A comparative analysis of Modal analysis techniques A Case study for Western Region of India

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Abstract—**With growing complexity of power systems including Indian power grid small signal stability problems are experienced in the form of in low frequency oscillations. The low frequency oscillations are mainly due to stress in the system and are triggered even during small changes in power system operating state. These low frequency may disrupt the system operations and hence need to be monitored. Since the deployment of phasor measurement units (PMUs) in the Indian grid its data has been of great help to identify such oscillations present in the system for further control actions. This paper deals with the analysis of PMU data for detection & analysis of low frequency oscillations using FFT, matrix pencil and wavelet transform. The three methods are compared with respect to modal frequency, damping & amplitude for various time durations. The simulation has been carried out in MATLAB using PMU data available at Western Region Load Despatch Centre.**

Keywords— PMU, low frequency oscillations, FFT, Matrix Pencil, wavelet transform,

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 to as N-E-W grid while the SR grid is asynchronously connected to the N-E-W grid through HVDC links.

The operation & control of such complex network is carried out by the hierarchy of load control centres with National load dispatch center (NLDC) at the top of the hierarchy, followed by five regional load despatch centres (RLDCs), thirty three state load despatch centres (SLDCs) and area load despatch centres (ALDCs) . Indian grid has recently installed PMUs at various locations as shown below in Fig. 1. [2]

PMUs are the devices which provide the time synchronised measurements of voltage and current phasors along with frequency, rate of change of frequency (ROCOF). These measurements are utilised for power system operation and control in real time & for analysis of events in post-despatch scenario [3].

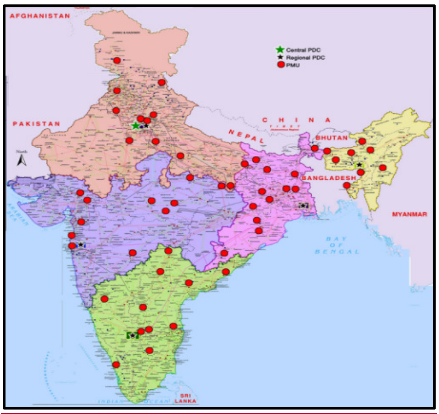

Fig. 1: Geographical locations oh PMU in Indian grid

Small signal disturbances during power system operation which may occur due to several reasons may affect the synchronism of power system. The ability of power system to maintain synchronism due to such disturbances is called small signal stability. During these small 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 & damping torque component. Low frequency oscillations are due to reduced damping torque [4]. These oscillations are categorised as inter-area & local modes of oscillations. Local modes of oscillations are associated with single generator or plant with frequency ranging from 0.7 Hz to 2 Hz. Inter-area modes are the oscillations associated with the groups of generators or plants with frequency ranging from 0.1 Hz to 0.8 Hz [5] . If these oscillations are not properly damped, they can increase in magnitude & may lead to instability and are therefore an object of study by various researchers.

There exist two techniques for estimating the modal content of the power system: model based techniques & measurement based techniques [6]. In the model based technique the nonlinear differential equations governing the system are linearized about an operating point & further the modes are obtained via Eigen value analysis, whereas in measurement based techniques direct measurements from PMU estimate the linear model. Some of the popular measurement based techniques for estimating modes are Prony analysis [7, 8], Matrix Pencil [9], Hilbert transform [10], wavelet transform [11, 12].

This paper presents a case study wherein the PMU data has been obtained from Western Regional Load Dispatch Centre (WRLDC) who is the system operator for Western region of India, a grid map of western region is available at [13]. In this case study the data has been analysed and compared using FFT, Matrix Pencil method and wavelet transformation technique. Section II introduces the techniques for identification of analysis of low frequency oscillations in power system, section III discusses the case study, section IV discusses and compares the simulation results and section V concludes the paper.

II. Brief of Techniques

(a) Fourier transformation technique:

Fourier transform is one of the most popular techniques used to obtain the frequency content of the time domain signal by decomposing it into exponentials of different frequencies [14]

Steps of FFT analysis are summarized as:

1) The FFT operates by decomposing an N point time domain signal into N time domain signals each composed of a single point.

