

Application of Synchrophasors - A Case Study in Northern Regional Power System in India

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I. ABSTRACT

The deployment of synchrophasor technology in India as a part of the pilot project has significantly improved the visibility of the system dynamics in real-time. The synchrophasor data has also been found to be of great help in off-line analysis of grid events. The grid disturbance in India in July 2012 has increased the need for exploring the possible applications of synchrophasor data in monitoring and analysis of the system dynamics and taking suitable actions to maintain the stability of the system. This paper presents one such application wherein the oscillations captured by the synchrophasors in the Northern Regional Grid were analysed using a signal analysis tool developed in MATLAB®. The analysis reveals the various modes of oscillation observed in the Indian Power System during a few grid events. The paper also suggests the effective utilization of Power System Stabilizers and Power Oscillation Dampers installed in the grid for damping of oscillations and enhancement of dynamic security.

II. INTRODUCTION

The Indian power system is one of the largest power networks of the world with the total installed capacity of 207 GW including 18 GW of grid integrated wind capacity (~ 9% penetration) which is likely to increase further. The peak demand being met is 120 GW with 2400 million unit/day consumption and 818 kWh per capita energy consumption.

The Indian grid is demarcated into five regional grids namely, NR (Northern Region), WR (Western region), SR (Southern Region), ER (Eastern Region) and NER (North Eastern Region). Of these, the NR, WR, ER and NER are synchronously tied together to form the NEW grid which is asynchronously connected with the SR. The bulk power flow across the nation is supported by the vast interconnected transmission system with 117725 ckt km of 400kV forming its backbone, 6698 ckt km of 765 kV lines, 142223 ckt km of 220 kV lines and 9432 ckt km of HVDC bipole. It has 4 HVDC lines operating as bipoles between Rihand-Dadri, Chandrapur-Padge, Talcher-Kolar and Balia-Bhiwadi and 3 back-to-back stations at Vindhyachal, Bhadravati and Gazuwaka. There are 6 thyristor controlled series compensators (TCSC) installed on the 400 kV double circuit lines between Muzaffarpur-Gorakhpur, Purnea-Muzaffarpur and Raipur-Raigarh [1].

The operation and control of a vast and complex network is coordinated by the State, Regional and National Load

Despatch Centres which are equipped with SCADA/EMS. Recently, as a part of a pilot project 14 Phasor Measurement Units (PMUs) have been installed on nine 400 kV substations in the Northern Region viz. Vindhyachal (HVDC back-to-back station), Kanpur (with Static Voltage Compensators (SVC)), Dadri (HVDC inverter terminal), Moga, Kishenpur, Agra, Bassi, Hisar and Karcham Wangtoo, two 400 kV WR substations viz. Raipur and Bhadravati and three 400 kV SR substations viz. Salem, Hyderabad and Bengaluru [2], as shown in figure 1. These PMUs have enhanced the situational awareness at the Regional Load Despatch Centres [3].

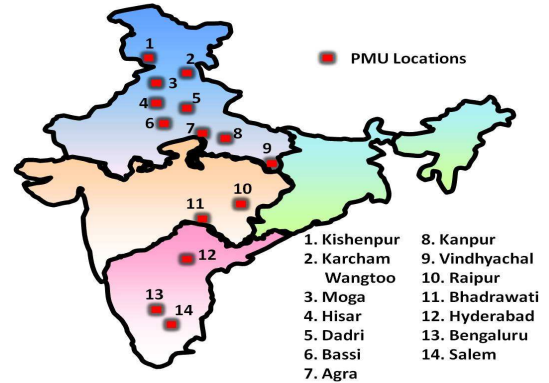


Fig. 1. Geographical locations of the PMUs on the Indian Grid

Any disturbance or a particular operating condition in the power system may lead to low frequency oscillations in the system. These may be categorized as inter-area and local modes of oscillations. Oscillations associated with a single generator or a single plant are called local modes, or plant modes with frequency ranging from 0.7 to 2 Hz. The inter-area mode of oscillations have lower frequencies ranging from 0.1 to 0.8 Hz [4]. These modes of oscillations occur between generating units closely located in one area swinging against another cluster of units located in another area. These oscillations may be contained to a great extent by effective coordinated damping control by Power System Stabilizers provided in generating units and Power Oscillation Dampers provided in FACTS devices such as TCSC and SVC

The historical 40 ms time series data available from the synchrophasors in Northern Region was analysed using signal processing tool developed in MATLAB®. The signal process-

ing techniques used were Fourier transform, S-Transform and Prony Analysis.

