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Two-Machine Stability Analysis and Inter-Area Oscillation Detection using Simulink Model of Phasor Measurement Unit

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Abstract: This paper presents the application of the Simulink model of Phasor Measurement Unit (PMU) based on algorithm from C37.118.1 for stability analysis and detection of inter-area oscillations using spectral measurement techniques in time, frequency and time-frequency domains. Also Prony analysis is applied for identification of oscillation properties i.e. mode frequency, mode damping, and mode shape. Since the stability problem of inter-area power oscillation may cause major system break-up and black-out if not detected and appropriate actions are not taken in time. Hence inter-area power oscillation stability is a determining factor in the power system design and operation. These analysis techniques will result in better monitoring, identification and helps to take prevention measures to avoid undesirable condition in the power system operation.

Keywords: Phasor Measurement Unit, stability, inter-area oscillation, Prony Analysis, Multi-Resolution Analysis, Matlab, Simulink.

I. INTRODUCTION

Synchronous phasor measurements are gaining importance in modern data acquisition technique in which Global Positioning System (GPS) time synchronized signals namely voltage (magnitude & phase), current(magnitude & phase), frequency obtained at different nodes/buses of the power system through PMUs. These signals are concatenated through Phasor Data Concatenators (PDCs) and transmitted through communication network to central monitoring/control station (EMS). This data can be monitored in real time and also stored in the data server for post disturbance analysis when required. Currently real time applications for early warning system using PMUs data for anamolies in the power system are in research and development phase. [1]

Phadke introduced the Modern synchronized phasor measurement technology in his article [2]. He presented a few uses of positive sequence voltage and current phasor measurements. First prototype of PMU based on GPS was developed by the Virginia Polytechnic Institute and State University (Virginia Tech) in the USA in early 1980s. However, modern GPS PMU technology is based on IEEE standard published in 2005.

More refined standards for estimation of positive sequence voltage magnitude, phase, frequency and rate of rise of frequency were published later as IEEE C37.118.1[3] and IEEE C37.118.2 (Data Transfer)[4]. More strict requirements were laid down to achieve required response to dynamic events and measure the harmonic contents of the signals. Furthermore an estimation algorithm basing on the above standards and testing was made under the EMRP EURAMET programme [5].

As a summary, PMUs through wide area monitoring provides the GPS time stamped high resolution data for state estimation, detection of system inter-area oscillations, voltage stability which was impossible with existing metering infrastructure e.g. SCADAs. Further it can facilitate load modeling and analysis tasks, and assist in system restoration and post disturbance analysis.

Remaining paper is organized as per following sections:

- Section II gives brief overview about PMU, its mathematical background & sample case simulation results.
- In Section III theoretical background of small signal stability & inter-area oscillation are discussed.
- Section IV gives signal processing techniques and their mathematical background.
- Section V presents the simulation environment.
- In Section VI objective and analysis are discussed in detail.
- In last in Section VII conclusion and future recommendations are presented.

II. PHASOR MEASUREMENT UNIT

A. Phasors

Consider a sinusoidal signal:

$$x(t) = X_m \cos(\omega t + \varphi), \quad (1)$$

Where, X_m is the amplitude, ω is the frequency (radians per second), and φ is phase angle (radians) of the signal $x(t)$. In phasors quantities we are generally interested in the root mean square (RMS) value of the input signal i.e. $(X_m/\sqrt{2})$. It is particularly useful in calculating active and reactive power in an AC circuit.

