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Synchronized Measurements Processing Methodology as a Tool for Monitoring Power System Oscillations

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Abstract: Monitoring, protection and control of the electrical power system require the design and implementation of specific applications that are based on analytical methods for the processing of synchronized measurements. Therefore, it is necessary to select the adequate type of mathematical analysis that best suits the requirements of a particular application. This paper describes analytical methods used for the processing of synchronized measured electrical quantities for detection and analysis of the variety of oscillations. The oscillatory phenomena of active power and frequency as a case study of one disturbance in the power system are analyzed. The results of processing the actual synchronized measurements for that case study are presented afterwards. Different data processing methods (spectral analysis methods) are compared, and finally, a recommendation for appropriate methods for processing synchronized measurements in application for recognition, processing and alarming of oscillations of active power is given.

Keywords: Fast Fourier Transformation; Phasor Measurement Units; Power System Oscillations; Prony analysis; Synchronized Measurement

1 INTRODUCTION

The idea of system monitoring, protection and control of the electrical power system (EPS) exists for many years; however, practical application began when the conditions of technological availability of the device and the theoretical basis for specific disturbances in the EPS were achieved. System monitoring based on the technology of synchronous phasor measurements is an example of using a new technology that provides a completely different concept of real-time monitoring, protection and control of the EPS [1-4]. The synchrophasor techniques are described in [5] that can help operators in understanding the dynamic behaviour of the power grid to improve real-time decision making in the systems with the increasing amounts of renewable and distributed energy resources, and therefore, more generation and load uncertainty.

After major disruption of the EPS in the world in 2003, systems for monitoring, protecting and controlling the EPS are developed and applied based on synchronized voltage and current phases with a sampling of 20 ms and 100 ms. Those systems are called Wide Area Monitoring, Protection and Control (WAMPAC) systems [6-9]. They are established on Phasor Measurement Units (PMU) for measuring voltage and current real-time amplitude and angle in EPS points of special importance. The real-time analysis of ambient PMU measurements in power systems using the method of frequency domain decomposition (FDD) is discussed in [10]. The application of FDD in power system is tested for the purpose of oscillation monitoring. The WAMPAC platform provides real-time dynamic image of EPS, greater accuracy of measurement, rapid data exchange, and enables creation of algorithms for analysing, protecting and managing the EPS [11-15].

Each application/function of the WAMPAC system requires processing of synchronized measurements [16-18]. For processing, it is necessary to select the adequate mathematical analysis that best suits the requirements of a particular function. The present practice determines the use of a particular mathematical analysis for basic applications/ functions. However, the design and application of specific applications/functions is required for advanced monitoring, protection and control of individual parts or the entire power system. Therefore, this paper determines and compares the advantages of individual mathematical analyses through their use in basic functions in order to predetermine the mathematical analyses for specific applications / functions.

The topics of this paper are the theoretical review of analytical methods for the processing of synchronized measurements, the processing of actual measured synchronized electrical quantities by various mathematical analytical methods in different applications and functions, and the proposal of an adequate analytic method used in basic applications for processing the synchronized measured electrical quantities.

2 APPLICATIONS FOR MONITORING, PROTECTION AND CONTROL

In the WAMPAC system, it is possible to realize a series of functions and their combinations, which can, besides monitoring, also have the character of running or protecting the system. The implementation is possible at the local level with the assigned functions within the phasor measurement units built into the objects, or within a region or the whole continent. Realization of those applications / functions takes place within the core of Phasor Data Concentrator (PDC) in national or regional centre. The review of researches about applications of PMU in transmission networks for system monitoring and about the integration of Flexible AC Transmission system (FACT) devices and Phase Shift Transformers (PSTs) in PMU environment is given in [19]. Current monitoring solutions have reversal effects on power plants (power plants and transformer stations) in terms of using control or protection functions [20].

The WAMPAC system consists of three basic modules:

- Acquisition of synchronized measurements,
- Processing of synchronized measurements using specially created applications/functions,
- Applying the results of processed synchronized measurements.