III. SIGNAL PROCESSING

A. Techniques

- 1) Fourier Transform (FT) is one of the most popular techniques. It is used to obtain the frequency content of a time domain signal by decomposing it into exponentials of different frequencies. However, FT cannot differentiate between stationary and non-stationary signals; therefore, the application of FT is limited to the frequency spectral analysis of the signals [5].
- 2) Short Time Fourier Transform (STFT) decomposes the original time domain signal into a set of signals belonging to different bands of frequencies by passing the signal through a set of high pass and low pass filters. A moving window is introduced in the FT equations that view the stationary portion in a non-stationary wave. This portion of the signal is multiplied to the window function and FT is performed on it to obtain the STFT of the signal. However, the simplicity of this technique has not quite proved useful for a detailed time-frequency analysis of a signal, because of the problem of resolution associated with it, i.e., one cannot know what spectral components exist at what instances of times, one can only know the time intervals in which certain band of frequencies exist [5].
- 3) Wavelet analysis is a multi-resolution analysis. It analyses the signal with different resolutions at different frequencies. This gives better time resolution and poor frequency resolution at high frequencies and poor time resolution with better frequency resolution at low frequencies. Practical signals have high frequency components lasting for a very short duration and the low frequency components persisting longer. The wavelet transform uses a window function with its width changing for every spectral component thereby giving better time and frequency resolution. However, wavelet transform is known to be sensitive to noise [5]. Therefore, another technique, the S transform, was developed in 1996 by Stockwell [6] which handles noise much better.
- 4) The S-transform gives the time frequency response (TRF) of the signal. It has frequency dependent resolution. S-transform of a signal can be directly obtained from the Fourier transform of the signal and convolving it with the Gaussian window function. A very important property of S-transform is the local phase information of the signal obtained from it, giving it an edge over wavelet analysis. It gives the amplitude-frequency-time spectrum and the phase-frequency-time spectrum both of which define the local spectral characteristics [6].
- 5) Another technique, called the Hilbert-Huang technique (HHT) is a data driven, empirical technique designed for non-stationary and non-linear signals. It is a two step process. First, the signal is decomposed into frequency bands known as intrinsic modes by a process called

empirical mode decomposition (EMD). Then, Hilbert transform is performed on them. Hilbert transform is time domain to time domain transformation, from which the analytic signal is obtained whose amplitude and phase give the true instantaneous amplitude and phase of the signal. This information is used to derive the instantaneous frequency of the signal. It also used to get the damping of the different modes presents in the signal [7].

- 6) Another transform for the identification of modal components is Prony analysis. The basic methodology of this analysis is to develop a linear prediction model for a set of data points that fits them in the best possible way. Then, the roots of the polynomial function pertaining to this model are obtained. Using these roots, by modal analysis, frequency, amplitude, phase and damping of the signal can be obtained [8]. It is well suited for ring down analysis of signals.

The following truth-table (table I) shows the various signal processing techniques and the different types of signals that they can handle.

TABLE I

Signals	FT	STFT	Wavelet analysis	S-Transform	Prony Analysis	HHT
Periodic	1	1	1	1	1	1
Non-periodic	1	1	1	1	1	1
Stationary	1	1	1	1	1	1
Non-stationary	0	1	1	1	0	1

For the purpose of this study, three technique, namely, Fourier transform, S-transform and Prony analysis, have been used for analysis of Synchrophasor data available at NRLDC.

B. Signal Processing Tool

In order to provide a common platform to access the techniques to extract information from the time series data, a GUI tool in MATLAB[®] was developed. The first step in processing the raw time series data involves removal of noise or any linear trends present in the signal. This is done by de-trending the signal. Next the desired technique is implemented. This tool was validated using a synthesized signal of known frequencies. The three techniques gave concurrent results confirming the authenticity of the tool.

IV. OSCILLATION ANALYSES: CASE STUDIES

The synchrophasors provide time series data of frequency, phase voltage and angle measured by the Phasor Measurement Units installed at various locations in the grid. The data is available at every 40 ms. A small window of this data recorded for four typical grid events was used to determine the modes of oscillation present, its amplitude and damping. A brief summary of the four cases is given in table II. The results obtained through signal processing may be seen in table III, IV and V. The screenshots of the Graphical User Interface used for signal processing of one of the cases, viz. Case 3, is placed as in fig. 2 to fig. 5.

