damping below 3% and cyan indicates negative damping. However, oscillations were not observed in the rest of the day and before coming back next day between 3.00 and 4:00 am.

B. *Overview of Day 2 (August 10, 2014)*

On August 10, 2014 also like previous day LFO was observed at about 0.75 Hz with damping below 3% from Oscillation Monitoring System (OMS) at NLDC as depicted in Figure 2. But as by that time no definite reason could be established for LFO of previous day, in a bid to mitigate LFO, power order of 2000 MW Talcher-Kolar bi-pole HVDC (with 25% overload capacity for 10 hours in a day) was reduced. By 4:00 am LFO disappeared and was not observed in the rest of the day.

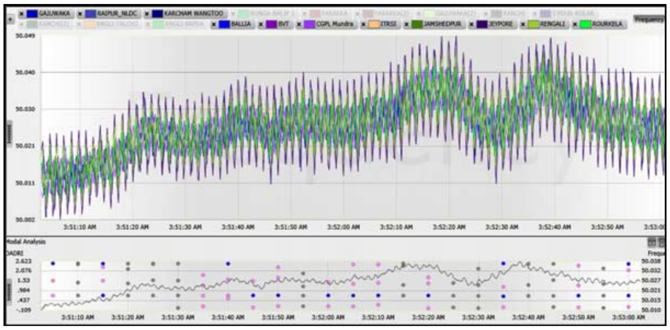

Figure 2. Zoomed view of Oscillation in frequency between 03:50- 03:53 Hrs along with Modal analysis. The blue dot indicates low damping below 3%.

C. *Overview of Day 3 (August 11, 2014)*

Next day grid observed LFO for a very short duration from 5:45 to 5:49 am. Frequency was observed to be around 0.75 Hz with low damping for a small period across India as shown in Figure 3. During the day, however, no such oscillations were felt.

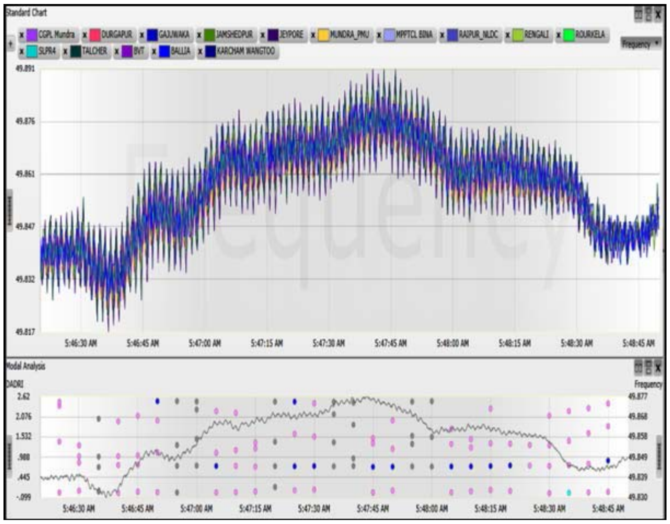

Figure 3. Zoomed view of Oscillation in frequency between 05:46- 05:49Hrs along with Modal analysis. The blue dot indicates low damping below 3%.

D. *Overview of Day 4 (August 12, 2014)*

On August 12, 2014 NLDC as well as RLDCs observed oscillations for hardly 45 seconds from 12:43:30 to 12:44:15 hours as shown in Figure 4. However, this time frequency was observed to be in the neighborhood of 0.60 Hz as against in the vicinity of 0.75 Hz in the previous 3 days.

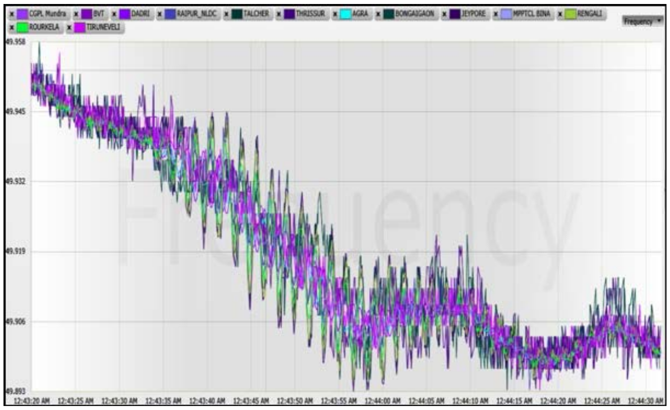

Figure 4. Oscillation observed in Frequency measured from various PMUs on August 12, 2014.