The results of processed synchronized measurement are very valuable for:

- Helping the EPS operator when deciding
- Automatic decision making
- Post-mortem analysis
- Preserving the integrity of EPS (System Integrity Protection Scheme - SIPS)

The functions of system monitoring are grouped into two categories:

- Basic functions (acquisition and archiving of data, viewing the data on the graphical interface, voltage and current amplitude monitoring, voltage and current angles monitoring, frequency monitoring, monitoring of power flows in EPS),
- Advanced functions (thermal control of the transmission line, voltage stability monitoring of the transmission line or corridor, monitoring of the frequency in the power system, monitoring of the low frequency oscillations, estimation of the stability of the load angle in the system, monitoring of large production units, monitoring of wind power generation).

The progress of technology and the Global Positioning System (GPS) becoming available for public usage has led to the advancement in the development of applications which include fully-functional PMU devices and controllers (PDC). The first available standard for synchronized data was IEEE1344, designed for point-to-point based applications, with limited data flow. IEEE1344 was accompanied by different releases of IEEE C37.118 in 2005 and 2011. The standard from 2005 was mainly used to determine accuracy of measurements in the stable state of EPS, and was introduced by the general approach focused on big data flow, including PDC concept. The current standard is divided into two parts which define the specifications of implementation of synchronized measurements, apart from communication protocols such as IEEE C37.118.1 & C37.118.2 (2011, rev 2014). The latest standard version introduced stricter requirements for performance and testing, and also enables more flexible applications with different speeds of data flow and structures of information. The standard IEEE C37.244 (2013) [8] also broadens roles, the functionality and the performance expected from PDC.

It is important to mention that standards IEEE C37.118.1 & 2 (2011) i C37.244 (2013) envision the usage of synchronized measurements in the protection and operation of EPS. However, the available hardware technology is already applied in the functions of monitoring and running. Within mentioned standards, the PMU`s may comply with the requirements of protection class (P class) and/or monitoring class (M class). The M class requires high accuracy and the stability of measurements, with accurate display of oscillations; therefore it is suitable for applications that require a better rejection of disturbances. The P class is more suitable for applications that need speed and lower latency [21]. Moreover, the standard C37.244 determines more possibilities for designing the measuring infrastructure, e.g. by determining the forwarding mode of incoming data from the large number of PMU devices and concentrating those data toward the multilevel applications. Some manufactures of the devices for protection and measuring the quality of electrical energy also install the PMU functionality as the standard characteristic of those devices, while other devices offer dedicated functions of PMU. It is also possible that some PMU devices receive data from so called "merging unit devices" according to the standard IEC 61850-9-2, avoiding the need for connecting with convertors and analogue transformers. Thereby, the PMU performs the calculation of the phasor from the sampled values on the process bus.

The applications based on synchronized measurements are installed worldwide, in the dispatch centres and in the services for planning and analysis of EPS as off-line applications. So far, there has been limited implementation of the WAM system within the dispatch centres, and only some of the transmission system operators have activated the WAM interface in their dispatch centres to provide additional tool to system operators for more comprehensive view of the system status. From earlier mentioned basic and advanced functions of system monitoring, according to [9], the following functions are used in the Control (Dispatch) Centres like this:

- Recognition of island operation of the EPS part and resynchronization using synchronized measurements;
- Oscillation monitoring (power and frequency)
  - Oscillation amplitude monitoring,
  - Identification of oscillation type and frequency,
  - Oscillation damping monitoring;
- Monitoring of disturbances in the system
  - Voltage stability monitoring,
  - Angular stability monitoring,
  - Thermal monitoring of the power line,
  - Non-symmetrical load monitoring,
  - Identification of failures and short circuits,
  - Precautionary protection;
- Restoration support;
- Synchronization and separation of "large" parts of the EPS using synchronous phasor measurements.

