Synchrophasor Based Ocillation Detection: A Case Study for Indian Power Grid

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Abstract—**The Indian electrical grid is one of the largest & complex networks in the world. Such complex system is subjected to stress or disturbances which manifest in the form of low frequency oscillations. Monitoring of these oscillations is necessary as they can disrupt the system if they are sustained for a longer period of time with significant magnitude. This paper presents the analysis of low frequency oscillation modes using the data from Phasor measurement unit located in Western and northern region of the country. It reports case studies of disturbances that occurred in the Indian power grid. The modes with low frequency oscillations were observed in both Western& northern region of the Indian grid.The Matrix Pencil technique was used to identify the oscillatory modes in system during the occurrence of the event. The importance of identifying critical oscillatory modes to improve the power system operation, has been brought out in this paper.**

Keywords—Phasor measurement unit, oscillations, power system stability, inter-area oscillations

I. INTRODUCTION

The Indian electrical grid is one of the largest and complex power grids in the world with an installed capacity of 227 GW [1]. It consists of five regional grids i.e. NR (northern Region), ER (Eastern Region), NER (North-Eastern Region), WR (Western Region) & SR (Southern Region) operating synchronously since December 2013. The operation & control of such complex network is carried out by the hierarchical network of load control centres. National load dispatch center (NLDC), five regional load despatch centres (RLDCs) thirty three state load despatch centres (SLDCs).

The system operation has now become complex due to integration of high capacity transmission lines, renewables etc. leading to several unforeseen stability problems into the system. The decision making time by the operator of such a large grid has to be reduced with the complexity & stabilityproblems especially small signal stability problems due tostress in the system caused by higher loading levels. Thus facilitating the need for advanced monitoring and visualization tools. The technological advent of phasor measurement unit (PMU), has come out to be as tool which provides the grid operator with the real time view of the system. Indian grid has installed a number of PMUs at various locations [2].

PMU provides the time synchronised measurements of voltage and current phasors along with frequency & rateof change of frequency (ROCOF)synchronised with GlobalPositioning System (GPS) satellite [3]. These measurementsare utilised for power system operation & for analysis of eventsin post-despatch scenario [4].Various applications with benefits of PMU are explained in [5]. These PMU measurements canalso be used for Low frequency oscillation (LFO) detection [6].

This paper presents a case study that demonstrates the application of PMU to detect LFOs in the system & actions tobe taken to damp these oscillations.The paper is organised asfollows:Section II reviews the theoretical background on smallsignal stability, LFOs and proposed technique for LFO modedetection Matrix pencil method. Section IIIand IV presents brief description of the events that occurred in the WR and discusses the results of modal analysis. Section V, concludes the paper.

II. THEORETICAL BACKGROUND

A. Small signal stability

Small signal disturbances during power system operationmay occur due to several reasons thereby affecting the powersystem. The ability of power system to be in steady state dueto such disturbances is called small signal stability. Transientstability is associated with the ability of power system tomaintain synchronism when subjected to large disturbanceslike line faults, bus fault, generator trip etc. During thesedisturbances the electromagnetic & mechanical torques ofeach synchronous machine need to be maintained. The electromechanicaltorque of synchronous machine can be resolvedinto two components: synchronizing torque component(K_s) &damping torque component(K_d)as shown in (1).

$$\Delta T_e = K_s\Delta\partial + K_d\Delta\omega = T_s + T_d \qquad 1$$

Where:
K_s: Synchronizing torque coefficient
$\Delta\partial$: 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 in damping torque coefficient (K_d) & variation in speed ($\Delta\omega$).Reduced damping torque (T_d) gives rise to low frequencyoscillations[7]. Undamped oscillations can increase inmagnitude & 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),intra-plant modes (1 Hz - 2.5 Hz), torsional modes (10 Hz-40Hz) & control modes. The inter-area modes are associatedwith swinging of groups of generators in one area of thesystem against generators in other area. They usually occurbecause of weak interconnecting network. The intra-plantmodes occur due to the swinging of units of generating stationwith respect to each other. The torsional modes are associatedwith turbine-generator shaft system and associated rotationalcomponents. The control modes are present in the systembecause of poor design of controllers of AVR, HVDC, SVC,AGC etc.

