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PMU Based Identification of Low Frequency Oscillations -A Case Study

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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 units located at two extreme parts in Western region. It reports a case study of an event that occurred in the Western & Eastern regions of Indian power grid. The modes with low frequency oscillations were observed in Western region of the Indian grid. The Prony & Matrix Pencil techniques were used to identify the oscillatory modes in system during the occurrence of the event. The importance of identifying dominant mode, computation of non-dominant oscillatory modes & the role played by phasor measurement unit & their locations has been brought out in this paper.**

Index Terms—**Phasor Measurement Unit (PMU), Low Frequency Oscillation(LFO), Matrix Pencil, Prony analysis**

I. Introduction

The Indian electricity grid is one of the largest power grids in the world with an installed capacity of 223.625 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). Amongst these NR, ER, NER, WR operate synchronously as N-E-W grid while the SR grid is asynchronously connected to the N-E-W grid through HVDC links.

System operation has now become complex due to integration of 765 kV transmission lines, 800 MW capacity generators and 4000 MW Ultra mega power plant. The 1200 kV transmission lines and 800 kV HVDC will be introduced into the system in the future. On the track of renewable integration, each year there is a large capacity addition in wind and solar power in Indian grid which has led to skewed load generation balance as the generation from renewables is unpredictable. Furthermore intermittency has led 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 & stability problems especially small signal stability problems due to stress in the system caused by higher loading levels. Hence the need for advanced tools for monitoring and visualizing the health of the system arises. With the recent technological advent, Phasor Measurement Units (PMUs), early warning system, intelligent electronic devices (IEDs), Wide area measurement protection and control (WAMPAC), optical fiber communication (OFC), etc. the visualization of the electrical grid has improved. Among these PMUs have come out to be a tool which has given the grid operator a real time view of the system with millisecond information. PMUs form an integral part of Wide area monitoring,protection and control (WAMPAC) systems. The Indian grid has recently installed PMUs at various locations as a part of its Unified Real Time Dynamic System Monitoring (URTDSM) [2].

Electrical grid being dynamic in nature and faces stability challenges in day to day operation. The stability issues can be classified on the basis of time scale into slow occurring and fast occurring phenomenon. The slow phenomenon in general, such as slow collapse of voltages that is voltage instability occurring over few minutes of time horizon can be depicted using the Conventional SCADA (supervisory control & data acquisition) system installed based on data fetched from RTUs every 10 secs. While on the other hand small signal stability cannot be observed using convetional SCADA data, thus fast measuring IEDs along with fast communication channel is required. The communication issues have been resolved with the help of OFC while the PMUs have solved the measurement issues. Now operators are able to visualize the small signal stability with the help of analysis of the PMU data from the field. Small signal instability needs to be addressed as most of the blackouts have been associated with it [3].

PMU provides the time synchronised measurements of voltage and current phasors along with frequency & rate of change of frequency (ROCOF)synchronised with Global Positioning System (GPS) satellite [4]. These measurements are utilised for power system operation & for analysis of events in post-despatch scenario [5].Various applications with benefits of PMU are explained in [6]. These PMU measurements can also be used for Low frequency oscillation(LFO) detection [7].

This paper presents a case study that demonstrates the application of PMU to detect LFOs in the system & actions to be taken to damp these oscillations.The paper is organised as follows:Section II reviews the theoretical background on small signal stability, LFOs and proposed techniques for LFO mode detection Prony analysis & Matrix pencil method. Section III presents brief description of the events that occurred in Western & Eastern regions. Section IV discusses the results.

II. THEORETICAL BACKGROUND

A. Small Signal Stability

Small signal disturbances during power system operation may occur due to several reasons thereby affecting the power system. The ability of power system to be in steady state due to such disturbances is called small signal stability. Transient stability is associated with the ability of power system to maintain synchronism when subjected to large disturbances like line faults, bus fault, generator trip etc. During these disturbances the electromagnetic & mechanical torques of each synchronous machine need to be maintained. The electromechanical torque of synchronous machine can be resolved into two components: synchronizing torque component(K_s) & damping torque component(K_d)as shown in (1).

