Comparative Analysis of Low Frequency Oscillations Using PMU and CPR-D Relay-A Case Study

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

Abstract—**Indian Electricity Grid is one of the largest electricity grids across the globe. With its growing size and complexity coupled with interconnection of Regional Grids, small signal stability issues are being encountered. Low Frequency Oscillations (LFO) are of serious concern to system operators as its poor damping result in prolonged oscillations in electrical parameters like voltages, current and power. These oscillations are undesirable as they trigger further modes and lead to mal-operation of protection devices. So it is necessary to monitor these oscillations in real time and operators should be alerted if they cross a certain threshold. Measurement and recording of low frequency oscillations with the advancement of Phasor Measurement Units (PMUs) based Wide Area Measurement System (WAMS) is a boon to the system operators. Decisive actions can be initiated to relieve stress in the system only after the veracity of measurements and analysis are verified through different methods or different tools. WRLDC has deployed PMUs at various locations and CPR-D relay of A-eberle at one location to detect LFO and its characteristics. This paper describes the comparative analysis of both the devices. With two level monitoring of LFO, operator confidence would enhance and help in taking decisive actions to increase the damping of LFO in the system.**

Index Terms*—Low Frequency Oscillation, Power system Stability, Small signal stability, Fast Fourier Transform,Matrix Pencil, Wavelet Transform, HTLS, CPR-D Relay

I. Introduction

Indian power system is one of the largest power systems in the world and consists of five regional grids namely Northern, Eastern, North Eastern, Western and Southern grids. Among these, the first four regions are operating synchronously with each other and together known as NEW grid. On the other hand Southern grid is connected through asynchronous links with the NEW grid. It has been planned that Southern grid will be synchronized with NEW grid by 2014. During the recent years there is significant addition of generation, transmission and distribution capacities in response to load growth. High capacity corridors at 765kV level and large generation addition during the 11^{th} plan period coupled with large power transfers across regions led to increased complexity. Often, open access transactions and skewed despatch conditions due to weather effects in one of the regions led to stressed conditions in the Grid and consequent small signal stability problems. Operating such a large grid in safe and reliable manner is a challenging job for system operators. The system operators have to be provided with tools which will alert them in real time if the system is drifting towards unstable zone. Also advanced real time tools for better visualization and to report presence of dominant modes along with damping information are required to enable the operators to take actions to relieve stress and bring back the system to stable operating state. With growing size and complexity of the grid, stability aspects of integrated grid are of utmost importance. System collapse prediction and related technological innovations need to be introduced in control centers operating large and complex Powergrids, especially when there are interconnections with other grids.

Most of the large power system in the world have experienced collapse one time or the other due to stability aspects and some of these collapses are characterized by the phenomenon such as low frequency oscillations, small signal stability or voltage collapse (slow and fast) [1]-[2]. The relevance of such phenomenon to large grids at present is due to market driven operation and the necessity to operate power system close to the stability limits. At times due to non-availability of certain transmission elements (transmission depletion), the grid may operate under stressed condition where the network damping would be very low. If subjected to further overloading or any tripping, the system may encounter stability problems such as voltage collapse or oscillatory instability. For analyzing the stability aspects, frequency domain and time domain methods are usually employed by the power system analysts [3]-[4]. The frequency domain techniques have an advantage of indicating the margin of stability and details of damping and its measure. The frequency domain techniques are based on eigenvalues of the system for determination of the margin of stability. The time domain techniques determine whether the system is stable or unstable, but not the degree of stability. Therefore, for power system planners and system operators dealing with pre-despatch issues (before real time operation), knowledge of the degree of stability, possible low frequency modes and the extent of damping of each of these modes is required so that

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the operators can prepare operational and contingency plans. Some of the new stability techniques like Lyapunov exponent are based on energy functions and the sign of Lyapunov exponent determines whether the system is stable or not. [5]. The energy function based techniques can be used for fast and "On line" computation of stability determination in case of assessment of voltage collapse aspects like determination of Nose point and its distance from operating point. This can be done effectively by tracking of eigenvalues and determination of HoPF bifurcation point.

This paper is based on two different devices to measure the small signal instability in the grid. Section II of this paper gives the background about Small Signal Stability aspects and tools. Section III deals with description of the case study used for the comparative analysis of results obtained from two different devices used for detecting LFO in the system. Sections-IV and V deal with the LFO detection using CPR-D relay and PMU respectively. Comparison between the two devices is given in section VI.