3 PROPOSED METHODOLOGY FOR POWER SYSTEM OSCILLATION MONITORING

3.1 Mathematical Methods

The described real-time monitoring applications for real-time monitoring with relevant input data and mathematical calculations are foreseen to assist the transmission system operator by providing a complete realistic view of the EPS state. Basic applications operate with relatively simple algebraic equations. Application for recognition and analysis of oscillation of active power and frequency requires a more detailed research of the use of mathematical methods.

According to available literature [22-28], the following mathematical methods are often used for the analysis of oscillation of active power and frequency:

- Fast Fourier Transformation (FFT),
- Phase Locked Loops (PLL),
- Prony analysis,
- Kalman Filter,
- Kaiser Window Transformation,
- Hilbert Huang Transformation.

More recent literature [29-32] also describes newer techniques proposed for oscillation detection, monitoring and analysis. The authors in [29] propose the algorithm using signal model and multitaper estimator based on Thomson's multitaper spectrum estimation and harmonic analyses [33], to separate the ambient noise from forced oscillations in syncrofasor measurements. Although traditional Prony analysis is used in the method described in [30] to determine the frequencies in a signal, wide area visualization was achieved using the capabilities of geographical data views (GDV). A modal analysis method named Iterative Matrix Pencil Method is proposed in [31] for fast calculations in large systems with multiple signals. Survey [32] is giving the review of existing methods for locating of oscillation sources with a general scheme for their practical applications.

The focus in this paper will be on two very often used methods, Fast Fourier Transformation and Prony Analysis, and Kaiser Window Transformation will be used to compare the results obtained on a real example of measured oscillations.

3.1.1 Fast Fourier Transformation (FFT)

The time-varying periodic signal can be constructed by summing the sinusoidal signals of different frequencies, amplitudes and phases. The Fourier analysis enables the display of a signal as a sum of sinusoidal signals i.e. as a sum of several components with different frequency. If a single frequency component has small amplitude or is equal to zero then it does not contribute to the amplitude of the total signal. Accordingly, Fourier's analysis of the pure sinusoidal signal will give a spike on the frequency component corresponding to the frequency of that sinus while the contributions of the other frequency components will be zero. The Fourier analysis enables the signal to be observed in the time or frequency domain. The preview in the frequency domain is called a signal spectrum.

FFT algorithms are based on the division of basic Discrete Fourier Transformation (DFT) into several shorter DFTs. The length of DFTs is usually the power of 2, which results with very fast performance. Such algorithms are efficient because they use the single sub-score multiple times which reduce the total number of multiplication required. The sum for the DFT calculation can be expressed as follows:

$$
\begin{aligned}
X(k) &= \sum_{0}^{N-1} x(n)\cdot \mathrm{e}^{-\frac{j2\pi kn}{N}} = \\
&= \sum_{0}^{\frac{N}{2}-1} x(2n)\cdot \mathrm{e}^{-\frac{j2\pi k2n}{N}} + \sum_{0}^{\frac{N}{2}-1} x(2n+1)\cdot \mathrm{e}^{-\frac{j2\pi k(2n+1)}{N}} = \\
&= \sum_{0}^{\frac{N}{2}-1} x(2n)\cdot \mathrm{e}^{-\frac{j2\pi kn}{\frac{N}{2}}} + \mathrm{e}^{-\frac{j2\pi k}{N}} \sum_{0}^{\frac{N}{2}-1} x(2n+1)\cdot \mathrm{e}^{-\frac{j2\pi kn}{\frac{N}{2}}} = \\
&= \mathrm{DFT}\frac{n}{2}\left[x(0)+x(2)+x(4)+, ..., +x(N-2)\right] + \\
&+W(kn)\mathrm{DFT}\frac{n}{2}\left[x(1)+x(3)+, ..., +x(N-1)\right]
\end{aligned} \tag{1}
$$

$W(kn)$ is called twiddle factor and it can be determined as:

$$W(kn) = \mathrm{e}^{-\frac{j2\pi k}{N}} \tag{2}$$

This procedure for separating original DFT (with the size N) into two smaller DFTs (with the size $N/2$), where one contains even, and the other odd coefficients, is called decimation in time.