TABLE II
DESCRIPTION OF THE CASE STUDIES

CASES	EVENT DATE	EVENT TIME	DESCRIPTION
Case-1	30th Nov 2011	22:09:34 to 22:14:40	A software crash in the digital control system at the Rihand stage-II power station caused the tripping of Unit I & II. On reloading the software, due to control system problem, low frequency oscillations were observed in the grid.
Case-2	16th July 2011	14:28:57	The tripping of one of the four lines of the Nathpa Jhakri generating station caused oscillations for 10 seconds when the power flow on the remaining three lines increased to 800 MW. The oscillations died down when one of the units of Karcham Wangtoo hydro station, connected to Nathpa Jhakri station, was tripped.
Case-3	12th Jan 2011	14:27:01	The tripping of 500kV Rihand-Dadri HVDC bipole carrying 1500 MW caused oscillations in the system. The first tripping occurred at 14:27:01.840, followed by the next tripping at 14:27:03. The tripping resulted in operation of the System Protection Scheme (SPS) intended to take care of the contingency and ensuring the security of the grid.
Case-4	12th June 2011	18:32:52	The Rihand-Dadri HVDC bipole tripped spurring oscillations.

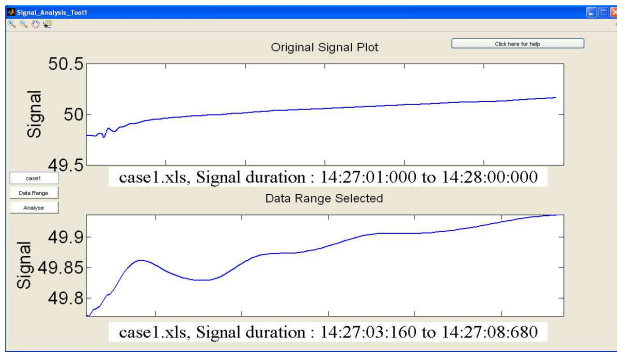


Fig. 2. Dadri frequency signal (Case 3)

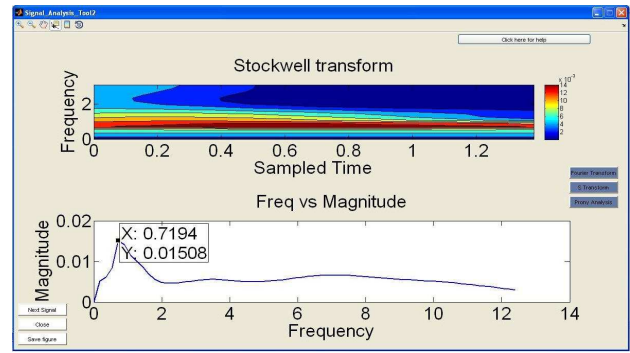


Fig. 4. Dadri frequency: S-transform results (Case 3)

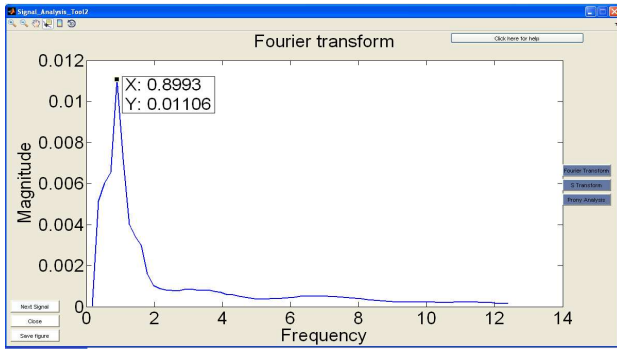


Fig. 3. Dadri frequency: Fourier transform results (Case 3)

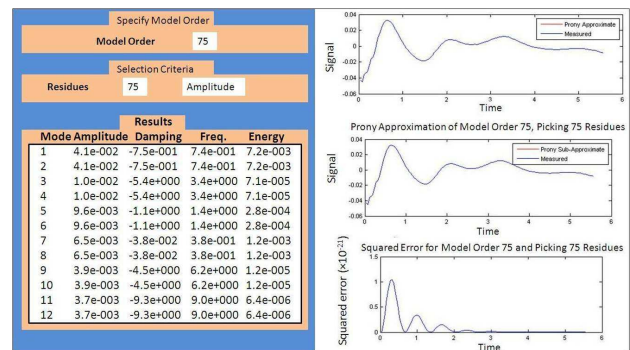


Fig. 5. Dadri frequency: Prony analysis results (Case 3)

V. OBSERVATIONS AND INFERENCES

The following observations and inferences can be made from the results displayed in Table-III, IV and V.