II. Small Signal Stability and Analysis Tools

There are various types of stability aspects which need to be considered in power systems – Angle stability, voltage stability, mid-term and long term stability [3]. This paper is based on angular stability aspect of power system. Angular stability is of two types viz. small signal stability (small disturbance to 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 in system. This instability is mainly due to insufficient damping torque associated with fast acting high gain automatic voltage regulators (AVRs). 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. [6].

Small signal stability analysis based on Eigenvalue Analysis technique is carried out through linearization of the nonlinear differential equations that represent the power system around an operating point. This approach is very comprehensive and is based on complete modeling of the Power System elements and gives all the modes in the system. The second approach is response based where spectral analysis of measured data from the field is done which directly gives the low frequency oscillation modes observed in the system along with their damping information. There are several methods out of which Fast Fourier Transform, Matrix Pencil method, Wavelet Transform method and Hankel's Total Least Square (HTLS) method are prominent [7,8].

To analyze the low frequency oscillations, system parameter measurement at a high reporting rate is required from the field. Western Regional Load Dispatch Centre (WRLDC) had installed PMUs at several locations for time synchronized data with higher sampling rate to enhance the observability of the system. Synchrophasor data is being used for LFO detection using Matrix Pencil and FFT methods [4].

Apart from PMUs, WRLDC has also installed A-Eberle Collapse prediction Relay (CPR-D) at 400 kV Boisar Substation in Maharashtra. This relay has embedded functionality of dynamic power system stability monitoring to detect the collapse of the system. It has inbuilt applications for oscillation monitoring, detection of voltage drift, stability measure exponents etc. It performs fingerprint analysis to find out the LFO modes and their associated parameters like damping and duration. The main feature of this relay is that it performs the analysis on the voltage signal using a combination of Fast Fourier transformation, Wavelet transformation (Morlet) and Hilbert transformation methods [9]. It can observe the modes in the range of 10 mHz to 124.9 Hz. The range includes detection of Sub-synchronous Resonance (SSR), oscillation due to tower shade effect and electromechanical oscillations.

Further it uses all the sampled data and also maintains history of events such as mode history. The CPR-D relay provides the following applications in the context of the aforesaid aspects:

1. Identification of all modes in the range of 10 mHz to 124.9 Hz,
2. Spectral analysis and computation of degree of damping to each of these modes.
3. Calculation of Lyapunov stability exponent and stability limits.
4. Tracking of eigenvalues and determination of HoPF bifurcation point for determining the voltage collapse
5. Use of Spectral wavelet-analysis instead of DFT to meet the requirement of non-linear analysis as required by real life power systems.

A case study is presented on comparative analysis of using measurements from PMUs and CPR-D relay for oscillation detection, frequency of oscillation modes and damping information, which is described in Sections – III & IV.

III. Case Study of Load crash in Northern Grid

Due to inclement weather and heavy rains in the night hours of 17th/18th January 2013, about 9000 MW of load crashed in the Northern region. About 2000-2300MW decrease in power flow observed on West to North corridor as compared to export of power on previous days. Further about 2000 MW demand reduction occurred in the Western Region as compared to the previous night. The load crash started at around 22:00 hrs of 17-01-2013. High frequency and high voltages prevailed throughout the night and about twelve 400 kV lines were either opened or tripped in a span of 1 hour 20 minutes, i.e., between 22:00 hrs-23:20 hrs. Active Power to the tune of 1100 MW was wheeled to western region through WR-NR Inter-regional links. Due to high frequency and low cost of UI (Unscheduled Interchange) power, states in Western Region started drawing power from Northern Region by backing down their own generation. Several major corridors inside western region got overloaded (400 kV Itarsi-Khandwa-II, 400 kV Sugen-Vapi and 400 kV Chorania-Kasor lines) and observed to be on increasing trend in the early hours of 18th January, 2013. Though transfer capability of Inter-regional corridors were not violated due to export of power from Northern Region to Western Region, import TTC (Total Transfer Capability) of states like Gujarat & Maharashtra were getting violated as import TTC in the absence of several lines (kept out on over voltage and not taken back into service) was much less. Frequency controller action on HVDC link of WR-

SR has caused ramping of power from Western grid to southern grid to the tune of 100/185 MW on two occasions. Figure.1 shows NEW grid frequency which was high most of the time due to demand crash. The demand crash was observed till 06:00 hrs. of 18th January 2013. Oscillations of different low frequency modes with poor damping were observed due to skewed despatch conditions, critical line loadings with simultaneous network depletion and unusual direction of power flows. This gave a good case to analyze the LFO measurements using both the devices, which is discussed in the next two sections.