The oscillations on consecutive four days with varying magnitude, time of occurrence, and mode frequency posed various challenges in system operation for taking remedial action. In order to find the root cause, therefore, it was felt necessary to analyze the event thoroughly. Accordingly data from all the generators, FACTS, HVDC were collected for an in-depth study based upon measured data as available.

V. ANALYSIS OF OBSERVED LFO FROM AUGUST 9 TO 12, 2014

From the data available on HVDC and FACTS response, Generating Units and Utilities, SCADA data from RLDCs and NLDC, no major change in the system was observed. Demand in the grid during that period was low with loading on lines too not critical. Further analysis was carried out using various available methods based on Synchrophasor Data.

Use of Matrix Pencil Method [6]-[10] on the PMU data provided mode frequency (during occurrence), damping (for how fast or slow), amplitude (of oscillations quantitatively), and shape (for coherency of generators). Mode shape corresponding to frequency of 0.75 Hz (for the first 3 days) and 0.6 Hz (for the 4th day) gave an idea of coherency of generators in terms of generator angle or speed. Corresponding to 0.75 Hz and 0.6 Hz, change in coherent group of generators was observed. These are depicted through Figure 5 and 6 respectively as distinctly marked.

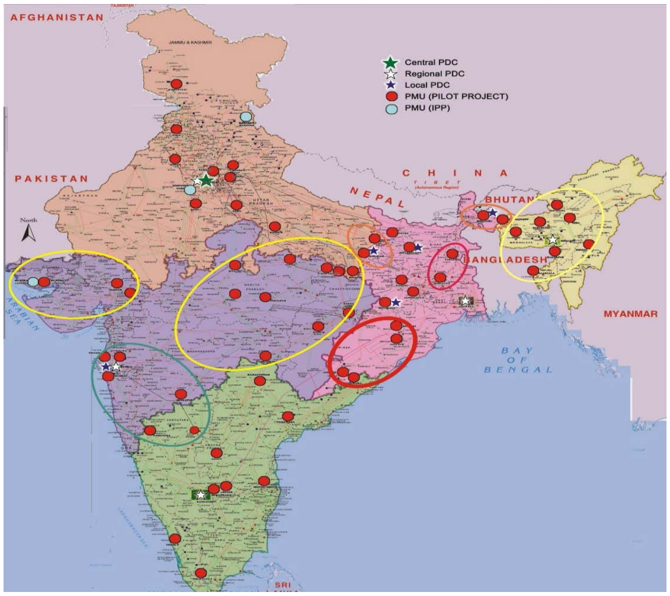

Figure 5. Coherent Group observed for 0.75 Hz.

For re-checking the results, eigen-value analysis of oscillations using Residual Method as well as Prony Analysis Method of Oscillations [9]-[11] was also carried out and mode shapes were computed. These were found to be in close conformity with those obtained using Matrix Pencil Method.

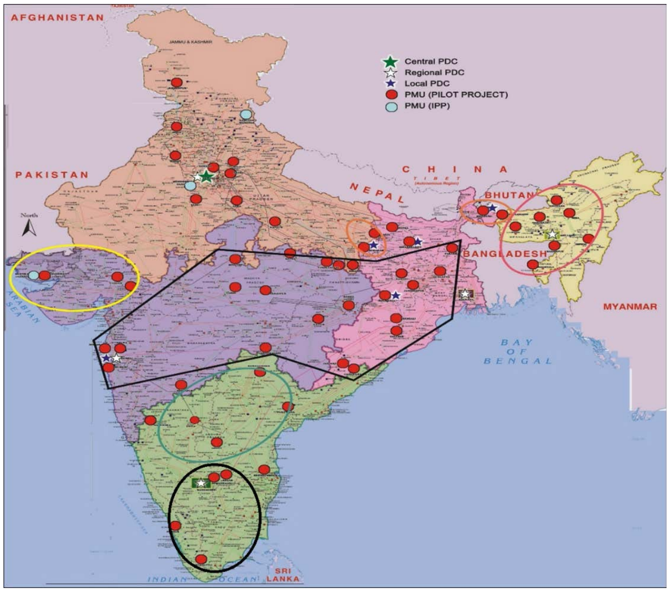

Figure 6. Coherent Group observed for 0.6 Hz.