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

where :
K_s : Synchronizing torque coefficient
$\triangle\delta$: Rotor angle perturbation
$\triangle\omega$: 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 ($\triangle\omega$). Reduced damping torque (T_d) gives rise to low frequency oscillations[18]. Undamped oscillations can increase in magnitude & lead to instability and are therefore an object of study by various researchers. These oscillations are classified into four major types inter-area modes (0.1 Hz - 1 Hz), intra-plant modes (1 Hz - 2.5 Hz), torsional modes (10 Hz-40 Hz) & control modes. The inter-area modes are associated with swinging of groups of generators in one area of the system against generators in other area. They usually occur because of weak interconnecting network. The intra-plant modes occur due to the swinging of units of generating station with respect to each other. The torsional modes are associated with turbine- generator shaft system and associated rotational components. The control modes are present in the system because of poor design of controllers of AVR, HVDC, SVC, AGC etc. The identification of modes is carried out using analytical techniques.

There exist two techniques for detecting the LFOs of the power system: model based techniques & measurement based techniques [8]. In the model based technique the non-linear differential equations governing the system are linearized about an operating point & further the modes are obtained via Eigen value analysis [9]. In the measurement based techniques direct measurements from PMU estimate the linear model. Some of the popular measurement based techniques for estimating LFOs are Fast Fourier Transform (FFT), Prony analysis [10] [11], Matrix Pencil [12], Hilbert transform [13], wavelet transform [14] [15][16]. A comparative study of various techniques for identification of oscillations has been examined in [17].

B. Analytical Techniques

Prony analysis & Matrix Pencil,are two of the many techniques that are used to analyse the synchrophasor data. The Prony technique is an extension of Fourier analysis as it directly estimates the frequency, damping, and relative phase of the modal components in a signal by fitting linear combination of exponential terms to the signal in (2).

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

where: A_i,σ_i,ω_i,ϕ_i are the amplitude, damping coefficient,angular frequency & phase shift of the i^{th} frequency component respectively.

Here each component having different frequency is regarded as mode of the original signal. The elements of each mode can be determined from the state space representation of equally sampled data with sampling period of T [19]. 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 developed. It directly estimates the parameters for the exponential terms in (2) to an observed measurement [20].

III. CASE STUDY

This section gives a brief description of the case taken up for the study of LFO modes during an event related to Western & Eastern Regions on 13th April 2013. Weather was stormy with heavy rain in Chattisgarh & Orissa states in the N-E-W grid. The system that was affected during the occurrence of this event is shown in Fig. 1. Initially Buddhipadar-Tarkera lines 1,2 tripped due to three phase fault & operation of over-current protection respectively. This led to the part of Orissa system comprising generation of IBTPS power station(2*230 MW),600 MW unit of Sterlite, Vendanta CPP(9*135 MW) & Bhusan steel CPP (2*120 MW) getting connected to Western grid. This led to the operation of backup over current protection on lines 220 kV Buddhipadar-Korba double cicuit,220 kV Buddhipadar-Raigarh single circuit, followed by tripping of 400 kV SEL-Raigarh II. All the feeders from 220 kV Buddhipadar substation tripped. IBTPS Units tripped due to loss of evacuation. Due to tripping 220 kV Vedanta- Buddhipadar lines, (9* 135 MW) Vendata CPP & 600 MW unit at Sterlite IPP got islanded (as depicted in Fig.1) & due to failure of islanding scheme operation, the island collapsed leading to loss of generation of CPP and

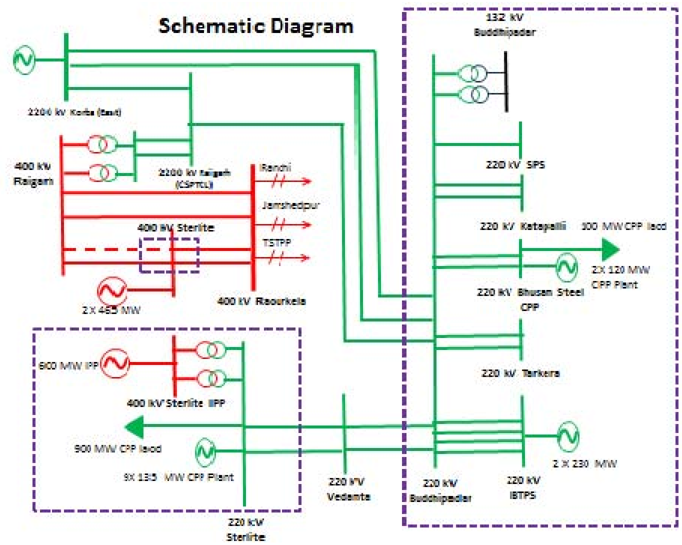

Fig. 1: Areas affected during the event

IPP and load of CPP. The 400 kV Sterlite Raourkela II tripped due to Y-B phase fault. The sequence of events of the disturbance have been tabulated in TABLE I.

