

Identifications and Monitoring of Power System Dynamics Based on the PMUs and Wavelet Technique

Samir Avdakovic, Amir Nuhanovic

Abstract—Low frequency power oscillations may be triggered by many events in the system. Most oscillations are damped by the system, but undamped oscillations can lead to system collapse. Oscillations develop as a result of rotor acceleration/deceleration following a change in active power transfer from a generator. Like the operations limits, the monitoring of power system oscillating modes is a relevant aspect of power system operation and control. Unprevented low-frequency power swings can be cause of cascading outages that can rapidly extend effect on wide region. On this regard, a Wide Area Monitoring, Protection and Control Systems (WAMPCS) help in detecting such phenomena and assess power system dynamics security. The monitoring of power system electromechanical oscillations is very important in the frame of modern power system management and control. In first part, this paper compares the different technique for identification of power system oscillations. Second part analyzes possible identification some power system dynamics behaviors Using Wide Area Monitoring Systems (WAMS) based on Phasor Measurement Units (PMUs) and wavelet technique.

Keywords—Power system oscillations, Modal analysis, Prony, Wavelet, PMU, Wide Area Monitoring System.

I. INTRODUCTION

POWER systems are subject to a wide range of disturbances, from small to large, and must be able to adjust to the changing conditions without losing stability. Power system has a number of monitoring, protection and control devices to ensure that the system response to any change in system parameters is controlled and its' stability is maintained. If the system is unstable it will result in progressive increase in angular separation of generator rotors, progressive decrease of bus voltages, or system frequency deviation.

Oscillations in power systems are classified by the system components that they affect. Some of the major system collapses attributed to oscillations are described [1]-[5]. Electromechanical oscillations are of the following types: interplant mode oscillations, local plant mode oscillations, inter-area mode oscillations, control mode oscillations,

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tensional modes between rotating plant. Machines on the same power generation site oscillate against each other at 2.0 to 3.0 Hz depending on the unit ratings and the reactance connecting them. This oscillation is termed as interplant because the oscillations manifest themselves within the generation plant complex. The rest of the system is unaffected. In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. Inter-area mode oscillations is observed over a large part of the network. It involves two coherent groups of generators swinging against each other at 1 Hz or less.

In first part of this paper is introduces of the practical techniques for identification and analysis low frequency oscillations in power system. The results of the Eigenvalue analysis are compared with the results coming from the Prony and Wavelet analysis. After multi-resolution signal decomposition, signal components physical characteristics of system oscillations are identified and presented on time-frequency domain representation map using the Fast-Fourier Transform (FFT). This approach provides identification of onset of the system disturbance and time-frequency behavior of the oscillation modes hidden into the signal. Second part of this paper analyzes possible identification some power system dynamics behaviors Using Wide Area Monitoring Systems (WAMS) based on Phasor Measurement Units (PMUs) and wavelet technique.

The remainder of this paper is organized as follows. Section II shortly presents WAMS. In Section III, basic theory of small signal stability of multi-machine systems, Prony and wavelet theory basics are presented. Practical application results identification and analysis low frequency oscillations on New England 39 bus test system are given in Section IV. In section V investigates dynamic characteristics of frequency oscillation after a disturbance based on the multiple synchronized phasor measurement and identification of inter-area oscillations in power system based on PMUs phase angle difference data and wavelet transform. Section VI contains the main conclusion.

II. WIDE AREA MONITORING SYSTEM- DYNAMIC EVENT IDENTIFICATIONS

The size and complexity of the power grid make the electrical system vulnerable and subject to collapse under situations such as line overloads, voltage and angular instability, frequency deviation, etc. Development of modern computer, communication and information technologies enables design of a new class of WAMPCS. Important function of these systems is identification of the initiating

disturbance event.

WAMS are essentially based on the new data acquisition technology of phasor measurement. In contrast to conventional control systems, where e.g. remote terminal units (RTUs) are used for acquisition of RMS values of currents and voltages, WAMS acquire current, voltage and frequency phasor measurements. These are taken by PMUs at selected locations in the power system and stored in a data concentrator every 100 milliseconds. The measured quantities include both magnitudes and phase angles, and are time-synchronised via Global Positioning System (GPS) receivers with an accuracy of one microsecond. Synchronized phasor measurements technology is very important for improvements in real-time monitoring, protection, and control. Implementation of this functionality has gained significant attention after recent blackouts. In most applications, the phasor data is used at locations remote from the PMUs [6]. Thus architecture involving PMUs, communications links, and data concentrators must exist in order to realize the full benefit of the PMU measurement system. A generally accepted architecture of such a system is shown in Fig. 1.

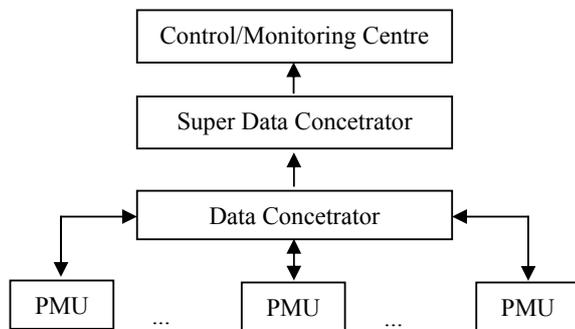


Fig. 1 Hierarchy of the PMUs, and levels of data concentrators

An accurate and fast automatic identification of type and location of the initiating event could help achieve early alerting of the operators, clear understanding of the ongoing disturbance, and ultimately triggering early corrective emergency control actions. Generally [7], the objectives of disturbance identification are detecting the onset in time of the disturbance, classify the type of disturbance, estimating the intensity and damping of the disturbance, estimate the end time of the disturbance and estimate the type and location of the initial event. PMU real-time monitoring helps to detect changes in voltage magnitude, voltage angle, frequency, or power flows as soon as they occur. Practical approach applied in some real power system and present in [8]-[9].