In this case, the FFT uses the results obtained by calculating a half shorter DFTs, combining them, summing them up and multiplying the result with the twiddle factor. Thus, transformations with the length $N/2$ and complexity 20 ($N^2/4$) transformations are calculated, and one of them is multiplied by $\mathrm{e}^{-\frac{j2\pi k}{N}}$.

The overall complexity is predominantly determined by the calculation of two DFTs. However, if the size (N) of the initial DFT is a power of 2, each of the DFTs (with the size $N/2$) can be further subdivided, so four DFTs (with the size $N/4$) will be obtained. The DFTs can be further and further divided, until the DFT gets the size 2. Finally, the DFT calculation can be divided into steps and the number of steps is equal to $\log_2 N$, while the total complexity of such algorithm is 0 ($N\log_2(N)$).

3.1.2 Prony Analysis

Here is a brief overview of the Prony analysis, while a more detailed explanation can be found in [27, 28]. The signal $f(t)$ that is uniformly sampled with N samples is presented as a series of damped complex values:

$$\hat{f}(t) = \sum_{i=1}^{N} A_i \cdot \mathrm{e}^{\sigma_i t} \cos(2\pi f_i t + \phi_i) \tag{3}$$

$$\hat{f}(t) = \sum_{i=1}^{N} \frac{1}{2} A_i \cdot \mathrm{e}^{\pm j\phi_i} \cdot \mathrm{e}^{\lambda_i t} \tag{4}$$

Where is:

$\lambda_i = \sigma_i \pm j\omega_i$ - Eigenvalues, σ_i, ϕ_i, f_i, A_i - Damping, phase angle, frequency and amplitude of each oscillation.

When the sampling period is T, and $t = kT$, the Eq. (4) can be defined as:

$$\hat{f}(kT) = \sum_{i=1}^{N} B_i \cdot z_i^{k} \tag{5}$$

Where B_i and z_i are given with Eq. (6) and Eq. (7), and in the Tab. 1 are given the expressions for damping, frequency and amplitude of oscillation.

Table 1 Calculation of damping, frequency and amplitude of oscillation using Prony analysis

Damping	$\alpha_i = \frac{\ln\lvert z_i\rvert}{T}$
Frequency	$f_i = \frac{\tan^{-1}\left\lvert\frac{im(z_i)}{re(z_i)}\right\rvert}{2\pi T}$
Amplitude	$A_i = \lvert B_i\rvert$

$$B_i = \frac{1}{2} A_i \cdot \mathrm{e}^{j\phi_i} \tag{6}$$

$$z_i = e^{(\sigma_i + j2\pi f_i)T} \quad (7)$$

3.1.3 Kaiser Window Transformation

Kaiser's Window Transformation, also known as Kaiser-Bessel Transformation, was developed by James Kaiser at Bell Laboratories. It is a single-parameter function, which is used in spectral analyses.

Kaiser window transformation is defined as follows:

$$w_K(n) \triangleq \begin{cases} \dfrac{I_0\left(\beta\sqrt{1-\left(\dfrac{n}{M/2}\right)^2}\right)}{I_0(\beta)}, & -\dfrac{M-1}{2} \le n \le \dfrac{M-1}{2} \\ 0, & \text{elsewhere} \end{cases} \quad (8)$$

Fourier transform $W(\omega)$ Kaiser Window spectral analysis ($W_K(t)$), t continuous quantities) is given as:

$$W(\omega) = \frac{M}{I_0(\beta)} \frac{\sinh\left(\sqrt{\beta^2 - \left(\frac{M\omega}{2}\right)^2}\right)}{\sqrt{\beta^2 - \left(\frac{M\omega}{2}\right)^2}} = \frac{M}{I_0(\beta)} \frac{\sin\left(\sqrt{\left(\frac{M\omega}{2}\right)^2 - \beta^2}\right)}{\sqrt{\left(\frac{M\omega}{2}\right)^2 - \beta^2}} \quad (9)$$