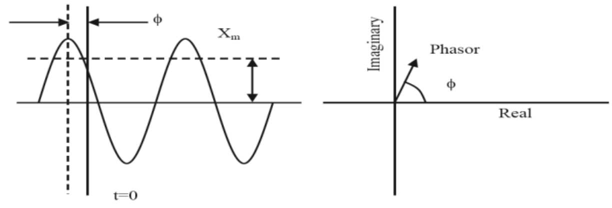
Eq. 1 in exponential form can be given as follows:

$$x(t) = Re\{X_m e^{j(\omega t+\varphi)}\} = Re[\{e^{j(\omega t)}\}X_m e^{j(\varphi)}] \quad (2)$$

It is understood for electrical signals that frequency is ω so it is customary to ignore the term $e^{j(\omega t)}$ in the above Eq. 2. The sinusoidal signal given in Eq. 1 in corresponding phasor representation is given as:

$$x(t) \leftrightarrow X = (X_m/\sqrt{2})e^{j(\varphi)} = (X_m/\sqrt{2})[cos\varphi + jsin\varphi] \quad (3)$$

Visual depiction of sinusoidal signal and its corresponding phasor form is shown in Figure 1.



(a) (b)

Fig.1 (a) A sinusoidal signal (b) and its corresponding phasor form

B. Block Diagram of the C37.118.1 algorithm

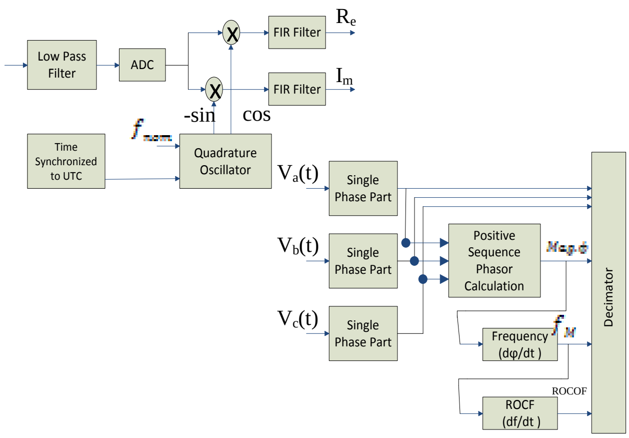


Fig. 2 Block diagram of algorithm C37.118.1

Where f_{nom} is the nominal frequency (50 or 60 Hz), $Mag.\Phi$ is the positive sequence phase, f_M is the measured frequency and ROCOF if the rate of change of measured frequency (f_M).

C. Matlab Simulink Model

Normally phenomenon of inter area oscillations are studied using the data collected from the PMUs installed in the field or some studies utilized just the phasor simulation environment to get the phase and magnitude of the analyzed quantities. But this paper provides the pioneer approach to utilize the PMU's data measured by the Matlab PMUs model as shown in Figure 3. Hence, virtual analysis can be carried out considering different scenarios which is impossible in the real time system operation.

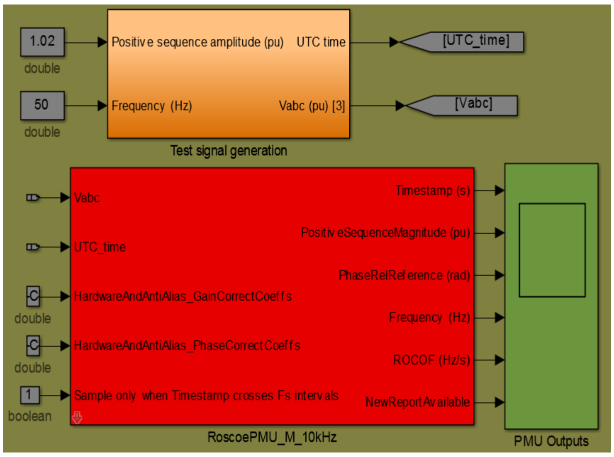


Fig.3 PMUs model in MATLAB simulink by Andrew Roscoe [6]