Further for insight to root cause of the problem, mode Amplitude and Energy of Oscillations were also computed. While Amplitude computation was by using Matrix Pencil Method, Energy computation was by Prony Analysis Method, as detailed in the Appendix. Results are shown in Figure 7 and 8 respectively corresponding to 0.75 Hz. In fact this is an alternative to application of Subspace State Space System for the identification of oscillation modes using ambient data [10] reported recently for the Brazilian Interconnected Power System [12].

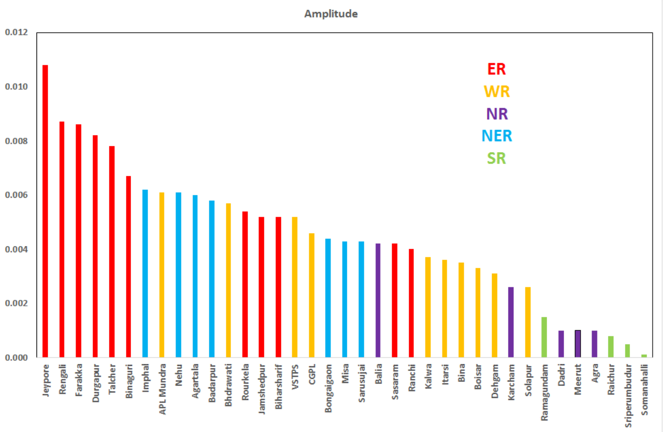

Figure 7. Mode Amplitude observed for the Frequency 0.75 Hz.

A close observation of the results shows that the values were highest with Eastern Region, followed by Western Region and North-Eastern Region. On the other hand those were quite less with Northern Region and Southern Region. Similar was the observation with 0.6 Hz too. In all the four days oscillations were observed in the early morning hours. It can be attributed to ambient change in generation schedules and load. Low Frequency Oscillations observed in such cases is a matter of concern. Therefore, finding of coherent groups of generators with Synchrophasor Data is important. It is more so, as it enables to identify strengthening of links required between the concerned areas.

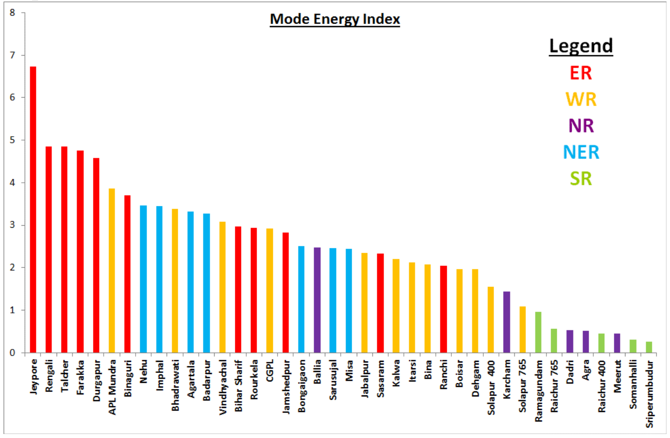

Figure 8. Mode Energy observed for the Frequency 0.75 Hz.

VI. CONCLUSIONS REGARDING ACTION PLAN

The Manual on Transmission Planning Criteria presently followed in Indian Power Sector requires further reference to Small Signal Stability and similar treatment to all concerned regulations, in addition to Transient Stability and Voltage Stability studies. In this context proper tuning of Power System Stabilizer as provisioned under regulation for over 100 MW generating sets should be enforced and duly validated from time to time to take care of changes in network configuration and system operation. Also power swing damping as a control function for HVDC System should be ensured. Considering in addition various forms of Flexible

AC Transmission Systems in use, all grid connected entities must be obligated to follow the regulation and remedial measures concerned with improving Small Signal Stability. It should go along with validation of network models periodically based on field data. For validation, not only measurement based studies, but also model based studies should be encouraged. For this accuracy of modeling is of utmost importance. In case of new device or equipment valid model should be insisted and necessary verification should be done.