- Case 1: 0.38Hz, 0.43Hz and 0.76Hz are identified as the prominent modes. 0.43Hz gets damped faster than the others. 0.38Hz and 0.76Hz are inter-area modes of oscillation.
- Case 2: 0.96Hz is a dominant mode with a low damping factor. 1.1Hz and 2.2Hz are also present, but they damp out quicker than the other modes. 0.96Hz is a local mode of oscillation.
- Case 3: 0.76Hz, 0.89Hz, 1Hz, 2.4Hz and 2.5Hz have been

identified as the prominent modes. Of these, the 1Hz and 2.4Hz modes damp out quicker than the rest. 0.76Hz is an inter-area mode and 0.89Hz is a local mode of oscillation.

- Case 4: The dominant presence of 0.13Hz, 0.8Hz and 1.1Hz is seen. 0.13Hz is an inter-area mode while the other two are local modes of oscillation.

The results of the four case studies indicate that the frequency of oscillations observed were predominantly in the range of 0.7 - 1 Hz. Thus it can be inferred that in all the four cases studies inter area oscillation modes were present. It may also be seen that 0.76 Hz inter area mode of oscillation gets excited very often. Analysis of other grid events may reinforce the above

finding. Further dynamic studies are required to locate ill-tuned PSS in AVR of generating stations and for coordinating the settings of PSS for damping of these modes.

VI. SUMMARY

This paper tries to demonstrate one possible application of synchrophasor data in the power system. Several such applications may be required to facilitate effective utilization of the large scale deployment of synchrophasors in the Indian power system in near future. The inter area oscillations observed during the studies highlight the urgent need for tuning the Power System Stabilizers installed at power generating stations as mandated by the Central Electricity Authority (Technical Standards for Construction of Electrical Plants and Electric Lines) Regulation 2010 [1] and the Indian Electricity Grid Code [9]. Further, there is also a need to examine and coordinate the response from the Power Oscillation Dampers available in the FACTS devices in the Indian Grid such that the oscillations are effectively damped out.

VII. ACKNOWLEDGEMENTS

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REFERENCES

- [1] Central Electricity Authority, "CEA - Regulations," <http://www.cea.nic.in/regulations.html>, 2010, [Online; accessed on 2-Nov-2012].
- [2] "Synchrophasors: Initiative in India," Power System Operation Corporation Limited, Tech. Rep., June 2012.
- [3] V. K. Agrawal, P. Agrawal, R. K. Porwal, R. Kumar, V. Pandey, T. Muthukumar, and S. Jain, "Operational Experience of the First Synchrophasor Pilot Project in Northern India," *CBIP*, 2010.
- [4] M. Klein, G. Rogers, and P. Kundur, "A Fundamental Study of Inter-area Oscillations in Power Systems," *IEEE Power Syst.*, vol. 6, no. 3, August 1991.
- [5] R. Polikar, *The Wavelet Tutorial*, Rowan University, College of Engineering, 2006.
- [6] R. G. Stockwell, L. Mansinha, and R. P. Lowe, "Localization of the Complex Spectrum: The S Transform," *IEEE Trans. Signal Process.*, vol. 44, no. 4, April 1996.
- [7] T. J. Browne, V. Vittal, G. T. Heydt, and A. R. Messina, "A Comparative Assessment of Two Techniques for Modal Identification from Power System Measurements," *IEEE Trans. Power Syst.*, 2008.
- [8] J. Hauer, C. Demeure, and L. Scharf, "Initial Results in Prony Analysis of Power System Response Signals," *IEEE Trans. Power Syst.*, 1990.
- [9] Ministry of Power, "Indian Electricity Grid Code," <http://www.powermin.nic.in/>, [Online; accessed on 2-Nov-2012].
- [10] S. Ventosa, C. Simon, M. Schimmel, J. J. Daobeitia, and A. Mnuel, "The S Transform from a Wavelet Point of View," *IEEE Trans. Signal Process.*, vol. 56, no. 7, July 2008.
- [11] D. Ruiz-Vega, A. R. Messina, and G. Enrquez-Harper, "Analysis of Inter-area Oscillations via Non-linear Time Series Analysis Techniques," in *16th PSCC, Liege*, August 2005.
- [12] Y.-H. Wang, *The Tutorial: S-Transform*, Graduate Institute of Communication Engineering, National Taiwan University, Taipei, Taiwan, ROC.
- [13] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power Quality Analysis Using Stransform," *IEEE Trans. Power Del.*, vol. 18, no. 2, April 2003.
- [14] A. R. Messina, V. Vittal, D. Ruiz-Vega, and G. Enrquez-Harper, "Interpretation and Visualization of Wide-area PMU Measurements Using Hilbert Analysis," *IEEE Trans. Power Syst.*, vol. 21, no. 4, November 2006.
- [15] D. J. Trudnowski, J. M. Johnson, and J. F. Hauer, "Making Prony Analysis More Accurate using Multiple Signals," *IEEE Power Syst.*, vol. 14, no. 1, February 1999.
- [16] S. K. Soonee, S. Narasimhan, R. Porwal, S.Kumar, R. Kumar, and V. Pandey, "Application of phase angle measurement for real time security monitoring of Indian Electric Power System- An Experience," *CIGRE*, 2008.