2) The second step is to calculate the N frequency spectra corresponding to these N time domain signals.

3) Lastly, the N spectra are synthesized into a single frequency spectrum.

Extraction of valid frequency information should follow Shannon's sampling theorem.

(b) 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 developed. It directly estimates the parameters for the exponential terms in eq. 1 to an observed measurement [15, 16].

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

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

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

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 $[\Sigma]$ 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.

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

(c) Wavelet transformation technique

The basic idea of the wavelet transform is to represent any arbitrary function *x*(t) as a superposition of a set of basis functions. These basis functions are obtained from a single prototype wavelet called the mother wavelet, by dilations or contractions (scaling) and translations (shifts). Due to this, the wavelet-transform gives flexibility of analysis in both (space) time & frequency domain.

Mathematically, the continuous wavelet transform (CWT) of a continuous time signal *x*(t) is expressed by the following inner product in the Hilbert space [11],

$$\mathrm{CWT}\{x(t)\} = W_x(\tau, s) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(t)\, \Psi\left(\frac{t-\tau}{s}\right) dt \qquad (7)$$

$$\tau, s \in R^+$$

$$\Psi_{\tau,s}(t) = \frac{1}{\sqrt{s}} \Psi\left(\frac{t-\tau}{s}\right), \qquad (8)$$

$$\tau, s \in R^+$$

Where, ψ = Mother wavelet function,

s =Scaling (dilation or contraction),

τ = Translations (shifts).

For the power system modal identification using wavelet analysis complex morlet wavelet is used [17].

The approach of wavelet transform is windowing technique with variable size windows. Localized transform in both space (time) and frequency extracts information from a signal that is not possible with a Fourier or even windowed Fourier transform.

Evaluation of damping ratio:

A particular mode decreases exponentially, having magnitude variation in ΔdB in the time interval Δb, thus its damping ratio evaluated using following relationship [18]:

$$\alpha = -\frac{\Delta bB.\log_n 10}{20.\Delta b} \qquad (9)$$

By performing a wavelet transform on the original signal using a dilated scale the low-frequency signals that precedes a power failure are extracted. The Identification of electromechanical low-frequency oscillation of the event in both time & frequency domain is vital for which wavelet-transform is adapted.

III. Case Study

This section analyses the case study taken up with the methods described in section II. A case study of an event -blocking of Badrawati pole 2 (500 MW) on16th August 2012 is taken up to study the effect on the modes of the system. The data of the PMU at Badrawati during the event is available for analysis. The plot of Raipur-Badrawati circuit 2 active power (MW) across time available from the PMU data is shown in Fig 2. The PMU plot clearly shows the drop in power by 40MW at the time of the event recorded.

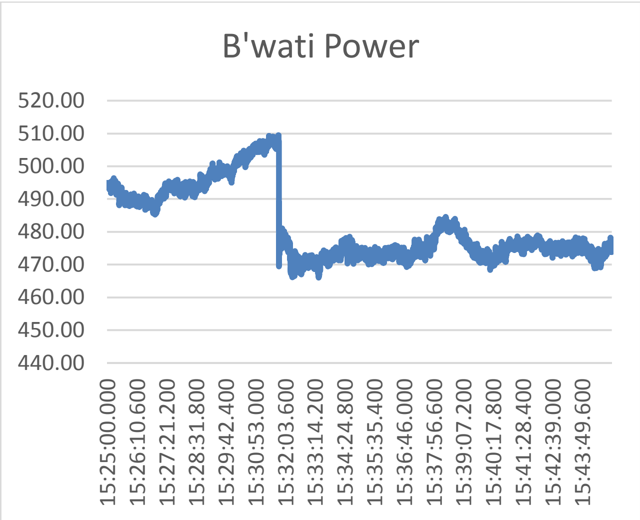

Fig. 2: PMU plot for Badrawati power

In order to study in detail the modes present in the system during this event we analyse this signal using FFT, matrix pencil and wavelet transformation technique in MATLAB platform. For analysis using wavelet the basis function (mother wavelet) chosen was complex morlet wavelet. We divide the signal into 3 durations for the purpose of clear understanding of the behaviour of modes.