In the event of oscillations, generating plants and utilities should submit relevant information to Regional Load Dispatch Centers and National Load Dispatch Center. Ultimately real-time operation would require and use tools to suggest mitigation of Low Frequency Oscillations in real-time. At the same time feedback is to be given to the planners too for strengthening of network as required between the areas as demarked by coherent groups of generators.

APPENDIX

A. *Matrix Pencil Method*

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 eigen-values of the matrix constructed [6], [7]. It directly estimates the parameters for the exponential terms in equation (1) to an observed measurement.

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

where

A_i : Amplitude of the ith frequency component

σ_i : Damping coefficient of the ith frequency component

ω_i : Angular frequency of the ith frequency component

ϕ_i : Phase shift of the ith frequency component

Data matrix [Y] is formed using input data shown in equation (2).

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

where N is number of measured samples, L is pencil parameter. Next Singular Value Decomposition (SVD) of matrix [Y] is calculated which gives

$$[Y] = [U]\,[\Sigma]\,[V^T] \tag{3}$$

In equation (3), [U] & [V] are unitary matrices composed of eigenvectors of $[Y]^T$ [Y] & [Y] $[Y]^T$ 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

$$[Y_1] = [U]\,[\Sigma']\,[V_1']^T \tag{4}$$

$$[Y_2] = [U]\,[\Sigma']\,[V_2']^T \tag{5}$$

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

$$[V_1']^T + [V_2']^T \tag{6}$$

Once n & poles (σ_i) are known residues are solved using least squares method.

$$\begin{pmatrix} y(0) \\ y(1) \\ \dots \\ \dots \\ y(N-1) \end{pmatrix} = \begin{pmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_n \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ z_1^{N-1} & z_2^{N-1} & \dots & z_n^{N-1} \end{pmatrix} \begin{pmatrix} B_1 \\ B_2 \\ \dots \\ \dots \\ B_n \end{pmatrix} \tag{7}$$

B. *Prony Analysis Method*

Prony Analysis Method involves fitting a linear combination of exponential terms to a signal as shown in equation (1) of the Matrix Pencil Method. Each exponential component with a different frequency is viewed as a unique mode of the original signal. The four elements of each mode can be identified from the state space representation of an equally sampled data record having time interval T [11], [13]. Using Euler's theorem and letting t = MT, the samples of y(t) are rewritten as

$$y_M = \sum_{i=1}^{N} B_i \lambda_i^M \tag{8}$$

where

$$B_i = \left(\frac{A_i}{2}\right) e^{j\phi_i} \tag{9}$$

$$\lambda_i = e^{(\sigma_i + j\omega_i)T} \tag{10}$$

Prony analysis consists of three steps. In the first step, the coefficients of a linear predication model are calculated. The Linear Predication Model (LPM) of order N, shown in equation (11), is built to fit the equally sampled data record y(t) with length M. Normally, the length M should be at least three times larger than the order N.

$$y_M = a_1 y_{M-1} + a_2 y_{M-2} + \dots + a_N y_{M-N} \tag{11}$$

Estimation of the LPM coefficients a_n is crucial for the derivation of the various parameters, like, frequency, damping, magnitude, and phase angle of the signal. To estimate these coefficients accurately, various algorithms can be used. A matrix representation of the signal at various sample times can be formed by sequentially writing the linear prediction of M_y repetitively. By inverting the matrix representation, the linear coefficients a_n can be derived from equation (12). The algorithm, which uses SVD for the matrix inversion to derive the LPM coefficients, is called SVD algorithm.