TABLE III
RESULTS OF THE SIGNAL ANALYSIS FOR THE FOUR CASE STUDIES CONSIDERING VOLTAGE SIGNALS

Case	Time	Signal taken	Fourier Transform		S-Transform		Prony Analysis		
			Frequency	Amplitude	Frequency	Amplitude	Mode	Amplitude (V)	Damping
Case-1: 30th Nov 2011	22:10:59:640 to 22:10:20:080	Dadri phase voltage			0.3788Hz	150	0.38Hz	160	0.00331
			0.4329Hz	134.3			0.43Hz	180	0.099489
			0.8117Hz	92.02	0.7576Hz	104	0.76Hz	100	0.003352
			2.543Hz	10.17	2.489Hz	37.98	2.3Hz	83	0.01869
			0.1082Hz	29.06	0.05411Hz	29.06	8.4Hz	97	0.162724
Case-2: 16th July 2011	4:28:57.760 to 04:29:07.120	Hisar phase voltage	0.5319Hz	30.4			0.38Hz	270	0.270306
			1.064Hz	632.7	0.9574Hz	688.9	0.96Hz	730	0.005308
			2.021Hz	27.82			2.2Hz	1500	0.685273
							5.6Hz	470	0.059607
							9.2Hz	270	0.104997
Case-3: 12th Jan 2011	14:27:03.120 to 14:27:11.040	Dadri phase voltage	0.2513Hz	243.2	0.1256Hz	243.2	0.74Hz	2300	0.087884
					0.8794Hz	2008	0.84Hz	5300	0.120439
			1.005Hz	902.1			1.3Hz	1000	0.180709
							2.2Hz	4200	0.364033
							8.1Hz	11000	0.411994
Case-4: 12th June 2011	18:32:53.480 to 18:33:03.320	Dadri phase voltage	0.2024Hz	43.27	0.4049Hz	91.83	0.48Hz	230	0.069497
			0.6073Hz	70.04			0.55Hz	150	0.154464
					0.1012Hz	43.24	0.82Hz	480	0.075518
			0.9109Hz	118.7	1.113Hz	221.3	1Hz	700	0.146492
			1.215Hz	61.87			1.4Hz	160	0.080493
			1.518Hz	40.44			1.5Hz	110	0.099295