Disturbances can occur in the interconnected power system due to faults, load changesand when these disturbances occur oscillations usually arise in the system. These oscillations are acceptable as long as they decay [7,8]. It is very important to monitor theseoscillations to ensure that no lightly damped oscillatory modes exist in the system asthey threaten the reliable operation of the power system. The small signal instabilityissues need to be addressed since most of the blackouts have been associated with it [9]. The oscillations can be regarded as the characteristic of the system i.e. oscillatoryparameters are dependent on the physical infrastructure. Every power grid is unique inits physical connections thus presence of oscillations vary with the networks. The powersystem oscillations are complex and difficult to analyse.

There exist two techniques for detecting the LFOs of thepower system: model based techniques & measurement basedtechniques [10]. In the model based technique the non-lineardifferential equations governing the system are linearizedabout an operating point & further the modes are obtainedvia Eigen value analysis [7]. In the measurement basedtechniques direct measurements from PMU estimate the linearmodel. Some of the popular measurement based techniquesfor estimating LFOs are Fast Fourier Transform (FFT), Pronyanalysis [11] [12], Matrix Pencil [13], Hilbert transform [14,15,16],wavelet transform [17,18,19]. A comparative study ofvarious techniques for identification of oscillations has beenexamined in [20,21].

B. Matrix Pencil method

Matrix pencil method is an efficient approach to fit measured date 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 developed. It directly estimates the parameters for the exponential terms in 1 to an observed measurement [1, 2].

$$y(t) = \sum_{i=1}^{n} A_i e^{\sigma_i t} \cos(\omega_i t + \varphi_i) \qquad 1$$

Data matrix [Y] is formed using input data shown in 2

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

Where N is number of measured samples, L is pencil parameter.

Next SVD of matrix [Y] is calculated which gives:

$$[Y] = [U][\Sigma][V^T] \qquad 3$$

Here [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

$$[Y_1] = [U][\Sigma'][V_1']^T \qquad 4$$

$$[Y_2] = [U][\Sigma'][V_2']^T \qquad 5$$

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

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

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

$$\begin{bmatrix} y(0) \\ y(1) \\ : \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & ... & 1 \\ z_1 & z_2 & ... & z_n \\ : & : & : & : \\ z_1^{N-1} & z_2^{N-1} & ... & z_n^{N-1} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ : \\ B_n \end{bmatrix}$$

III. CASE STUDY-I

This section analyses the event that took place in the WR of the Indian power grid. On 3rd March 2013 at 18:04 hours, a bus fault occurred at Parli in Maharashtra state. The frequency and rate of change of frequency (ROCOF) recorded by PMU located at Badrawati are shown in Fig. 1
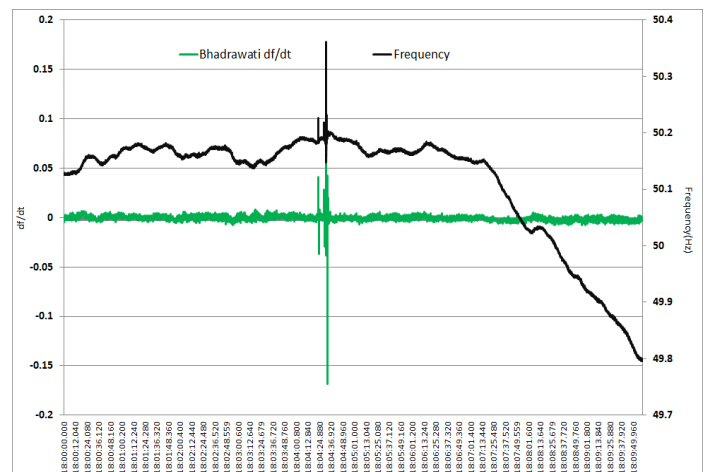