$$\begin{pmatrix} y_N \\ y_{N+1} \\ \cdots \\ \cdots \\ Y_{M-1} \end{pmatrix} = \begin{pmatrix} y_{(N-1)} & y_{(N-2)} & \cdots & y_0 \\ y_N & y_{(N-1)} & \cdots & y_1 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ y_{M-2} & y_{M-3} & \cdots & y_{M-N-1} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ \cdots \\ \cdots \\ a_N \end{pmatrix} \tag{12}$$

In the second step, the roots λ_i of the characteristic polynomial shown in equation (13) as associated with the LPM from the first step are derived. The damping factor σ_i and frequency ω_i are calculated from the root λ_i according to equation (10).

$$\lambda^N - a_1\lambda^{N-1} \ldots - a_{N-1}\lambda - a_N = (\lambda - \lambda_1)(\lambda - \lambda_2)\ldots(\lambda - \lambda_N) \tag{13}$$

In the last step, the magnitude and the phase angle of the signals are solved using the least squares method. According to equation (8), equation (14) is built using the solved roots λ_i:

$$Y = \phi B \tag{14}$$

$$\text{where } \phi = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ \lambda_1 & \lambda_2 & \cdots & \lambda_i \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \lambda_1^{N-1} & \lambda_2^{N-1} & \cdots & \lambda_i^{N-1} \end{pmatrix} \tag{15}$$

$$\text{and } B = [B_1 \quad B_2 \quad \cdots \quad B_N]^T \tag{16}$$

The magnitude A_i and phase angle ϕ_i are thus calculated from the variables B_i according to equation (9).

ACKNOWLEDGMENT

The authors wish to thank colleagues in their respective organizations for the support as well as the authorities over there to make available the relevant documents, based on which it has been possible to prepare the paper.

REFERENCES

[1] Prabha Kunur et al, “Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions”, IEEE Transactions on Power Systems, vol. 19, no. 3, pp.1387-1401, Aug 2004.

[2] Graham J Rogers, “Power System oscillations”, Springer Science and Business Media, New York, 2000.

[3] F. Alvarado, C. DeMarco, I. Dobson, P. Sauer, S. Greene, H. Engdahl, and J. Zhang, “Avoiding and suppressing oscillations,” PSERC Project Final Report, 1999.

[4] Analysis And Control Of Power System Oscillations, CIGRE, Final report by the Task force 07 of Advisory Group 01 of Study Committee 38 , Dec 1996.

[5] http://posoco.in/2013-03-12-10-34-42/synchrophasors.

[6] Y. Hua, and Tapan K. Sarkar, “On SVD for estimating generalized eigenvalues of singular matrix pencil in noise”, IEEE Transactions on Signal Processing, vol. 39, pp. 892-900, Apr 1991.

[7] Tapan K. Sarkar, and O. Pereira, “Using the matrix pencil method to estimate the parameters of a sum of complex exponentials”, IEEE Antennas Propagation Magazine, vol. 37, pp. 48-55, Feb 1995.

[8] Mariesa L. Crow, and A. Singh, “The matrix pencil for power system modal extraction”, IEEE Transactions on Power Systems, vol. 20, no. 1, pp. 501-502, Feb 2005

[9] Lisa L. Grant, and Mariesa L. Crow, “Comparison of Matrix Pencil & Prony Methods for power system modal analysis of noisy signals”, North American Power Symposium (NAPS), Aug 2011.

[10] Identification of Electromechanical Modes in Power Systems, IEEE Task Force Report, Jun 2012.

[11] J. F. Hauer, C. J. Demeure, and L. L. Scharf, “Initial results in Prony analysis of power system response signals”, IEEE Transactions on Power Systems, vol. 5, no.1, pp.80-89, Feb 1990.

[12] R. B. Leandro, A. S. e Silva, I. C. Decker, and M. N. Agostini, “Identification of the Oscillation Modes of a Large Power System Using Ambient Data”, Journal of Control, Automation and Electrical Systems, Springer, Apr 2015.

[13] L. Qi, L. Qian, S. Woodruff, and D. Cartes, "Prony Analysis for Power System Transient Harmonics", EURASIP Journal on Advances in Signal Processing, vol. 2007, no. 48406, Dec 2006.