TABLE IV
RESULTS OF THE SIGNAL ANALYSIS FOR THE FOUR CASE STUDIES CONSIDERING FREQUENCY SIGNALS

Case	Time	Signal taken	Fourier Transform		S-Transform		Prony Analysis		
			Frequency	Amplitude	Frequency	Amplitude	Mode	Amplitude (Hz)	Damping
Case-1: 30th Nov 2011	22:09:59:560 to 22:10:20:320	Dadri frequency			0.3846Hz	0.01	0.38 Hz	0.00092	0.000163
			0.4327Hz	0.0089			0.48 Hz	0.00017	0.028849
			0.09615Hz	0.0022	0.048Hz	0.002	0.58 Hz	0.0016	0.0712
			0.8173Hz	0.0021	0.8173Hz	0.0026	0.76 Hz	0.0024	0.000251
Case-2: 16th July 2011	4:28:57.800 to 04:29:07.320	Hisar frequency	0.3138Hz	0.00108	0.2092Hz	0.001089	0.18Hz	0.0044	0.318642
			0.523Hz	0.00109	0.523Hz	0.001565	0.46Hz	0.0025	0.072503
							0.9Hz	0.0074	0.174223
			1.046Hz	0.0048	0.9414Hz	0.005385	0.96Hz	0.0069	0.008127
							1.1Hz	0.0032	0.12354
Case-3: 12th Jan 2011	14:27:03.160 to 14:27:08.680	Dadri frequency			0.7194Hz	0.1508	0.76Hz	0.0059	0.189275
			0.8993Hz	0.1106			1.1Hz	0.005	0.601405
							1.4Hz	0.0009	0.109662
							3.4Hz	0.00095	0.206223
							7.8Hz	0.00069	0.141467
							8.5Hz	0.00059	0.21933
Case-4: 12th June 2011	18:32:53.240 to 18:33:01.280	Dadri frequency			0.1238Hz	0.002712	0.13Hz	0.0022	-0.0526
					0.495Hz	0.002612	0.45Hz	0.0051	0.056527
			1.114Hz	0.001195	1.238Hz	0.003991	1Hz	0.0085	0.14495
			0.2475Hz	0.002712			1.5Hz	0.0014	0.054061
			0.6188Hz	0.00214			3Hz	0.016	0.62287
							5.7Hz	0.0034	0.149167

TABLE V
RESULTS OF THE SIGNAL ANALYSIS FOR THE FOUR CASE STUDIES CONSIDERING THE MW FLOW SIGNALS

Case	Time	Signal taken	Fourier Transform		S-Transform		Prony Analysis		
			Frequency	Amplitude	Frequency	Amplitude	Mode	Amplitude (MW)	Damping
Case-2: 16th July 2011	4:28:57.600 to 04:29:07.760	Hisar Bawana flow	0.5882Hz	0.3157	0.4902Hz	0.4304	0.28Hz	0.67	0.179043
							0.72Hz	0.64	0.101211
			1.078Hz	1.804	0.9804Hz	2.075	0.96Hz	2.2	0.004478
							1.2Hz	1.6	0.127662
							2.7Hz	0.6	0.196605
							5.9Hz	1.4	0.037758
							13Hz	7.8	0.324419
Case-3: 12th Jan 2011	14:27:04.240 to 14:27:09.040	Dadri HVDC-Dadri NTPC flow	1.446Hz	0.2381			1.8Hz	2.5	0.11425
			2.273Hz	0.5299			2.4Hz	13	0.188944
			2.686Hz	2.877	2.473Hz	3.259	2.5Hz	2.7	-0.00338
			4.959Hz	0.4737			3.2Hz	2.7	0.038288
							3.9Hz	1	0.01633
			8.678Hz	1.012			9.6Hz	1.3	0.029843

TABLE VI
RESULTS OF THE SIGNAL ANALYSIS FOR THE FOUR CASE STUDIES CONSIDERING THE ANGLE SIGNALS

Case	Time	Signal taken	Fourier Transform		S-Transform		Prony Analysis		
			Frequency	Amplitude	Frequency	Amplitude	Mode	Amplitude (deg)	Damping
Case-3: 12th Jan 2011	14:27:03.120 to 14:27:12.120	Dadri-Vindhyachal angle	0.2212Hz	0.4653	0.1106Hz	0.4653	0.35Hz	4.3	0.588522
			0.4425Hz	0.4473			0.69Hz	6.7	0.143876
			0.7743Hz	1.091	0.885Hz	2.768	0.86Hz	2.4	0.068348
			0.9956Hz	1.106			5.4Hz	1.4	0.240434
							11Hz	0.47	0.171149
Case-4: 12th June 2011	18:32:52.840 to 18:32:59.600	Dadri-Vindhyachal angle	0.5882Hz	0.3134			0.47Hz	0.18	0.040622
			0.8824Hz	0.5615			0.81Hz	1.6	0.086177
			1.176Hz	0.5335	1.029Hz	1.207	1Hz	2.8	0.129474
							1.8Hz	0.31	0.207685
							4.2Hz	0.22	0.171808
							8.3Hz	8.7	0.418236