TABLE I: Sequence of events

Sr.No.	Time of event occurrence	Name of line
1	22:01:16.600	220 kV Buddhipadar Tarkera line 1 & 2
2	22:01:49.559	220 kV Buddhipadar-Raigarh
3	22:02:53.325	400 kV SEL-Raigarh II
4	22:04	All feeders from Buddhipadar tripped.
5	22:04	220 kV Buddhipadar Korba(E) -3
6	22:04:39.160	Units at IBTPS tripped.Sterlite CPP ,IPP got islanded .loss of Generation of CPP and IPP and load of CPP .
7	22:08.17.377	400 kV Sterlite Raurkela II

Fig.2 indicates the occurrence of an event at 22:02:38.520 Hrs. This is encircled in the figure. It can be seen that oscillations are initiated & present in this time interval viz .Fig. 2 shows the plot of frequency which was 49.9 Hz at the initiation of the event at 22:02:38.520 Hrs. It is steadily falling down to approximately 49.8 Hz at 22:04:39.520 Hrs. There is a steep fall in frequency at this instant & reaches less than 49.6 Hz & later starts increasing to 50.03 Hz.

It can also be observed from Fig. 2 that sharp pulses occur indicating large ROCOF when (i) 220 kV Buddhipadar Tarkera line 1 & 2, (ii) oscillation started, (iii) tripping of 400 kV SEL-Raigarh-II line, (iv) tripping of various units indicated in TABLE I at the instant 22:04:39.160 & (v) tripping of 400 kV Sterlite- Rourkela II at 22:08:17.377 Hrs.

The zoomed view of frequency & ROCOF in Fig.2,is shown in Fig 3. This clearly shows the oscillations in frequency (plot in black) & ROCOF (plot in green), also sudden reduction in frequency & ROCOF indicates the tripping of 400 kV SEL-

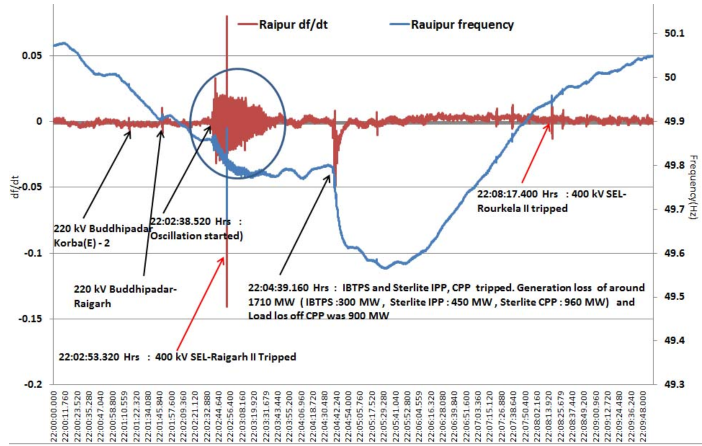

Fig. 2: Frequency & Rate of change of frequency (ROCOF) during the event

Raigarh II line.