Table I: time durations for analysing signal

Duration 1	15:31:29.080 to 15:31:47.880	18.8 secs
Duration 2	15:31:49.920 to 15:32:08.920	59 secs
Duration 3	15:32:26.440 to 15:32:34.440	8 secs

The signal is analyzed for three time durations, to include pre-switching, switching & post switching as shown above. The screenshots of the graphical output of the original signal & the approximated signal using the techniques for duration 3 are placed in Fig. 3 to Fig. 5.

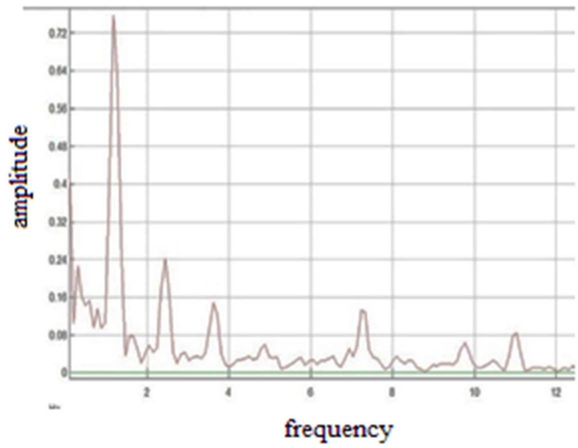

Fig. 3: FFT of Badrawati power for duration 3

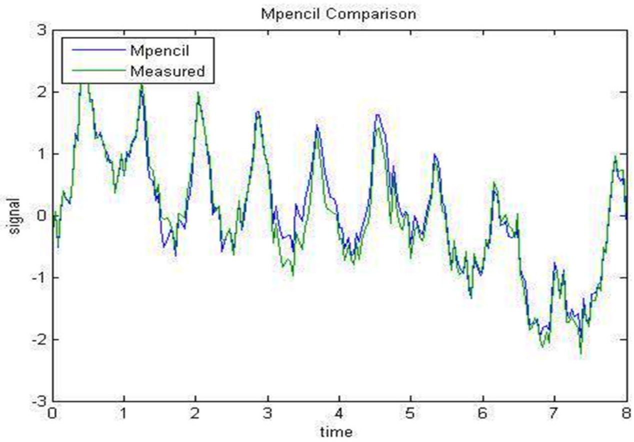

Fig. 4: Matrix pencil approximation of Badrawati power for duration 3

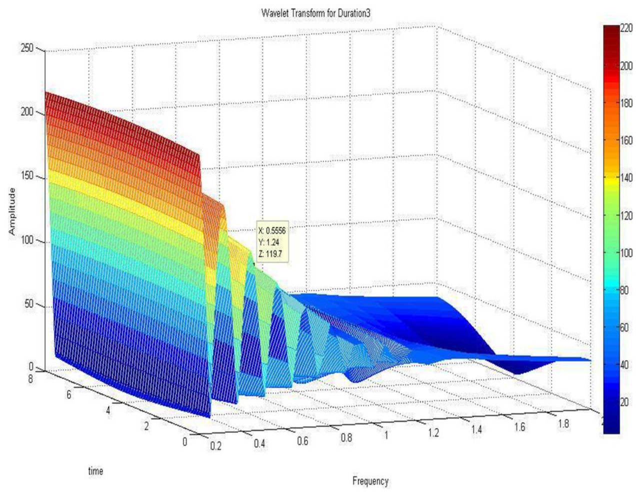

Fig. 5: wavelet transform of Badrawati power for duration 3

IV. RESULTS AND DISCUSSION

The results of the analysis using FFT, Matrix Pencil and Wavelet transformation technique are tabulated in Table II for comparison. The estimated frequencies using FFT, Matrix Pencil and wavelet give close values for the respective modes, e.g.: row 1 indicates 0.34Hz using FFT, 0.33Hz using Matrix Pencil & 0.33Hz using wavelet transform. The damping ratio could be computed only with Matrix Pencil & wavelet transform. Computation of damping is very important because modes with negative damping indicate the security concern of the system and may lead to oscillatory stability problems. The table II indicates that in duration 1, modes with frequencies of 0.46 Hz, 0.97 Hz, 1.13 Hz & 1.4 Hz have negative damping coefficient & 0.33 Hz mode has highest magnitude but sufficient positive damping using Matrix pencil as well as wavelet transformation technique. During duration 2, 1.1 Hz and 1.5 Hz modes were identified with least damping. For third duration 0.6Hz, 1.6Hz & 2.7 Hz modes were identified having negative damping using matrix pencil method whereas using wavelet only 0.6 Hz mode was found to have negative damping coefficient & 1.6Hz & 2.7 Hz with almost zero damping. Local plant mode with frequency 1.1 Hz was observed in all durations, this mode had adequate damping in duration 1, later in the second duration this mode had negative damping coefficient, but in third duration again this mode was observed with adequate damping coefficient. The 1 Hz & 1.5 Hz mode is observed in all durations with very low damping. The modes observed with least damping and higher magnitude are 0.46Hz in duration 1, 1.14Hz in duration 2 and 0.6 Hz in duration 3, correctly identified by matrix pencil & wavelet analysis. The amplitudes obtained using matrix pencil and wavelet transform vary because of normalization used in matrix pencil method.