Fig. 1. Frequency and ROCOF at Bhadrawati

The measurements at Badrawati indicate sharp fall in the frequency and ROCOF. Three spikes were observed in the measurements with, and the third spike was the severe one indicating tripping of all elements. The ROCOF reached approximately 0.17 Hz/sec when the event occurred. The frequency also started dropping and reached 49.8 Hz within 1 sec.
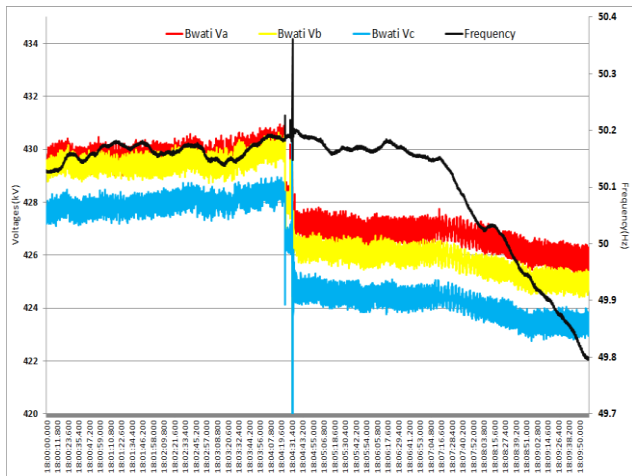

Fig. 2. Line voltages recorded at Badrawati

The line voltages recorded by PMU placed at Bhadrawati are shown in Fig. 2. The disturbance at Parli is indicated by sharp pulses.It can observed that after the event occurred at Parli, line voltages reduced.
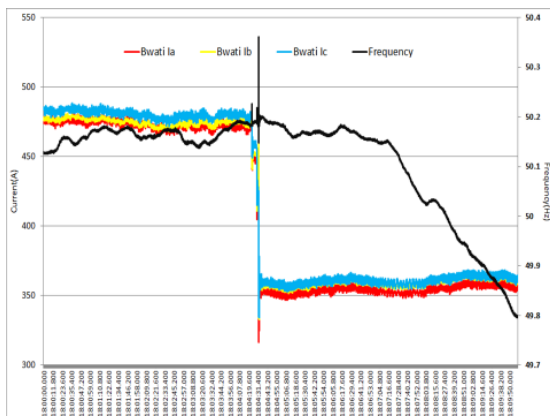

Fig.3. Phase currents recorded at Badrawati

Fig-3, shows the plot for linecurrents recorded by PMU at Badrawati. The measurements show sharp pulses indicating loss of elements in the system. The line currents were observed to have reduced values after the disturbance. The measurements also show the presence of oscillations in the system.
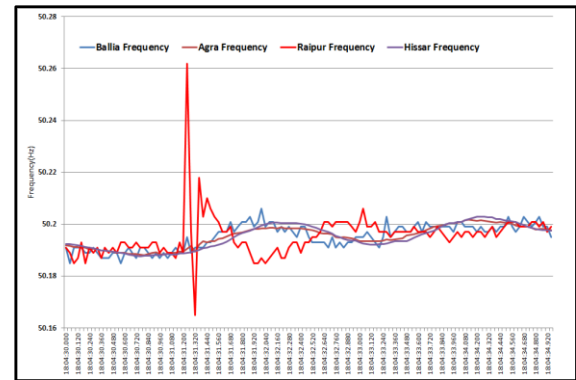

Fig. 4. Frequency plots NR and WR

After the bus fault at Parli in WR, the frequency measurement obtained from at Raipur in WR and Agra, Ballia, Hissar in NR were compared for the behavior of the system. It can be clearly observed from Fig-4 that WR machines are oscillating against the NR machines till the new equilibrium point reached in 3 secs.

TABLE I.   RESULTS OF MODAL ANALYSIS CASE STUDY- I

Sr.No.	Location of PMU	Freq (Hz)	Damping	Amplitude
1		0.6	-0.01509	0.04124
2		0.8	0.06814	0.08434
3	Raipur (WR)	1.5	0.0365	0.031
4		2.7	0.0025	0.0042
1		0.6	-0.03529	0.02148
2		0.8	0.01722	0.01041
3	Agra (NR)	1.5	0.00235	0.006
4		2.7	0.00079	0.00378

The results of modal analysis using Prony method have been tabulated in Table-1. The voltage measurements at recorded by PMU at Raipur in WR and Agra in NR have been used for analysis. It can be observed from the results that the modes with frequencies of 0.6 Hz, 0.8 Hz, 1.5 Hz and 2.7 Hz, were identified with negative and close to zero damping.