III. THEORETICAL BACKGROUND

An important aspect of power system operation and control is the monitoring of power system oscillating modes. Non-prevented low-frequency power swings can be cause of cascading outages that can rapidly extend effect on wide region [10]. The analysis and monitoring of transient oscillations can be accomplished by means of several methodological approaches. Each approach has its own

advantages and feasible applications, providing a different view of the system dynamic behavior. Eigenvalue analysis technique is based on the linearization of the nonlinear equations that represent the power system around an operating point which is the result of electromechanical modal characteristics: frequency, damping and shape. Direct spectral analysis of power response signals is possible use the Fourier Transforms (or Short Time Fourier Transform), Prony or Wavelet analysis technique.

A. Modal analysis - small signal stability of multi-machine systems

Analysis of practical power systems involves the simultaneous solution of equations representing the following: (i) synchronous machines, and the associated excitation systems and prime movers, (ii) interconnecting transmission network (iii) static and dynamic (motor) loads and (iv) other devices such, as HVDC converters, static VAR compensators [1]. Low frequency electromechanical oscillations range from less than 1 Hz to 3 Hz other than those with sub-synchronous resonance. Multi-machine power system dynamic behavior in this frequency range is usually expressed as a set of non-linear differential and algebraic equations. The algebraic equations result from the network power balance and generator stator current equations. The high frequency network and stator transients are usually ignored when the analysis is focused on low frequency electromechanical oscillations. The initial operating state of the algebraic variables such as bus voltages and angles are obtained through a standard power flow solution. The initial values of the dynamic variables are obtained by solving the differential equations through simple substitution of algebraic variables into the set of differential equations. The set of differential and algebraic equations is then linearized around the equilibrium point and a set of linear differential and algebraic equations is obtained:

$$\dot{x} = f(x, z, u) \quad (1)$$

$$0 = g(x, z, u) \quad (2)$$

$$y = h(x, z, u) \quad (3)$$

where f and g are vectors of differential and algebraic equations and h is a vector of output equations. The inputs are normally reference values such as speed and voltage at individual units and can be voltage, reactance and power flow asset in FACTS devices. The output can be unit power output, bus frequency, bus voltage, line power or current etc. By linearization (1) to (3) around the equilibrium point following equations (4) to (6) are given:

$$\Delta \dot{x} = \frac{\partial f}{\partial x} \Delta x + \frac{\partial f}{\partial z} \Delta z + \frac{\partial f}{\partial u} \Delta u \quad (4)$$

$$0 = \frac{\partial g}{\partial x} \Delta x + \frac{\partial g}{\partial z} \Delta z + \frac{\partial g}{\partial u} \Delta u \quad (5)$$

$$y = \frac{\partial h}{\partial x} \Delta x + \frac{\partial h}{\partial z} \Delta z + \frac{\partial h}{\partial u} \Delta u \quad (6)$$

Elimination of the vector algebraic variable Δz from (4) and (6), gives:

$$\Delta \dot{x} = A\Delta x + B\Delta u \quad (7)$$

$$\Delta y = C\Delta x + D\Delta u \quad (8)$$

where A, B, C, D are the matrix of partial derivatives in (4) to (6) evaluated at equilibrium. Power system state space representation is normally linearized around an operating point. The symbol A from (7) and (8) is omitted so as to follow the standard state space making x and u into the incremental values. This is the representation of a linearized differential and algebraic equations model of a power system on which standard linear analysis tools.

B. Basis of Prony analysis

Prony analysis is a signal processing method that extends Fourier analysis. It is a technique of analyzing signals to determine model, damping, phase, frequency and magnitude information contain within the signal [11]. Prony method is a technique for sample data modeling as a linear combination of exponentials, it has a close relationship to least squares linear prediction algorithm used for AR (Autoregressive) and ARMA (Autoregressive moving average) parameter estimation. Prony analysis is a method of fitting a linear combination of exponential terms to a signal. Each term in (9) has four elements: the magnitude A_n , the damping factor σ_n , the frequency f_n , and the phase angle θ_n . Each exponential component with a different frequency is viewed as a unique mode of the original signal $y(t)$. The four elements of each mode can be identified from the state space representation of an equally sampled data record. The time interval between each sample is T :

$$y(t) = \sum_{n=1}^N A_n e^{\sigma_n t} \cos(2\pi f_n t + \theta_n), \quad n = 1, 2, 3, \dots, N. \quad (9)$$

Using Euler's theorem and letting $t=MT$, the samples of $y(t)$ are:

$$y_M = \sum_{n=1}^N B_n \lambda_n^M \quad (10)$$

$$B_n = \frac{A_n}{2} e^{j\theta_n} \quad (11)$$

$$\lambda_n = e^{(\sigma_n + j2\pi f_n)T} \quad (12)$$

Prony analysis consists of three steps. In the first step, the coefficients of a linear prediction model are calculated. The linear prediction model (LPM) of order N , shown in (13), is built to fit the equally sampled data record $y(t)$ with length M . Normally, the length M should be at least three times larger than the order N :

$$y_M = a_1 y_{M-1} + a_2 y_{M-2} + \dots + a_N y_{M-N} \quad (13)$$

Estimation of the LPM coefficients a_n is crucial for the derivation of the frequency, damping, magnitude, and phase angle of a signal. To estimate these coefficients accurately, many algorithms can be used. A matrix representation of the signal at various sample times can be formed by sequentially writing the linear prediction of y_M repetitively.