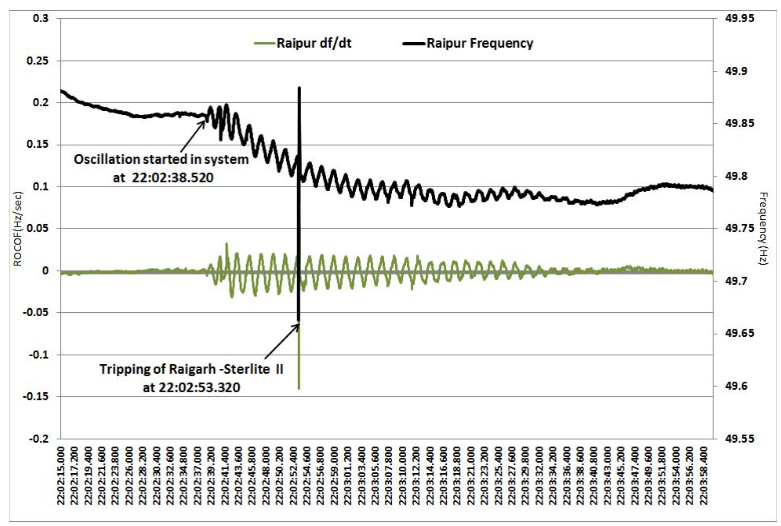

Fig. 3: Oscillation in frequency & ROCOF during initiation of the event

The interested readers may refer to the interconnections between Western & Eastern region from the Western region power grid map [21].The probable cause for the oscillation could be change in the controller action of some generators in nearby areas i.e. IBTPS, Sterlite, Korba (E), Korba(W), Sterlite CPP, TSTPP, Sterlite IPP preceded by tripping of some lines of multiphase faults & stress in 220 kV system due to over loadings. The presence of inter area mode (0.51 Hz) with very low damping is the outcome of stress in the system. An attempt was made to identify coherent group of generators oscillating against each other by studying the data from different PMUs. The plot of frequencies recorded by PMU at Raipur & Sugen indicate that the, frequency at Sugen had a phase shift with respect to the frequency at Raipur presented in Fig. 4. This phase shift indicates formation of coherent groups of generators. The modal analysis of LFOs is given in the ensuing section.

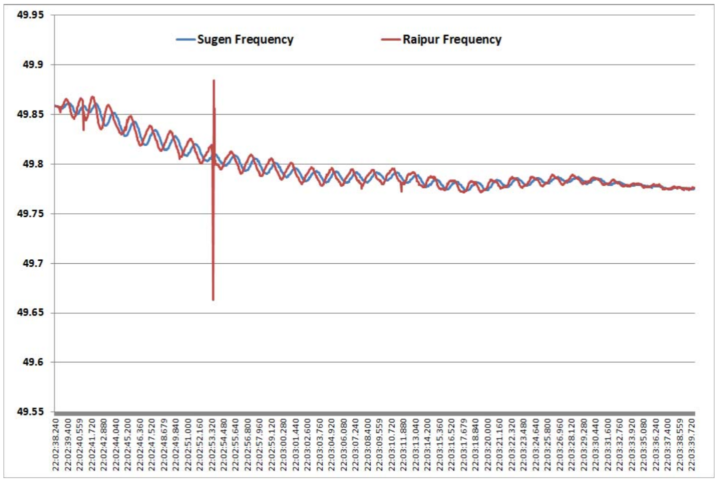

Fig. 4: Phase Shift in frequencies

IV. MODAL ANALYSIS

For the analysis of the event the PMU data from two locations, Raipur & Sugen in the Western region (WR) are used. The frequency measurements from these PMUs as shown in Fig. 4 have been analysed using Prony analysis & Matrix Pencil method to identify the LFO modes that initiated the event leading to tripping Raigarh- Sterlite II lines. The results of modal analysis are tabulated in TABLE II

TABLE II: Results

Raipur					
Matrix Pencil Method			Prony Analysis		
Frequency	Damping Ratio	Amplitude	Frequency	Damping Ratio	Amplitude
0.1878	0.00253	0.00015	0.19	0.039	0.0004
0.5135	0.00616	0.0063	0.51348	0.00689	0.0237
1.53	0.0007	0.00028	1.52	0.00716	0.00039
Sugen					
Matrix Pencil Method			Prony Analysis		
Frequency	Damping Ratio	Amplitude	Frequency	Damping Ratio	Amplitude
0.18037	-0.01012	0.00007	-	-	-
0.51428	0.00649	0.00448	0.51479	0.00888	0.0125
-	-	-	1.50370	0.04773	0.00002

The modes with frequency of 0.18 Hz, 0.51 Hz & 1.53 Hz are correctly identified using both Prony analysis & Matrix Pencil method which were also validated by FFT analysis using data from PMU placed at Raipur. Comparison of results using Matrix pencil method & Prony method indicates 0.18 Hz mode with a damping ratio of 0.00253 & amplitude of 0.00015, while this mode was observed using Prony analysis with damping ratio of 0.039 & amplitude of 0.0004. It can be observed that there is a variation in damping ratio & amplitude using both the methods. The 0.51 Hz mode was observed with least damping ratio of 0.00616(close to zero) having amplitude 0.0063 using matrix pencil & using Prony method the same mode was detected with damping of 0.00689 & amplitude of 0.0237. The 1.53 Hz mode was identified to have damping ratio of 0.0007 using both matrix pencil & Prony analysis having amplitude of 0.00028 & 0.00039 respectively. The mode with higher amplitude & least damping is quantified as the dominant mode, which in this case is 0.51 Hz.