The 0.6 Hz oscillatory mode was estimated to have negative damping both in Raipur as well as Agra. The 0.8 Hz, 1.5Hz and 2.7 Hz modes were observed to have close to zero damping but comparatively lower amplitudes as compared to the 0.6 Hz mode. Since the 0.6 Hz inter-area oscillatory mode has negative damping and higher amplitude is quantified as the critical mode in the system. The amplitude of all the oscillatory modes at Raipur are more than those observed at Agra. This is because Agra is located far from the place where the event occurred (i.e. Parli).

IV. CASE STUDY -II

This section analyses a disturbance that occurred at Sipat in WR on 14th September 2012 at 18:58:22 hours. The PMU measurements at recorded at Raipur in WR clearly indicate unstable behavior of the system.
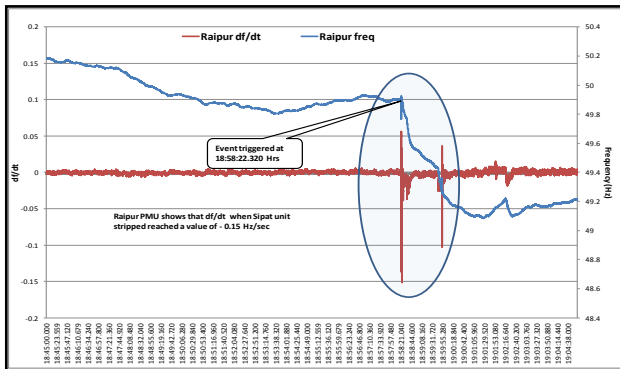

Fig.5. Frequency and ROCOF at Raipur

The frequency and ROCOF measurements at recorded at Raipur during the disturbance in Sipat as shown in Fig. 5. The measurements at Raipur clearly indicate when the event was triggered at Sipat i.e. at 18:58:22.320 hours as shown in the encircled section in the figure. It can also be observed that when Sipat unit tripped Raipur PMU shows that ROCOF reached a value of -0.15 Hz/sec.
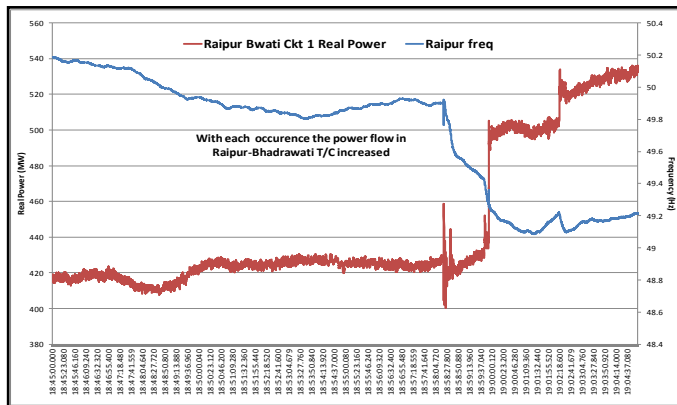

Fig.6. Raipur-Bhadrawati power flow

The real power flow on Raipur- Bhadrawati line also indicates the occurrence of disturbance at Sipat. It can be clearly observed in Fig.6 that with the loss of units at Sipat the power flow on Raipur- Bhadrawati increased.
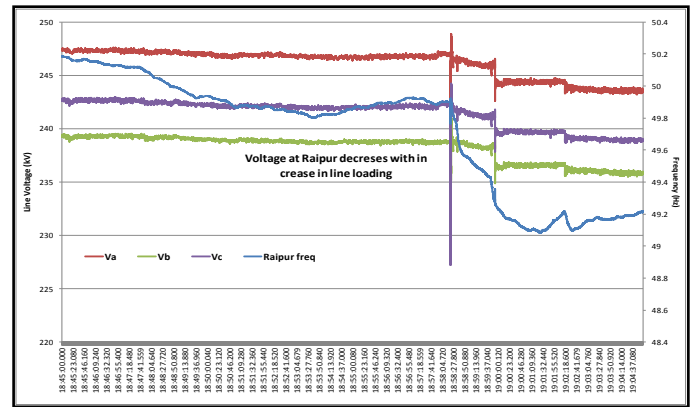

Fig.7. Line voltages recorded by PMU located at Raipur

The voltage measurements at Raipur also indicate sharp voltage dips at the time of disturbance. With the disturbance at Sipat, increased power flow on Raipur- Bhadrawati line resulted in decrease in line voltages at Raipur as shown in Fig. 7.