In the second step, the roots λ_n of the characteristic polynomial shown as (14) associated with the LPM from the first step are derived. The damping factor σ_n and frequency f_n are calculated from the root λ_n according to (12):

$$\lambda^N - a_1 \lambda^{N-1} - \dots - a_{N-1} \lambda - a_N = (\lambda - \lambda_1)(\lambda - \lambda_2) \dots (\lambda - \lambda_n) \dots (\lambda - \lambda_N) \quad (14)$$

In the last step, the magnitudes and the phase angles of the signal are solved in the least square sense. According to (10), (15) is built using the solved roots λ_n :

$$Y = \phi B \quad (15)$$

$$\phi = \begin{bmatrix} 1 & 1 & \dots & 1 \\ \lambda_1 & \lambda_2 & \dots & \lambda_N \\ \cdot & \cdot & \cdot & \cdot \\ \lambda_1^{M-1} & \lambda_2^{M-1} & \dots & \lambda_N^{M-1} \end{bmatrix} \quad (16)$$

$$B = [B_1 \quad B_2 \quad \dots \quad B_N]^T \quad (17)$$

The magnitude A_n and phase angle θ_n are thus calculated from the variables B_n according to (11).

C. Wavelet transform

A wavelet is an oscillatory waveform of effectively limited duration that as average value of zero. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet [12]- [16]. The wavelet transform of a time dependent signal $f(t)$ consists of a set coefficients $W_s(a, b)$. These coefficients measure the similarity between the signal $f(t)$ and a set of functions $\psi_{a,b}(t)$. All the functions $\psi_{a,b}(t)$ are derived from a 'mother wavelet' as follow:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right), \quad a > 0 \quad (18)$$

Where a represent a time dilatation and b a time translation. The Continuous Wavelet Transformation (CWT) of a time domain signal is defined by:

$$CWT_f(a, b) = (f, \psi_{a,b}) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \overline{\psi\left(\frac{t-b}{a}\right)} dt \quad (19)$$

where: $\psi(t)$ is the basis wavelet function (or mother wavelet), that can be real or complex, a is the dilatation scale parameter, b is the time scale parameter, $\psi\left(\frac{t-b}{a}\right)$ are the daughter wavelet function.

The application of wavelet transform in engineering areas usually requires a discrete wavelet transform Discrete Wavelet Transformation (DWT). A square integrable signal $f(t)$ is decomposable into different time-frequency scales. In wavelet analysis, such a signal can be represented by a linear combination of two parameter wavelet functions:

$$f(t) = \sum_{k=-\infty}^{\infty} a_{j_0}(k) \phi(t-k) + \sum_{j=j_0}^{\infty} \sum_{k=-\infty}^{\infty} d_j(k) 2^{j/2} \psi(2^j t - k) \quad (20)$$

The wavelet functions $\phi(t)$ and $\psi(t)$ are localized in time. Parameters k and j perform translation and time scaling of the original functions. The functions $\phi(t)$ and $\psi(t)$ are usually chosen so that the functions on the right side of (2) form an orthonormal basis. Then decomposition and reconstruction are efficient using orthogonal projection. The $a_j(k)$ and $d_j(k)$ terms are referred to as approximation and detail coefficients, respectively (coefficients of low-pass and high-pass filters). These coefficients can be order according relations (4). They reflect a range from local to global characteristics of the original signal $f(t)$ because their associated functions have different time-frequency scales. A very useful implementation of DWT is multiresolution analysis. Multiresolution analysis leads to a hierarchical and fast scheme. This can be implemented by a set of successive filter banks. The signal is passed through a highpass filter (HPF) and a lowpass filter (LPF). Then the outputs from both filters are decimated by 2 to obtain the detail coefficients and the approximation coefficients at level 1 (A1 and D1).

$$a(k) = \frac{1}{\sqrt{2}} \int_{-\infty}^{+\infty} \phi(t) \cdot \phi(2t - k) dt \quad (21)$$

$$d(k) = \frac{1}{\sqrt{2}} \int_{-\infty}^{+\infty} \psi(t) \cdot \psi(2t - k) dt$$

The approximation coefficients are then sent to the second stage to repeat the procedure. Finally, the signal is decomposed at the expected level.

IV. IDENTIFICATION OF LOW FREQUENCY OSCILLATIONS - SIMULATION RESULTS

When a disturbance occurs in a power system creating an imbalance between the mechanical power being supplied to a generator by its turbine and the electrical power being supplied to the power system, this imbalance is translated into a change in the kinetic energy of the rotor. In other words the generators begin to speed or slow down. Normally various damping phenomena within the power system will act so that the system will attain a new steady state operating point.