Modal analysis of data from PMU placed at Sugen indicated the 0.18 Hz mode with negative damping of -0.0102 & amplitude of 0.00007 using matrix pencil. This mode was not identifiable using Prony analysis.The 0.51 Hz mode was observed with damping ratio of 0.00649 & amplitude of 0.00448 using matrix pencil whereas Prony analysis gave 0.00888 damping & amplitude of 0.0125. The mode with frequency of 1.53 Hz mode was observed with sufficient damping & low amplitude using Prony analysis but was unidentifiable using Matrix Pencil.

Comparison of analysis at Raipur & Sugen indicates that 0.51 Hz is the dominant inter-area mode, this mode is of particular interest as the same was also observed during the major grid disturbance on 31 july 2012 where the Western & Eastern region (ER) separated from each other preceded by separation of Northern region by Western region. The presence of inter-area mode indicates weak interconnection between the two regions. The plot of Fig.5 shows that the 0.51 Hz mode is not getting completely damped even after $2\frac{1}{2}$ cycles.

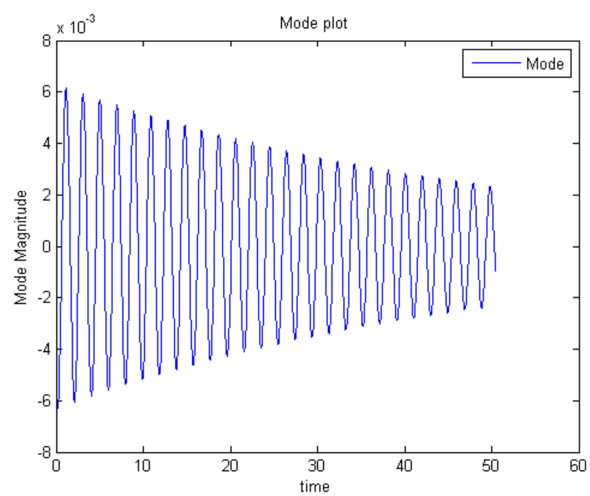

Fig. 5: 0.51 Hz mode with damping

Analysing PMU data from WR alone provides information of the modal content in that particular region & also indicates occurrence of events as explained above. For this case study PMU data from Western region at different locations was available during the event, which was helpful in identifying the common dominant modes between these two regions. The system operator would endeavour to relieve stress in WR &

ER corridors to damp this 0.51 Hz mode of oscillation.

The analysis of PMU data at Raipur indicates 0.51, 1.53 & 0.18 Hz modes of oscillation with 0.51 being the dominant, whereas the analysis of PMU data at Sugen indicates 0.51 Hz as the dominant. The two methods indicate only one non-dominant frequency for Sugen PMU data. This appears to indicate the importance of PMU placement. The disturbance that originated at Raigarh has resulted in a dominant 0.51 Hz oscillation which is observable in both the extremes of Western regions (Western & Eastern part) after carrying out the analysis.

The importance of conducting modal analysis using different methods like Prony & Matrix pencil gets highlighted from this case study, this will enable cross-check results to increase the confidence level of the system operator. The case study shows the importance of PMU placements for identification of inter-area LFOs.

V. Conclusion

This paper presented a case study in which low frequency oscillations were observed in the Western & Eastern parts of WR, possibly between WR & ER during operation of the grid under stress due to tripping of lines. This case study has illustrated the sequence of occurrence of a disturbance in Western & Eastern regions and stress in the interconnection due to loss of inter regional lines. The data from the PMUs placed in the Western region at different locations have been analysed. The modes of LFOs were computed using Matrix Pencil & Prony methods. The study concluded the following:(i) the PMU placed in Raipur showed dominant mode clearly, (ii)The Prony & matrix pencil could identify only one non-dominant mode from the PMU at Sugen. The oscillations with 0.51 Hz frequency were observed with damping less than 5% which needs to be addressed with corrective actions to relieve the stress in the system. Some of the devices in the power system to counteract negative damping include PSS in excitation system of generator & controls of FACTS devices. The real time actions by system operator include generation re-dispatch, load shedding, circuit switching etc. to relieve the stress in the system. This case study has indicated the importance of PMUs & their location towards identification of LFOs. Extensive research needs to be carried out on the optimum placement of PMUs to record the events & for analysis of LFOs in the system.

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