D. Results for the sample case

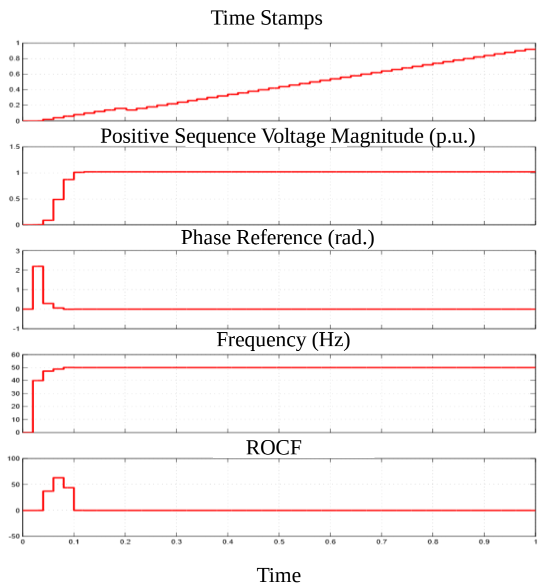


Fig. 4 Output results of PMU. Here the applied sample signal parameters are Voltage magnitude: 1 p.u., frequency: 50 Hz

III. SMALL SIGNAL STABILITY AND INTER-AREA OSCILLATIONS

Electromechanical oscillations have been a topic of interest for researchers since many years. Characteristic features of these oscillations can be obtained in time domain as phase & amplitude and in frequency domain as modal frequency and damping. These oscillations, along with causing instability, also limit the capacity of transmitted power due to insufficient damping because of remote generation setups. Generally power system stabilizers are used to counter the condition of insufficient damping. Power system stabilizers controls generator output by changing the set point of the voltage regulator. Traditionally, this close loop feedback control is based on the locally measured signals such shaft rotational speed, real power output and frequency.

Nowadays, performance of these power system stabilizers can be enhanced using the remotely available accurately time stamped information provided by PMUs e.g. voltage magnitude, voltage phase angle, frequency. This synchronized measured data is generally characterized in appropriate time frame as per requirement of damping control. Hence, it provides a flexible environment in which data can be measured at any desired point/node in the power system and communicated to the several control stations for different objective such as energy management, damping control, isolation of different regions in case of instability and much more.

In WAMS reliable detection and monitoring of power system oscillations is one of the most critical application. So that a valuable information of increasing oscillations and instability be provided to the system operators and detection algorithms. So that operator is alerted to observe and monitor the synchronized phasor measurements to find the root cause of instability by comparing the data and events occurred during the same time instants. Also corrective actions can be taken to safe guard the further instability [7, 8].

Extraction of features of inter-area oscillations using signal processing techniques is more convenient than the conventional model analysis method using eigenvalues analysis for a specific system configuration [7]. Although one such application based on model based approach has been developed for WAMS. Through this approach optimal model parameters were identified by applying autoregressive model and Kalman Filtering techniques using data measured from carefully allocated PMUs [8]. Traditionally model analysis is used for detection of modes of the oscillations [9]. With the current encouraging deployment trend of PMUs, oscillations can be measured in real time due to high resolution measured data. Post disturbance analysis along with the estimation of system qualitative parameters such as eigenvalues as described by Liu and Venkatasubramanian can be measured. [10].

IV. SIGNAL PROCESSING TECHNIQUES & THEIR MATHEMATICAL BACKGROUNDS

A. Short Time Fourier Transforms

J. Fourier, French mathematician, expressed periodic function as an infinite sum of periodic sines and cosines functions. Later his studies were generalized to non-periodic continuous time signals (Fourier Transform) and non-periodic discrete time signals (Discrete Fourier Transform). These generalizations made possible for adaptation of this powerful mathematical interpretation in computers. Due to large computational requirements, DFT was not widely utilized in computer applications. Later more efficient algorithm, known as Cooley Tukey algorithm, was introduced in 1965 which became more popular in computer related applications [11].

However, above techniques cannot capture the non-stationary changes within the signals. Later this limitation was removed by applying FT on small data sets by sliding the window function over the time axis. This technique was known as short time Fourier Transform (STFT) and was first introduced by Dennis Gabor. [12]

General expression for the STFT is given as follows:

$$\hat{f}_w(\omega,t) = \int_{-\infty}^{+\infty} f(u)\overline{\omega(u-t)}e^{-j\omega u}\,du \qquad (4)$$

,

In Eq. 4, the bar is the sign of complex conjugation on the window function $\omega(u-t)$. One drawback here is that window length is fixed resulting in fixed time-frequency resolution all the time.