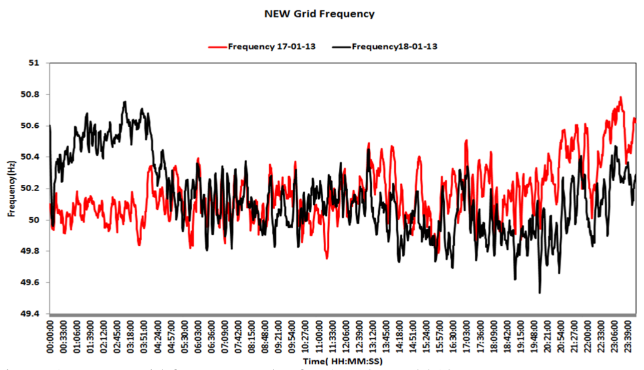

Figure 1. NEW grid frequency Plot for 17-18 Jan 2013

IV. LFO ANALYSIS FROM CPR-D RELAY

Table 1 summarizes the major modes of LFO observed by the CPR-D Relay of A-Eberle. The modes are obtained by the CPR-D relay which uses a combination of FFT, wavelet transformation and Hilbert transformation [5]. The major modes observed in the system are 0.76 (0.72-0.78 Hz) Hz and 3.4 Hz (3.2- 3.6 Hz) during 22:21:00-22:28:00 hrs. Both these modes appeared with durations ranging from 1.02 seconds to 50.85 seconds with either negative damping or almost zero damping.

Table 1: Major Modes observed by CPR-D Relay

Time(HH:MM:SS)	**Frequency(Hz)**	**Damping ratio**	**Decay time (Sec)**
22:21:00	0.74067	-0.00405	49.9752
22:22:00	0.747156	0.005504	13.5985
22:23:00	0.747156	0.010594	13.0126
22:23:00	0.743004	0.001144	50.5123
22:23:00	0.747156	-0.00939	15.9911
22:23:00	0.733341	-0.00371	6.81148
22:23:00	0.732932	-0.00376	6.8603
22:23:00	0.732932	0.013464	7.56831
22:24:00	0.749076	0.000848	50.8541
22:24:00	0.754331	0.004293	17.285
22:25:00	0.745648	0.001445	26.2938
22:26:00	0.742243	0.000393	50.4147
22:26:00	0.745602	-0.00023	50.6588
22:28:00	3.41839	-0.0068	1.64061
22:28:00	3.56815	-0.00682	1.56005
22:28:00	3.41839	0.020676	1.687
22:28:00	3.66855	-0.01721	1.40868
22:28:00	3.67045	-0.05209	1.02782
22:28:00	3.6499	-0.05216	1.03759
22:28:00	3.6499	0.01415	2.65379

V. LFO ANALYSIS FROM PMU DATA

To verify the LFO observed from CPR-D relay, Voltage data from the PMU at Jabalpur was extracted for the period 22:26:00-22:26:09 hrs (during the changeover from 0.76 Hz to 3.4 Hz as observed from the table 1) and was analyzed using Matrix Pencil Method as well as Fast Fourier Transform (FFT). Figure 2 shows the voltage plot from the PMU data which has been used for the analysis of LFO. This analysis was done offline using MATLAB. Table 2 gives the modes obtained after analyzing the voltage signal using Matrix Pencil Method.

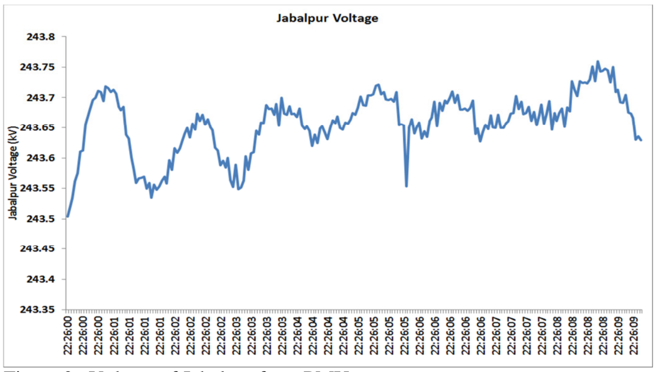

Figure 2. Voltage of Jabalpur from PMU

Table 2: Modes observed by MP analysis on PMUs data

Frequency	Phase	Sigma	Damping ratio
0.72273	1.7495	0.8316	-0.17775
3.24706	1.56838	-0.04929	0.00242