The zero-order of the modified Bassel's first-order functions (I_0) is given with (10), and the β - parameter of Kaiser Window Transformation provides a suitable continuous control over basic window changes.

$$I_0(x) \triangleq \sum_{k=0}^{\infty} \left[\frac{(x/2)^k}{k!}\right]^2 \quad (10)$$

3.2 Proposed Methodology

One of the earliest applications of Wide Area Monitoring is detection and analysis of power system oscillation. Based on results conducted from theoretical analysis of various oscillatory phenomena in EPS, a recommendation is to use at least two spectral analysis methods divided in two layers:

- First layer - Using FFT (or Kaiser Window) method for recognition and early alarming, and activating the method of Prony analysis
- Second layer - Using Prony analysis for detailed analysis of amplitude, frequency and damping.

Fig. 1 shows flow-chart of the proposed methodology that can be applied as a separate sub real time function for early warning and alarming of oscillatory phenomena in the power system. Sub real time analysis means that proposed methodology should be applied on specific interval of data (couple of thousands measurements with sampling of 20 ms) and by that analysis can last for a couple of hundred of seconds.

4 EVALUATION OF THE PROPOSED METHODOLOGY

The signal processing performed with the actual measured values of synchronized phasor measurements for specific operational states will be presented here. The oscillatory phenomena of active power and frequency were analysed. Different data processing methods (spectral analysis methods) described earlier, were compared, and in the end, the results obtained by using different mathematical methods were compared.

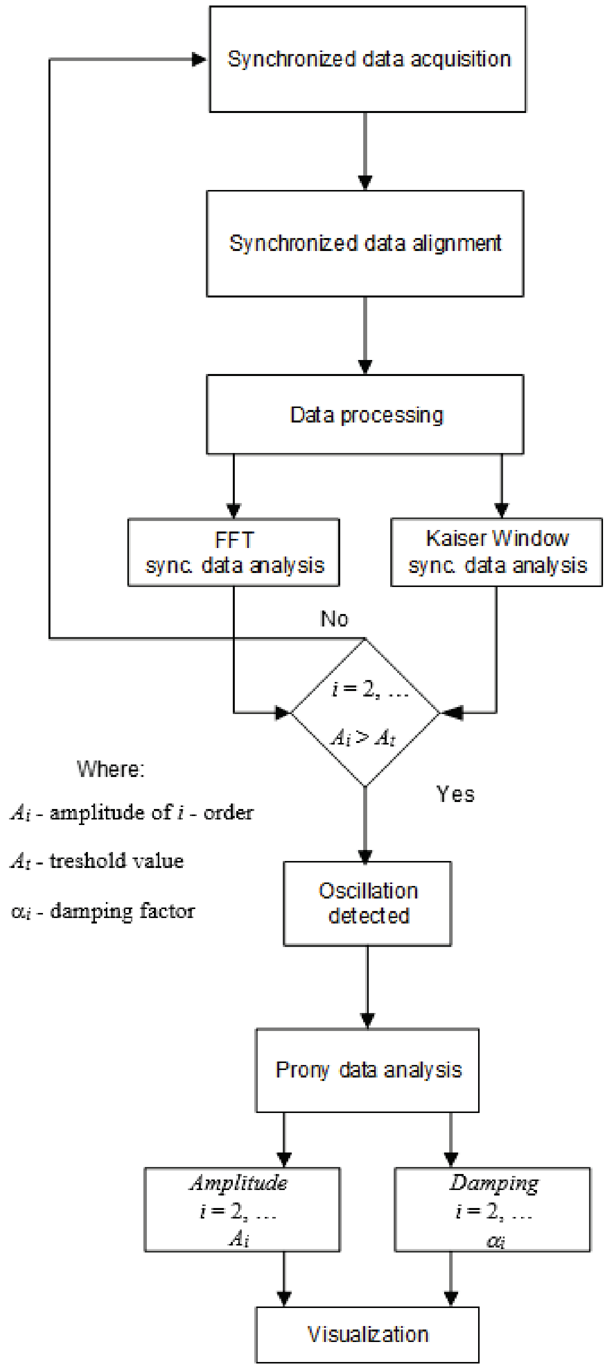

Figure 1 Chart - flow of the proposed methodology for early warning and alarming on power system oscillation