Simulation results obtained from detailed time-domain simulation using New England 39 bus system (Fig. 2). The 39 bus New England test system consists of ten generators connected at buses 30 to 39 in which bus 31 is a slack bus. As shown on Fig. 2, generator bus 30 and bus 39 and load buses

1 through 9 with the exception of bus 6 in area 1; generator bus 32 and slack bus 31 as well as load bus 6 and buses 10 through 15 are in area 2; generator buses 33 through 36 and load bus 16 and load bus 19 through 24 are in area 3; all others are in area 4. The areas are interconnected through seven tie-lines. The tie-lines are connecting buses 2 and 25, 3 and 18, 4 and 14, 5 and 6, 6 and 7, 15 and 16, and buses 16 and 17. This is an arbitrary decomposition and it is not based on the strength of interconnections among the subsystems. All generators are equipped with identical automatic voltage regulator (AVR) and turbine governor (TG) and the loads are modeled as voltage dependent loads. Optimal PMU placement present on the Fig. 2 and it is taken in [17].

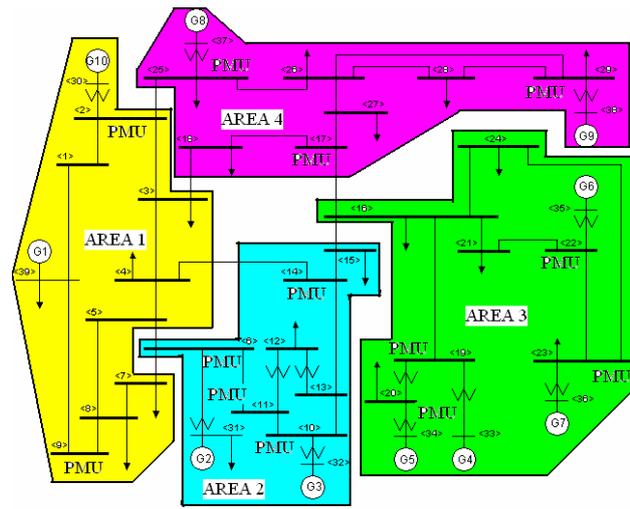


Fig. 2 New England 39 bus Test System with the PMUs optimal placement

The eigenvalue analysis of the system for a specific operating point led to the identification of several modes of oscillation. The frequency of the system oscillations modes are shown in Table I.

TABLE I
MODES OF OSCILLATIONS

Mode	Eigenvalue	Frequency
1	-0.67883 ± 0.04327	0.00689
2	-0.66829 ± 0.06567	0.01045
3	-0.69742 ± 0.12692	0.02020
4	-0.71177 ± 0.19739	0.03142
5	-0.80141 ± 0.27401	0.04361
6	-0.76468 ± 0.30923	0.04922
7	-0.06405 ± 4.09950	0.65245
8	-0.24594 ± 6.80010	1.08230
9	-0.22002 ± 7.18200	1.14310
10	-0.24883 ± 7.55560	1.20250
11	-0.10552 ± 7.70520	1.22630
12	-0.31853 ± 8.53810	1.35890
13	-0.31364 ± 9.84160	1.56630
14	-0.36567 ± 9.93590	1.58140
15	-0.50576 ± 10.5700	1.68230

After simulation small disturbance (the system has been perturbed by applying active power load increase at bus 16) observed oscillation throughout the system. Fig. 3 shows the simulation results of the voltage deviation on the bus 14.

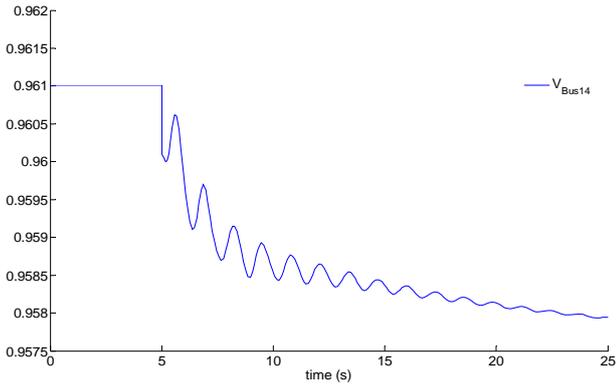


Fig. 3 Waveform of voltage deviation V_{14}

Prony method is widely used to analyze low frequency oscillations. It uses the linear combination of exponential functions to fit equal-interval sampling data. This method can identify time-domain signals and real-time measured data. Although some methods try to improve the efficiency of Prony method, this method is particularly valid under the condition that the linearity of the signal to be analyzed has been restored.

Prony analysis signal phase angle in frequency domain is present on Fig. 4. The results of Prony analysis are reported in Table II. The values of dominant modes of oscillation #1, #2 and #3 are correctly identified in agreement with the eigenvalue analysis. More specifically, the Prony method identifies some spurious frequency modes which are not consistent with the eigenvalue analysis. Furthermore, it is necessary to tune the number of the selected frequency values in order to find the right values of the damping.