The line currents measurements for Raipur- Bhadrawati line are shown in Fig.8. This recorded data also indicates the event occurrence with the sharp pulses. It can also be observed that with the event occurrence power flow on this line increased which lead to decreased line voltages at Raipur thus leading to increased line currents. This can be clearly observed in Fig. 8.

Modal analysis of the power flow measurement on Raipur-Bhadrawati line was carried out using matrix pencil technique in-order to identify the oscillatory modes excited in the system due to the disturbance. The analysis was carried out for two instances Duration 1 (before) and Duration 2 (after) the disturbance in-order study the behavior of the modes.
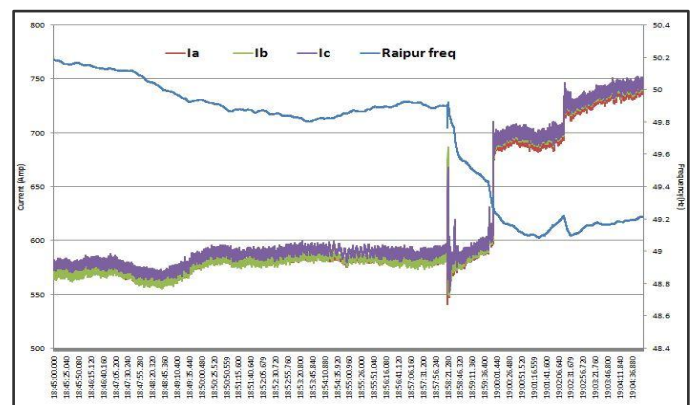

Fig.8. Raipur- Bhadrawati Line current

TABLE II.   RESULTS OF MODAL ANALYSIS CASE STUDY- II

Event 1			
Time Instant	Frequency	Damping	Amplitude
Duration 1	0.35	0.06561	11.00855
	0.69	0.1065	11.33678
	1.2	0.05737	7.1932
Duration 2	0.34	0.16818	8048.51036
	0.7	0.1334	162507.274
	1.2	0.05391	683.88899
Event 2			
Duration 1	0.33	0.26122	44.43362
	0.71	0.06076	3.44972
	1.2	-0.0087	0.18098
Duration 2	0.36	0.01412	1.17597
	0.69	0.05844	16.34748
	1.18	-0.00506	0.31271

The results of modal analysis are tabulated in TABLE II. It can be observed for event 1 in the system the oscillatory modes with frequencies of 0.35 Hz, 0.7 Hz and 1.2 Hz for both the time instants before and after the disturbance. The 1.2 Hz mode was identified to have low damping for both the time instances.All the oscillatory modes were observed to have higher amplitudes after the event 1.

Analyzing event 2 in the network (i.e. second spike in the measurements) indicated presence of 0.3 Hz, 0.7 Hz and 1.2 Hz modes. The 0.3 Hz mode had improved damping before the second disturbance and it reduced to 0.014 after the disturbance. Similarly the damping of 0.7 Hz mode also reduced after the event 2. After the occurrence of event 1 the 1.2 Hz mode was observed to have negative damping for both time instants for event 2.

V.   CONCLUSION

Low frequency oscillations (LFOs) are inherent to interconnected power systems. These oscillations need to be stable in order to have secure power system operations. The Indian grid has recently installed a number of PMUs in the system which increase the situational awareness amongst the operators. This paper tries to demonstrate one possible application of PMU measurements in the power system i.e. identification of low frequency oscillations. This paper uses Matrix pencil for identification of LFOs. This paper also indicates that as the location of PMU increases from the event located the amplitude of modal parameters is observed to have reduced. Thus it can be concluded that the PMU placed far away from the event location will indicate lower amplitude for a critical mode observed in the system.

Some of the devices in the power system to counteract negative damping include PSS inexcitation system of generator & controls of FACTS devices.The real time actions by system operator include generationre-despatch, load shedding, circuit switching etc. to relievethe stress in the system. This case study has indicated theimportance of PMUs & their location towards identificationof LFOs and its source identification. Extensive research needs to be carried out on theoptimum placement of PMUs to record the events & foranalysis of LFOs in the system.

Ongoing work deals with developing tools for advanced monitoring of the power grid operations. With increase in the number of PMUs placed in the system will lead to increased observability.

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