4.1 Processing of Measured Synchronized Data

The first set of synchronized measurements that is processed was recorded for a disturbance at the testing of the facility in Zlatoličje (Slovenia) on April 18, 2008. That disturbance was propagated up to 400 kV voltage level line. The oscillations of active power with the frequency of 1.25 Hz were recorded. Active power and frequency measurements every 20 ms and 100 ms were processed, with data set of 3000 and 1200 records, respectively.

The following analyses were conducted:

1. The original records of measured values (in the time domain) are transmitted with the FFT method to the frequency domain, and the harmonic spectrum is displayed (the size of single harmonic in relation to the base harmonic, as well as the damping of the individual harmonics.
2. The Prony analysis is applied to the original record of measured data. After that, by generating an impulse response of that digital filter, a response in the time domain that can be displayed in the frequency domain is created, and again the harmonic spectrum and the damping of the individual harmonics are displayed.
3. A harmonic spectrum analysis is performed using Total Harmonic Distortion (THD) by the Kaiser Window Transformation method.

4.2 Description of the Disturbance in April 2008

On April 18, 2008 around 15:26 and on April 28, 2008 around 15:35 and 15:52 the operator in nuclear power plant (NPP) Krško in Slovenia observed strong oscillations of the aggregate and informed the operator of the Croatian power system with a request for exchange of knowledge and information [34, 35]. The analysis revealed that the oscillations of aggregates in NPP Krško coincided with the occurrence of pulsating electromechanical oscillations during the testing and commissioning of the revitalized aggregate in hydro power plant (HPP) Zlatoličje in Slovenia. It was estimated that the pulsating electromechanical oscillations of aggregates in HPP Zlatoličje were caused by the regulating instability of the stimulated electromechanical resonance circuit of that aggregate. These pulsating electromechanical oscillations of aggregates in HPP Zlatoličje were most likely the cause of the oscillations (stimulations of the electromechanical resonance circuit) of the aggregates in NPP Krško. By timely exclusion of aggregates in HPP Zlatoličje at the first occurrence of the oscillations and timely silencing of the aggregates at the second and third occurrence of the oscillations by the testing personnel, further dangerous and uncontrollable events were avoided. The reaction of the testing personnel was good even though they did not know what was happening in the system and that very dangerous occurrence of oscillation of the aggregates in NPP Krško occurred.

Figure 2 Overview of the Transmission Power System of Croatia and Slovenia (highlighted hydro-power plant Zlatoličje and 400 kV transmission line Melina - Velebit)

The part of Transmission Power Systems of Croatia and Slovenia with highlighted hydro-power plant Zlatoličje and 400 kV transmission line Melina – Velebit is shown in Fig. 2. Fig. 3 shows the active power values measured every 20 ms on the 400 kV Melina-Velebit line and shows a disturbance that occurred on April 18, 2008 in the afternoon.

The application that processes the recorded data was created in MATLAB and its execution (on the computer with i5 CPU, 1.6 GHz, 8 GB RAM) takes about 1 second, and can vary depending on the type of disturbance and on the number of data in the sample.