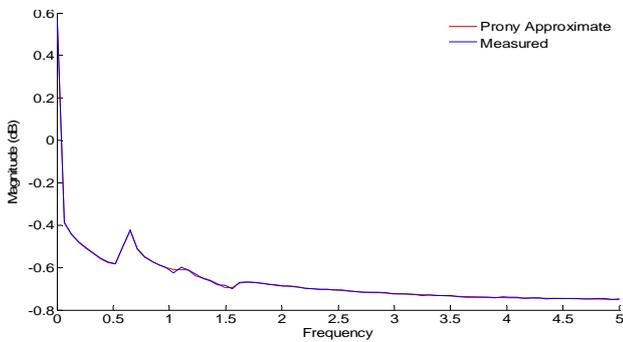


Fig. 4 Prony analysis in frequency domain

TABLE II

OSCILLATION MODES ANALYZED BY PRONY METHOD			
Mode	Amplitude	Damping	Frequency
1	6.0e-002	-1.5e-001	0.63
2	3.3e-004	-2.6e-001	1.10
3	4.2e-004	-7.0e-001	1.60
4	6.2e-006	-1.0e+000	2.30
6	9.6e-006	-1.2e-000	3.00
7	7.2e-006	-1.3e+000	3.60
8	1.7e-006	-9.6e-001	4.20

Implementation of the DWT can be realized by considering multiresolution decomposition- the digital filter equivalent of the DWT. The algorithm uses digital filters, highpass and lowpass, which when combined in a structure, constitute a

filter bank able to decompose the signal equally into high and low frequency components. The *db4* wavelet is selected to analysis voltage signal. Using DWT this signal is decomposed on approximations and details coefficients at the five levels (Fig. 5). And afterward, by using the Fast-Fourier Transform (FFT) in time-frequency domain representation as shown on Fig. 6 the frequency characteristic and power spectrum of the dominant oscillation mode in the frequency domain of component is done.

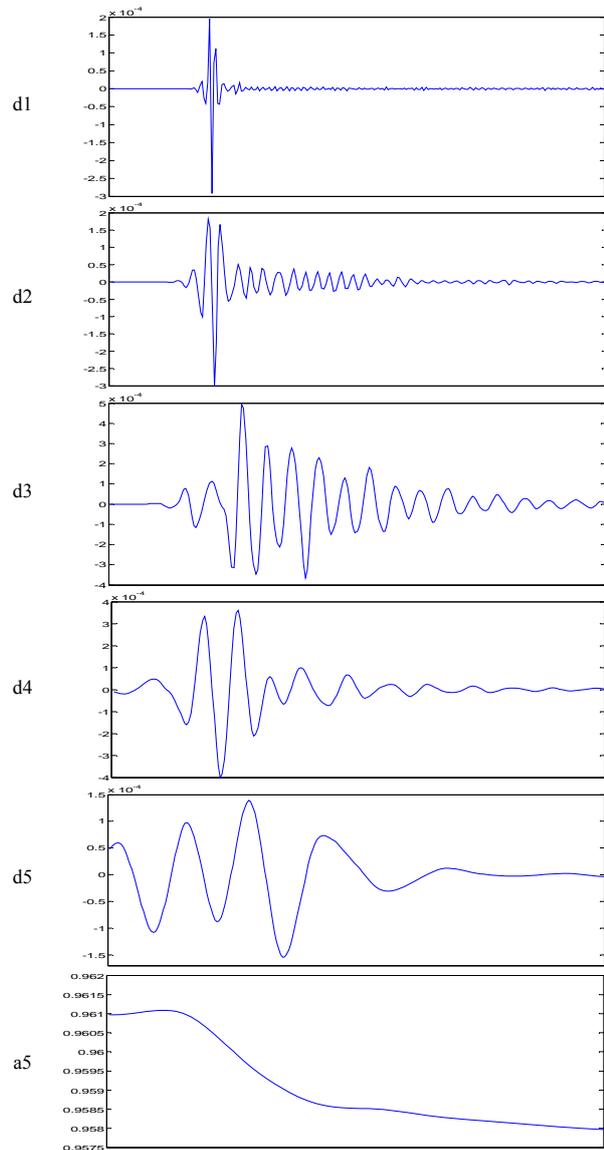


Fig. 5 Wavelet analysis in waveform of voltage on bus 14

It is clearly evident that through multiresolution signal decomposition of DWT, two important properties are manifested: the first is the localization property in time for disturbance. The disturbance inception is accurately detected and localized at the finer level (d1) by the presence of large coefficients at the time of disturbance. The second property is

the partitioning of the signal energy at different frequency band. This gives an indication of the frequency content of the disturbance signal, and reveals the important features in the signal. Notably, the frequency band $[f_m/2 : f_m]$ of each detail scale of the DWT is directly related to the sampling rate of the original signal, which is given by $f_m = f_s/2^{l+1}$, where f_s is the sampling frequency, and l is the level of decomposition. In this study, the sampling time is 0.1 sec or sampling frequency is 10 Hz of the original signal. The highest frequency that the signal could contain, from Nyquist' theorem, would be $f_s/2$ i.e. 5 Hz.

The frequency range of the decomposed signal in different decomposition levels is: level 1- d1 [2.5–5.0 Hz], level 2- d2 [1.25–2.5 Hz], level 3- d3 [0.625–1.250 Hz], level 4- d4 [0.315–0.625 Hz], level 5- d5 [0.157–0.315 Hz] and a5 [0–0.157 Hz].