Table II: Comparison of FFT, Matrix pencil, Wavelet transform techniques

Duration	FFT		Matrix pencil			Wavelet		
	Frequency	Amplitude	Frequency	Damping	Amplitude	Frequency	Damping	Amplitude
Duration 1	0.34	0.57869	0.33	0.24	5.06089	0.33	0.36	77.48
	0.48	0.27358	0.46	-0.027	0.04858	0.47	-0.036	55.8
	0.97	0.05656	0.97	-0.013	0.01823	0.95	-0.011	41.29
	1.12	0.07165	1.13	-0.0058	0.02757	1.11	-0.025	50.69
	1.36	0.15084	1.4	-0.0069	0.0254	1.33	-0.071	45.83
Duration 2	0.195	0.57355	0.24	0.29	2.73059	0.2	0.041	46.75
	1.07	0.77445	1.14	-0.0068	0.1173	1.17	0.0015	35.01
	1.5	0.08698	1.5	0.00057	0.04611	1.53	0.0302	32.79
Duration 3	1.17	0.75588	1.15	0.12	1.07722	1.12	0.022	56.4
	0.58	0.15228	0.69	-0.037	0.05852	0.55	-0.015	119.7
	1.6	0.07892	1.6	-0.019	0.02107	1.6	0.035	41.65
	2.4	0.24192	2.7	-0.015	0.00845	2.5	0.012	27.53

V. CONCLUSION

Low frequency oscillations (LFOs) are inherent to interconnected power systems. These oscillations need to be adequately damped 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 FFT, Matrix pencil & wavelet transformation technique for identification of LFOs. The results obtained from FFT are compared with matrix pencil & wavelet transform for the case study. Matrix pencil and wavelet transform techniques are advantageous as compared to FFT because later does not provide the information on damping. Wavelet-transform has added advantage over matrix pencil that is it provides information of the low frequency oscillation in both time & frequency domain.

Those oscillations observed in the studies with negative damping need to be addressed with corrective actions to relieve the stress in the system. Some of the devices provided in power system to counteract negative damping are PSS provided in excitation system of generator & controls of FACTS devices. The real time actions by system operation include generation despatch, load shedding, circuit switching to relieve stress in the system. The actions can be initiated if both matrix pencil & wavelet indicate damping ratio less than 5%.

Other techniques for identification of modes like Hilbert transform, Prony analysis etc. have already been developed and used at WRLDC. All these methods (matrix pencil, prony analysis, wavelet transform, Hilbert transform) can work online on one platform to detect the oscillations i.e. if a particular mode is detected having low damping coefficient and higher amplitude using atleast three methods an alarm signal can be provided to the operator to take control actions.

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