B. Wavelet Transform

Wavelet Transform (WT), being an alternate to STFT, solves resolution related discrepancies by introduction of scaling parameter which gives variable resolution. However, the time and frequency cannot be measured accurately at a given time instant. There is always been a tradeoff between these two values. In other words, it is impossible to calculate the exact spectral component at any given instant of time. At best in a given time interval we can find out the corresponding spectral components. Consider a family of functions: $g_{(a,t)}(u) = \frac{1}{\sqrt{a}} g(\frac{u-t}{a})$. Here we have two parameters to alter. The shifting parameter "t" achieves the sliding feature while parameter "a" alters the width of the window function e.g. shrinking (a < 1) or dilating (a > 1). General expression for WT is given as:

$$L_g f(a,t) = \int_{-\infty}^{+\infty} f(u)\overline{g_{(a,t)}(u)}\,du \qquad (5)$$

C. Prony Analysis (Prony’s Method)

Originally the Prony analysis (PA), while studying the expansion of various gases, was developed by Gaspard Riche, Baron de Prony in 1795. But practical applications based on this technique were possible after the advent of digital computers [13]. In his original work, Prony proposed fitting a sum of exponentials to equally spaced data points and extended the model to interpolate at intermediate points. PA is a parametric method which computes amplitude, phase, frequency and damping coefficients of the signal segments. Also PA can be considered as system identification method. Nowadays, PA is widely used in power system for detection of electromechanical oscillation, biomedical applications, speech signal processing etc.

For a mathematical expression of PA, consider $y(t)$ a signal consisting of N evenly spaced samples. PA gives the function $\hat{y}(t)$ by directly estimating the parameters by fitting a sum of complex damped sinusoids to equally spaced data points in time, as given below:

$$\hat{y}(t) = \sum_{i=1}^{L} A_i e^{(\sigma_i t)} \cos(2\pi f_i t + \emptyset_i) \qquad (6)$$

Where, A_i is amplitude, σ_i is damping coefficient, $\emptyset_i$ is phase and f_i is frequency of component i, respectively. And, L provides the total number of damped exponential components.

V. SIMULATION ENVIRONMENT

Two machines model is considered for the analysis as show in Figure 5.

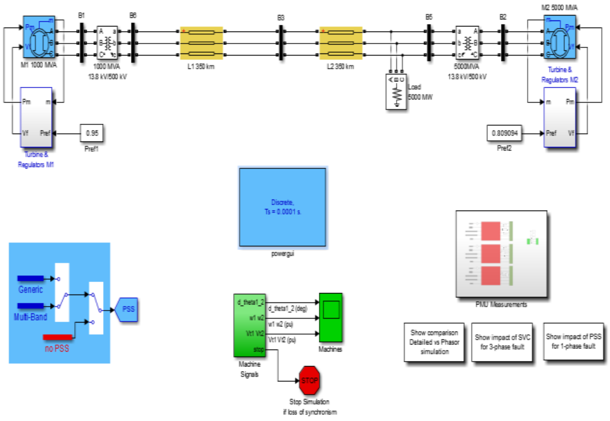


Fig.5 Two machines model in Matlab Simulink

VI. OBJECTIVES AND ANALYSIS

Machines stability analysis was carried out using outputs obtained through the Simulink-PMU model installed at the respective buses of machines. Events and their features extractions were analyzed using the spectral measuring techniques in time, frequency and time-frequency domains e.g. Short Time Fourier Transform, Continuous Wavelet Transforms etc. Furthermore Prony analysis was applied on the acquired signals for identification of oscillation properties i.e. mode frequency, mode damping, and mode shape. Scenarios were created by applying faults, load changes while keeping power system stabilizer (PSS) on different setting. And impacts of all scenarios were investigated using the foresaid analysis techniques.