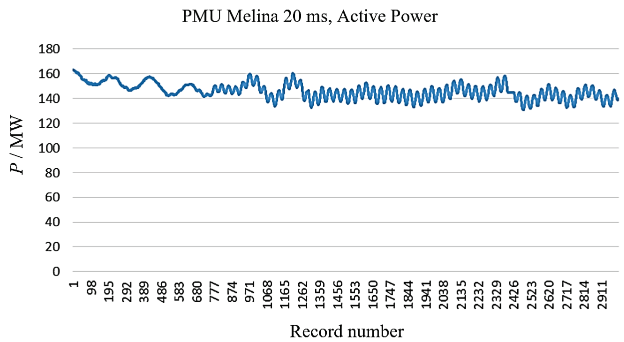

Figure 3 Active power on April 18, 2008, transmission line Melina Velebit

The following figures show the results of processing the input measurement shown in Fig. 3, using the described methods: FFT, Prony and Kaiser Window. Graphs show amplitude, frequency, and oscillation damping. Although Fig. 4 and Fig. 5 show the results of processing the same package of recorded data (the same input signal), the amplitude spectrum is different due to different mathematical methods used. Damping factor (the spectrum of power oscillation damping) presented in Fig. 7, Fig. 8 and Fig. 9 was calculated with predefined MATLAB function (damp).

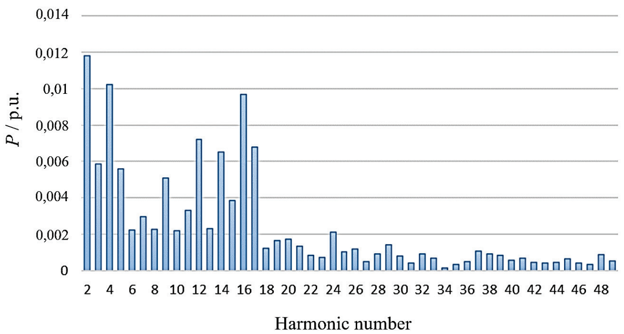

Figure 4 Amplitude spectrum of power oscillation on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by FFT method

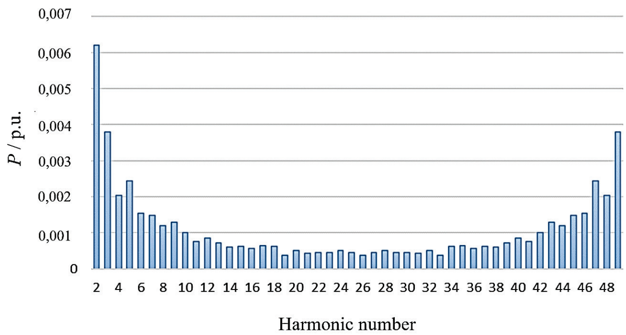

Figure 5 Amplitude spectrum of power oscillation on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by Prony method

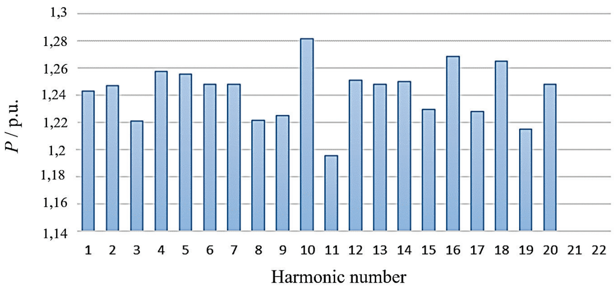

Figure 6 Amplitude spectrum of power oscillation on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by Kaiser Window method

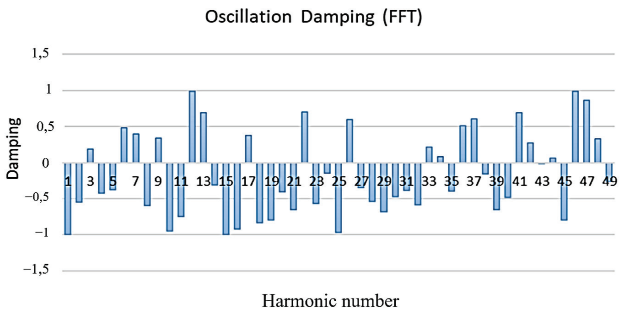

Figure 7 Spectrum of power oscillation damping on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by FFT method