After time frequency analysis of the component signal, it is possible to detect character of low frequency oscillations in the signal. The value of the oscillations modes of 0.6 Hz, 1.1 Hz, 1.3 Hz and 1.6 Hz is correctly identified in agreement with the Eigenvalue analysis. The chart on the Fig. 6 shows the time-frequency behavior of the oscillation modes hidden into the signal and gives rise to a qualitative approach for estimation the damping of the oscillation modes. Like the Eigenvalue and Prony analysis, wavelet analysis identifies dominant modes and characters of these oscillations with obvious identification of onset of system disturbance.

V. SYSTEM BEHAVIORS AFTER A DISTURBANCE

The wide-area phenomenon given most attention in the power system secure is inter-area power oscillations. Inter-area oscillation is a common problem in large power systems world-wide [18]. Many electric systems world-wide are experiencing increased loading on portions of their transmission systems, which can, and sometimes do, lead to poorly damped, low frequency inter-area oscillations. Inter-area oscillations can severely restrict system operations by requiring the curtailment of electric power transfers as an operational measure. These oscillations can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory power swings. WAMS based on PMUs at nodes help system operators to gain a dynamic view of the power system and initiate the necessary measures in proper time. The phasor measurement provides relations between phase differences and frequency deviations. The phase angle δ is calculated as a phase difference between observed instantaneous voltage and 60Hz reference signal produced by the PMU based on the time stamps of GPS. Without information about system parameters and configuration, both the phase angle value itself and the phase difference value itself are not so useful because, for example, the phase angle can be directly shifted by an angular displacement at a wye-delta transformer [19].

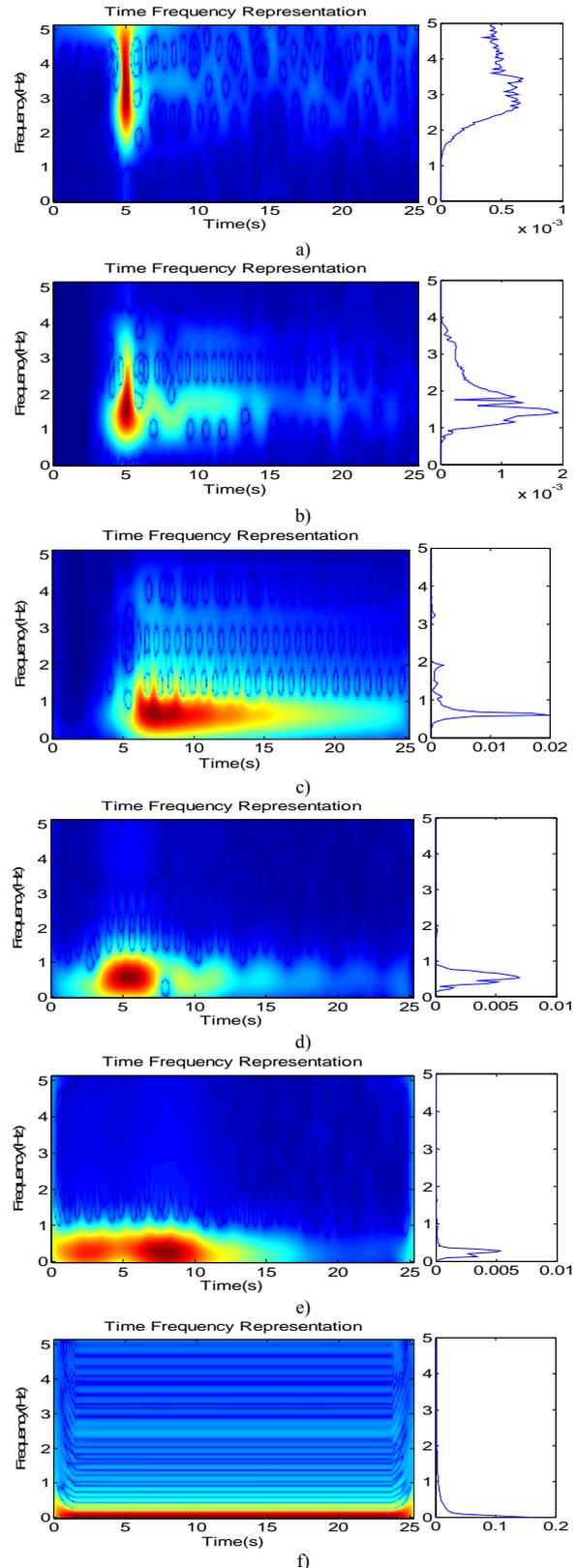


Fig. 6 FFT analysis and power spectrum in waveform voltage V_{14} a) d1 component, b) d2 component, c) d3 component, d) d4 component e) d5 component and f) a5 component

On the other hand both varying phase angle and varying phase difference between two points give us very useful information. Increasing phase angle represents that the frequency of the observed voltage is higher than the system nominal frequency, 60Hz. Decreasing phase angle means that the frequency of the observed voltage is lower than 60Hz. The time derivative of phase angle corresponds to the deviations of system frequency. So the frequency deviations can be calculated as $\Delta f_n = (\delta_{n+1} - \delta_n) / 360 \Delta t_n$, where Δt_n [s] is a sampling interval of sequential phase data δ_n and n is the number of accumulated phase angle data. Therefore frequency variation can be observed by the PMU with accumulating the sequential frequency deviations Δf_n . The variation of phase difference between two points means that the power flow between the two points has changed. Increasing the phase difference represents the power flow has been increased, and decreasing the phase difference means the power flow has been decreased, conversely.