A. De-noising and filteration of the Signal

As signal obtained from the output of the Simulink PMU model generates a noisy signal due to dynamic behavior during the transient conditions. Also we are interested in extraction of low frequency signals (generally inter-area oscillations lies within the range of 0.2 to 1 Hz). To achieve both objectives of de-noising and filteration, Mallet Algorithm [14] based on Multi-resolution Analysis (MRA) is used.

Schematic layout of MRA showing the low- and high-frequency decomposition is given as follows:

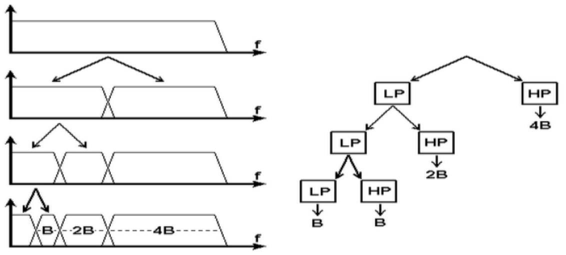


Fig.6 Spliting of signal spectrum using MRA. Here, LP: Low Pass Filter, HP: High Pass Filter & B: Bandwidth

An example for de-noising and filtering of the given signal to obtain the detail coefficient taken from one of the simulation scenarios (based on load variation) obtained at the decomposition level j=9 is given in Figure 7:

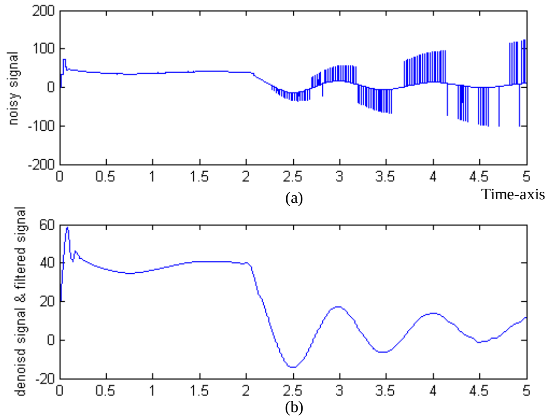


Fig.7 De-noising and filtration of signal (a): Noisy signal, (b): Filtered Signal

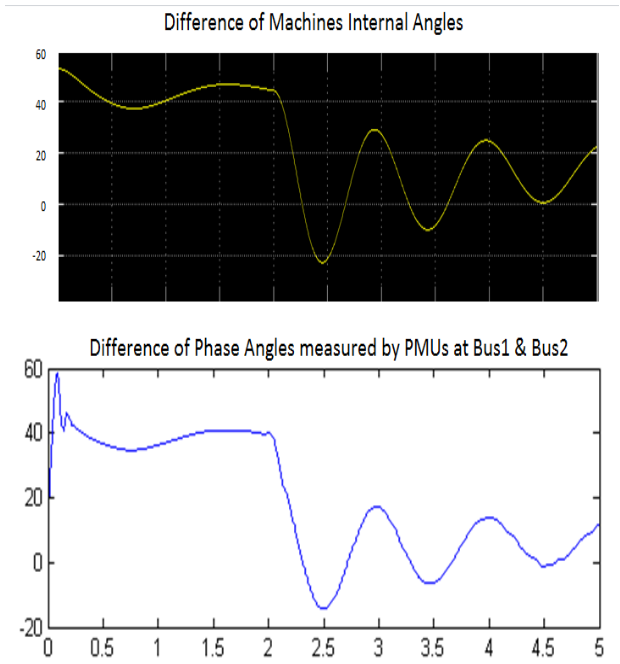
B. Simulation Scenarios

Simulations were carried out based on the different modes of the power system stabilizer (PSS) setting, faults and load changes. And impacts of all scenarios were investigated using the foresaid signal analysis techniques. However, for the matter of conciseness and limitation of space following two scenarios are given in detail with results and graphs:

- Scenario I: Based on load variation having PSS set at "Generic Mode"
- Scenario II: Based on 2-phase fault having "No PSS"