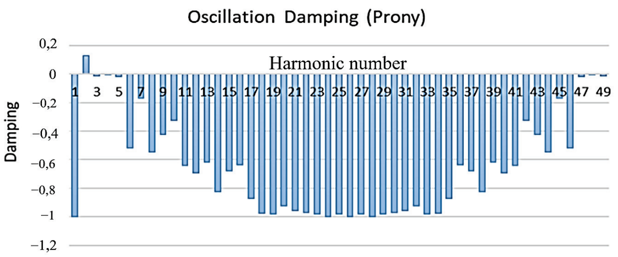

Figure 8 Spectrum of power oscillation damping on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by Prony method

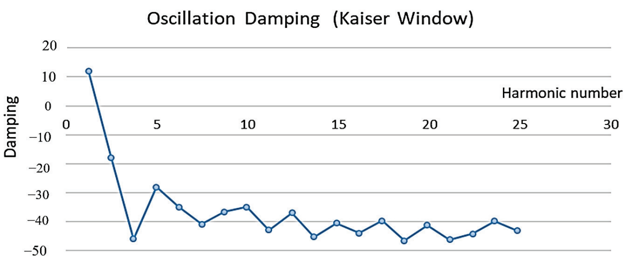

Figure 9 Spectrum of power oscillation damping on 400 kV power line Melina - Velebit for the event on April 18, 2008 obtained by Kaiser Window method

The proposed methodology for monitoring and detection of oscillatory phenomena in the EPS uses two levels and it was applied to measured synchronized data set. It can be concluded that by using Fast Fourier Transformation in the first level, on the given set of synchronized data, it performed detection of power swing. The second level, in which Prony analysis is used, provides more detailed information of oscillation, such as, decomposition of the original oscillatory signal to spectrum of oscillation amplitudes and damping factors.

5 CONCLUSIONS

Mathematical methods of data processing (primarily related to spectral analysis), as well as applications/ functions within the Wide Area Monitoring, Protection and Control (WAMPAC) system which use synchronized phasor measurement as input value, it is necessary to use specific mathematical analyses in applications which process oscillatory phenomena in electrical power systems. The most significant applications should have the function for recognition, analysis and alarming of power oscillatory phenomena; oscillations of turbine regulator, inter area and local electromechanical oscillations and subsynchronous oscillations.

After the analysis of the papers related to studying the phenomena of power oscillations in the electrical power system, this paper focused on three methods of spectral analysis: Fast Fourier Transformation (FFT), Prony Analysis and Kaiser Window Transformation. These methods were applied on synchronized measurements of voltage and current phasors for the described actual disturbance that occurred in the Croatian Power System. Analyzing the results of processing synchronized measurements by different methods revealed that when setting parameters for a single method, it is not necessary to analyze measured values up to the 50th order, since for periodical functions with the period of 20 ms it is sufficient to analyze results until the 25th order (after that point the results of the analysis are repeating).

The results obtained with Kaiser Window Transformation, as presented here, show that this method does not give significant results, and therefore is not recommended for oscillations disturbance analyses.

The analysis of results given by FFT and Prony methods showed that FFT gives preliminary results of amplitude, frequency and damping for oscillatory changes of active power on lines, while Prony method can accurately detect dominant values of frequencies, as well as associated damping.

Proposed methodology should be implemented as Wide Area Monitoring application in existing PDC software by using raw synchronized measurements of voltage and current phasors and linked with alarming module and database and Data Warehouse module.

The length of data package (time interval) that will be processed varies upon wide area monitoring application. Presented method is tested on recorded active power and frequency data after real disturbance in power transmission grid and time interval of recorded data is determined empirically. According to the length of processed data package impact depends on noise and data uncertainty and usually applications that use proposed method are pseudo-real time applications. When implementing the analysis in a real-time application, the computation time can be increased by optimizing the code.

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