In this subsection, possibility identification some power system dynamics behaviors using PMUs and wavelet transform will be discussed. Fig. 7 shows the simulation results of the phase difference between PMUs and phase angle measured in 14 bus after simulate line 16-17 outage. Bus 14 is selected arbitrarily as one of the central nodes.

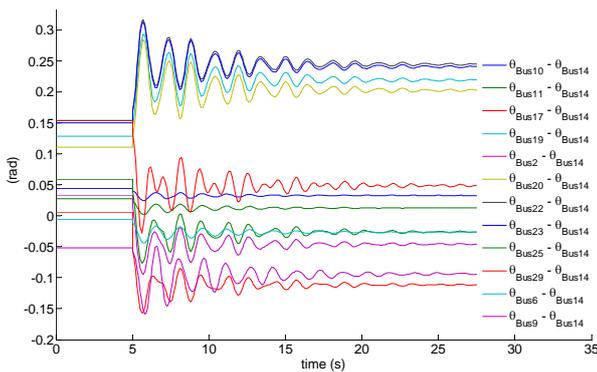


Fig. 7 Waveform of PMUs phase angle difference

The result of the phasor measurement is expected to show some similar behaviors because the phase difference between some two areas is closely related to the power flow between them. Fig. 8 shows frequency deviation calculated on data phase difference between PMUs and selected central nodes.

Fig. 8a shows frequency deviation in time as result disturbance in system. First several microseconds are results transient mode. Frequency deviation calculate on PMUs in area 3 on test system oscillates in the opposite direction of that of other PMUs. Fig. 8b shows frequency deviation compared for phase difference. As shown, each result presents almost a shape of concentric ellipse. In real system, in case study-state or without disturbance, data in concentric ellipse are stiff, while during the disturbances spread ellipses.

Waveform of phase difference all PMUs are analyzed using wavelet transform and db4 mother wavelet. Dominant power system oscillations are observed at a frequency around 0.6 Hz and it is present inter-area oscillations. Since the waveform at

a frequency around 0.6 Hz corresponds to d3 component in DWT analysis, this power system oscillation was verified by comparison with d3's PMU phase difference signals in each area. Fig. 9 demonstrates the power system oscillation at a frequency around 0.6 Hz detected from signals phase difference all PMU (d3 component of signals).

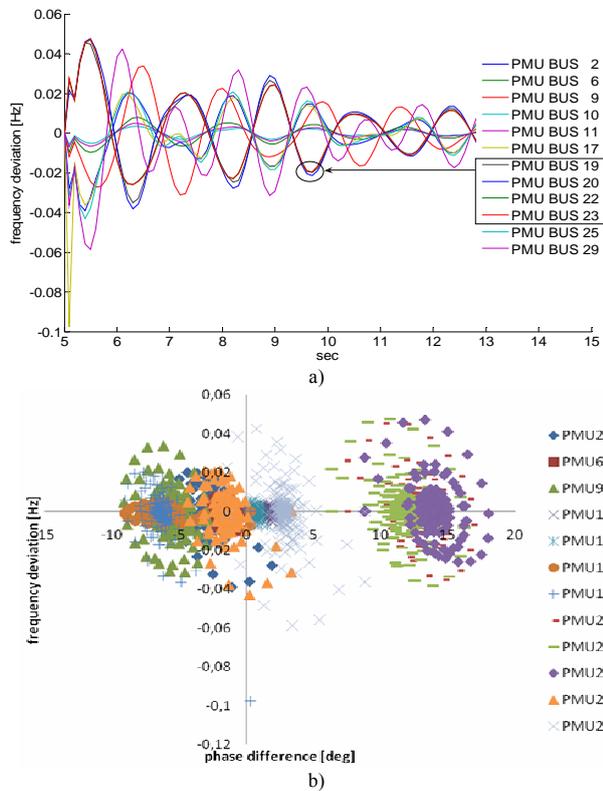


Fig. 8 a) Frequency deviation in time b) Phase difference

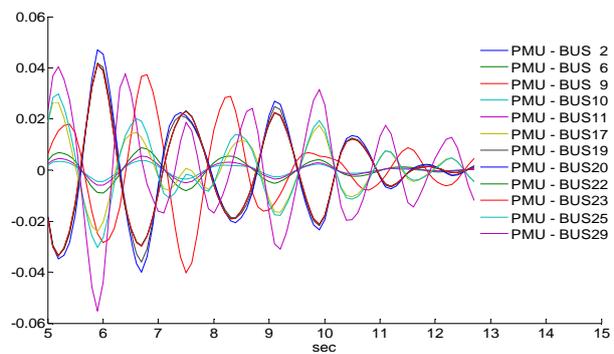


Fig. 9 Analysis of long term oscillation after applying wavelet transformation

As seen from the Fig. 9, the waveform of phase angle at PMUs on bus 19, 20, 22 and 23 oscillates in the opposite direction of that of other PMUs. Generally speaking, oscillation that arises in the power system is inertia oscillation and each phase at both ends of power system tends to oscillate in the opposite direction. The waveforms of frequency oscillation as results of wavelet analysis are very similar with each other. This is why the interconnected power system

could keep its synchronization before and after the disturbance.

Finally, frequency oscillations have been converged to zero value, that is, the system attained synchronization.