(1) Scenario I: Based on load variation having PSS set at "Generic Mode"

Complete static load of 500MW was disconnected suddenly at 2 sec while keeping power system stabilizer (PSS) in the "Generic" position. PSS successfully damped the oscillations and machines connected to Bus-1&2 remained in their stability limits as shown in Figure 8. An important phenomenon observed was that the angle-difference measured by PMU block installed at Bus-1&2 is almost same as the difference of internal angle of machines connected to the Bus1&2 respectively, which is shown below:



(b)

Fig.8 Comparison of measured angle difference of (a): Machines internal agnles connected to Bus-1&2, (b) PMUs installed at Bus-1&2

Hence, PMU installed at Machine-connected buses gives an insight into the angle stability of the machines because rotor angle inherently captures the nonlinear and non-stationary dynamics of the system and can be used to determine linear and nonlinear attributes of system oscillations. This provides a basis for online stability analysis of the machine connected to the respective bus which was impossible in previous SCADA system because of low resolution.

Prony analysis using Prony-Toolbox [15] is applied on different segments (based on time) of the de-noised and filtered signal of angle difference measured by PMU block installed at Bus-1&2. And it is observed that inter-area oscillation (0.2-1 Hz) modes are successfully damped by the PSS. Also local modes (generally in the range 1-2 Hz) i.e. at 1.1 Hz are observed b/w time 2-5 seconds were also damped out. Results are given in following Table I:

Table 1 Prony Analysis of scenario I

Time Segment (Sec)	Results				
	Mode	Amplitude	Damp -ing	Frequency	Energy
1.5– 1.9	1	82	-0.31	0	5.7x106
	2	0.004	-91	0	2.3x10-4
	3	0.0032	-2.2	0	4.7x10-3
2 – 2.5	1	49	-4	1.1	7.2x105
	2	49	-4	1.1	7.2x105
	3	0.0064	-130	0	4.2x10-4
3.9– 4.4	1	26	-4.6	0	1.8x105
	2	0.085	-100	0	9.0x10-2
	3	0.019	-4.6	0.51	9.0x10-2

Short time Fourier Transform of the same is given as following Figure 9:

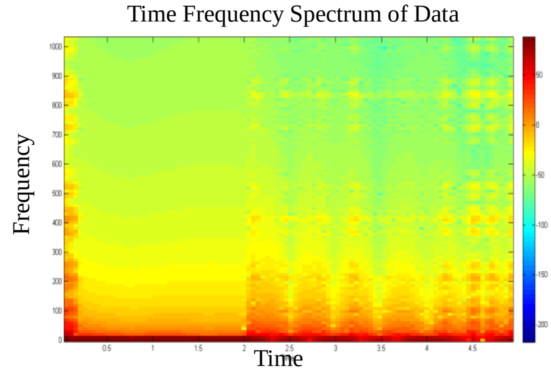


Fig.9 STFT of the analysed signal

Zoomed view of STFT of the above figure highlighting the low frequencies components is given as following Figure 10:

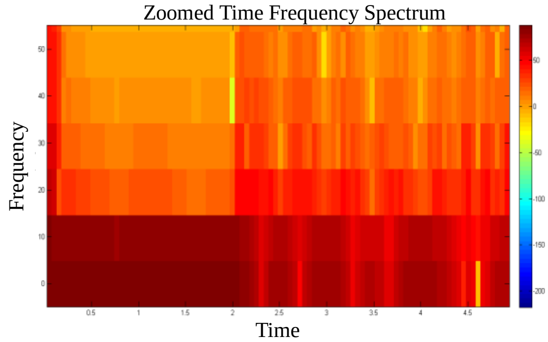


Fig.10 Zoomed STFT of the analyzed signal

Also the continuous wavelet transform the same signal highlighting more features is given in Figure 11. It gives more insight by highlighting the low frequency components which can be clearly seen during different time intervals after 2 sec when disturbance was applied. Low frequency components can easily be seen at high scale values with their intensity basing on color (e.g. blue color as highest intensity while red color is showing lowest intensity). Also it can be observed that low frequency components present at time interval 2 sec to 2.5 are successfully damped by the PSS. Hence, it provides a visual add for the operators to observe low frequency components and their intensities during given interval and can take appropriate action.