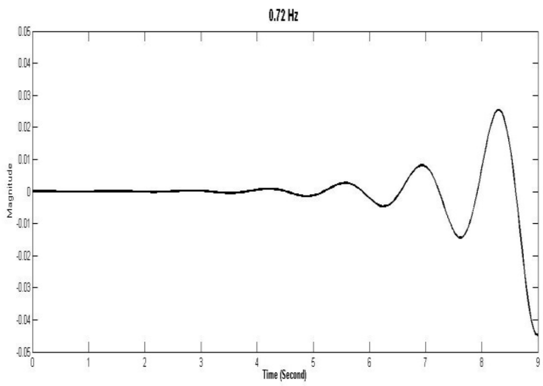

Figure 3: 0.72 Hz with Negative damping of 17.77 % but its amplitude is low

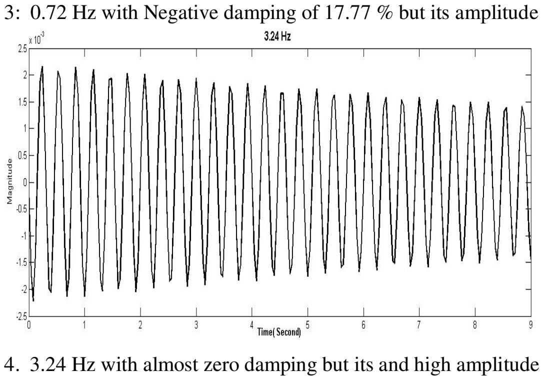

Figure 4. 3.24 Hz with almost zero damping but its and high amplitude

Figure 3 shows the 0.72 Hz mode with negative damping while 3.24 Hz mode was observed with almost zero damping as shown in Figure 4.

Fast Fourier transform (FFT) was performed on the same signal (22:26:00-22:26:09 hrs) to find out the dominant modes in the system. Figure 5 shows the various frequency components present in the system during the event. 0.74 Hz was having the highest magnitude as observed. While 3.32 Hz is also observed with significant magnitude in the system.

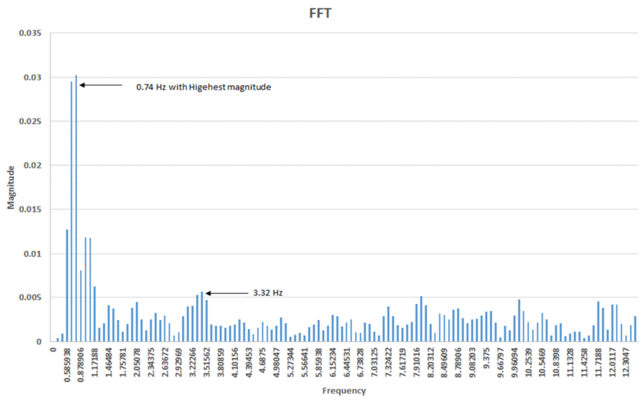

Figure 5. FFT Analysis of Voltage signal from PMU at Jabalpur

VI. COMPARATIVE ANALYSIS

From the analysis of the voltage signal from the two devices, it can be observed that, both devices have complemented each other in detection of 0.76 Hz (0.72-0.78 Hz) and 3.4 Hz (3.2-3.6 Hz) modes. These two modes are having poor damping as observed from CPR-D relay and PMU data. Hence it can be inferred that both the devices gave similar information on the presence of dominant modes along with damping information. PMU based measurements cannot be used for analyzing oscillation modes with frequency above 12.5 Hz (considering the reporting rate of 25 frames per second) while CPR-D relay can be used for modes up to 124 Hz. Wide presence of both devices can be useful for confirmation of the dominant modes and damping information and to cross check for ascertaining confidence levels before initiating operator actions to relieve stress in the system.

VII. CONCLUSIONS

Small signal stability being one of the important aspects in operation of power system, the new devices and methods to observe the LFOs would help system operator to initiate corrective actions in safeguarding the system. From the above analysis and results it can be concluded that both PMUs and CPR-D relay are suitable devices to measure the LFO in the system. Also one system will confirm the observation from the other. It will help operator in deciding the need of PSS tuning at generators, source of LFOs and location of damping devices like TCSCs. Also the detection of frequency of LFO will help in correct setting of PODs of HVDC, TCSCs and other damping devices available in the Grid.

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