VI. CONCLUSION

Electromechanical oscillations are inherent to interconnected power systems. However, the frequency of oscillations and the number of generators that oscillate in any electromechanical oscillatory mode depend on the structure of the power system network. The stability of those oscillations is of vital concern, and is a prerequisite for secure system operations. The technological infrastructure for improvements in system monitoring, protection and control is already available in the form of broadband communication networks, high precision synchronized GPS devices and real-time monitoring systems. Hence, there is a great potential for new development of Wide- Area Monitoring Protection and Control systems, which could protect power systems against different sets of blackout-inducing contingencies.

In this paper, the practical technique for identification and analysis low frequency oscillations in power system is presented. The results of the Eigenvalue analysis, applied to the test system, are compared with the results coming from Prony and wavelet analysis.

As seen from the results of analysis, WAMS and wavelet transformation has a great possibility to investigate the global power system dynamics in an easy way.

REFERENCES

- [1] B. Pai, B. Chaudhuri, *Robust Control in Power Systems*, New York, Springer, 2005.
- [2] P. Kundur, *Power System Stability and Control*, New York, McGraw-Hill Inc., 1994.
- [3] D. Novosel, M. Begovic, V. Madani, "Shedding Light on Blackouts", *IEEE Power and Energy Magazine*, vol. 2, February 2004, pp. 32-43.
- [4] D. Novosel, V. Madani, B. Bhargava, K. Vu, J. Cole, "Down of the Synchronization", *IEEE Power and Energy Magazine*, vol. 6, December 2008, pp. 91-97.
- [5] M. Kusljagic, D. Novosel, M. Glavic, J.A.D. Pinto, "Wide Area Monitoring of Power System Dynamics", presented at the International Conference on Electrical Engineering, CEE05 Coimbra, Portugal, 2005.
- [6] A.G.Phadke, J.S.Thorp, *Synchronized Phasor Measurements and Their Applications*. New York: Springer, 2008.
- [7] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, Definition and Classification of Power System Stability, *IEEE Trans. Power Systems*, vol. 19, 2004, 1387-1399.
- [8] I. Ngamroo, Y. Mitani, S. Dechanupapritta, PMU Based Monitoring of Inter-Area Oscillation in Thailand Power System via Home Power Outlets, *ECTI Transactions On Electrical Eng., Electronics, And Communications*, vol. 5, August 2007, 199-205.
- [9] T. Hashiguchi, Y. Mitani, O. Saeki, K. Tsuji, M. Hojo, H.Ukai, "Monitoring power system dynamics based on phasor measurements from demand side outlets developed in Japan Western 60 Hz System", presented at the Power Systems Conference and Exposition, IEEE PES, vol. 2, Oct. 2004, 1183-1189.
- [10] M. Bronzini, S. Bruno, De Benedictis, La Scala, Taking the pulse of Power Systems: Monitoring Oscillations by Wavelet Analysis and Wide Area Measurement System, IEEE-PES Power Systems Conference and Exposition, Atlanta, USA, vol. 1, 2006, 436-443.
- [11] L. Qi, L. Qian, S. Woodruff, D. Cartes, "Prony Analysis for Power System Transient Harmonics", *EURASIP Journal on Advances in Signal Processing*, vol. 2007, no. 48406, December, 2006.
- [12] N. Zhang, M. Kezunovic, Transmission Line Boundary Protection Using Wavelet Transform and Neural Network, *IEEE Transaction On Power Delivery*, vol. 22, 2007, 859-869.
- [13] S. Nath, A. Dey, A. Chakrabarti, Detection of Power Quality Disturbances Using Wavelet Transform, *Proceedings of World Academy of Science, Engineering and Technology*, vol. 37, 2009, 2070-3740.
- [14] S.Sutha, N.Kamaraj, Real Power Contingency Ranking Using Wavelet Transform Based Artificial Neural Network (WNN), *International Journal of Electrical and Power Engineering- Medwell Journals*, vol. 2, 2008, 116-121.
- [15] K.Gayathri, N. Kumarappan, Comparative Study of Fault Identification and Classification on EHV Lines Using Discrete Wavelet Transform and Fourier Transform Based ANN, *International Journal of Electrical, Computer, and Systems Engineering*, vol. 2, 2008, 127-137.
- [16] M. Uyara, S. Yildirima, M. T. Gencoglu, An Effective Wavelet-based Feature Extraction Method For Classification of Power Quality Disturbance Signals, *Electric Power Systems Research*, vol. 78, 2008, 1747-1755.
- [17] B.Mohammadi-Ivatloo, Optimal placement of PMUs for Power System Observability Using Topology Based Formulated Algorithms, *Journal of Applied Science*, vol. 9, 2009, 2463-2468.
- [18] H. Breulmann, E. Grebe, M. Lösing, W. Winter, R. Witzmann, P. Dupuis, M.P. Houry, T. Margotin, J. Zerényi, . Dudzik, PSE S.A., J. Machowski, L. Martín, J. M. Rodríguez, E. Urretavizcaya, "Analysis and Damping of Inter-Area Oscillations in the UCITE/CENTREL Power System", CIGRE 2000, pp 38-113. Paris, France, 2000.
- [19] M.Hojo, K. Ohnishi, T. Ohnishi, "Analysis Of Load Frequency Control Dynamics Based On Multiple Synchronized Phasor Measurements", *Power Engineering Society General Meeting*, vol. 2, July 2003, 13-17.