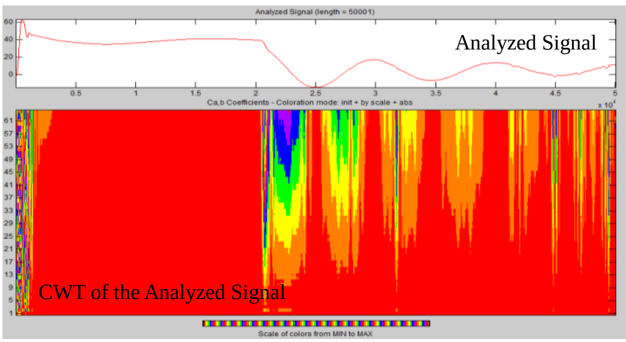


Fig.11 Continuous Wavelet Transform of the analysed signal

(2) Scenario II: Based on 2-Phase Fault "Without PSS"

Two phase fault was generated at the output of the Transformer (1000MVA) output bus (Bus-6) at 2 sec while keeping power system stabilizer (PSS) at the "No PSS" position. Angle stability of the machines was not achieved as angle difference is getting larger and larger. Output signal of the angle difference measured by the PMUs installed at Bus-1&2 is shown in Figure 12.

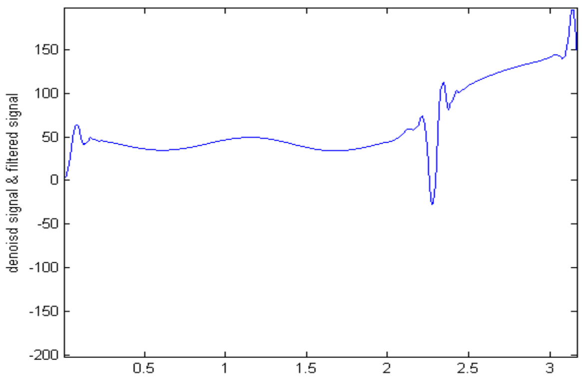


Fig.12 Angle difference measured from PMUs installed at Bus-1&2.

Prony analysis results showed the presence of the dominant inter-area oscillation mode at 0.29 Hz having the largest energy in the signal (as shown in Table II) before the fault and the same resulted in the instability of the machines when 2-phase fault was applied at time 2 seconds for next 12 cycles during the simulation. Results of the same are given in Table II.

Table II Prony Analysis of scenario II

Time Segment (Sec)	Results				
	Mode	Amplitude	Damp -ing	Freque- ncy	Energy
0.9 – 1.4	1 2 3 4	79 0.047 0.015 0.000056	+0.46 -88 +0.46 -1800	0.29 0 0.29 320	1.2x107 3.1x10-2 4.3x10-1 2.6x10-9

VII. CONCLUSION AND FUTURE RECOMMENDATIONS:

During this study a simulation environment based on Simulink model of PMU was built and successfully feature extraction of the signals was achieved. This provides a virtual environment to test and analyze the power system using measurement based system from the retrieved information of PMUs. Observation of the similar behavior of the difference of internal angle of machines and difference of angle measured from the PMU connected to the relevant buses was quite interesting as it provided the basis to extract useful information.

In future these analyzed results can be made basis to categorize these signals e.g. into steady-state (normal operation) and transient (in case of disturbances) conditions. Furthermore, features can be extracted from the categorized signal which can be used in machine learning algorithms so that online automatic detection of these scenarios can be achieved. Utilization of this information in damping control can be an effective method of improving the performance of the power system, particularly for inter-area oscillations i.e. by using the PMU to identify frequency oscillations and initiate damping activities. And when inter-area oscillations are unstable, the interconnected network can be broken up, potentially leading to islanding.

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