

On Line Electromechanical Oscillations Detection in Transmission Network with Synchrophasor

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Abstract—The power system is an example of a nonlinear system with many different oscillation sources and accordingly many oscillation types, including electromechanical oscillations, oscillations caused by control elements, or sub-synchronous oscillations. The estimation of oscillation types in the power system gives a direct insight into the state of the system stability. The ability to estimate oscillations in real time is facilitated by installing a Wide Area Monitoring System (WAM), which enables accurate metering with accurate timestamps. The HOPS synchrophasor concentrator, in addition to its main role of collecting and processing synchrophasor measurements, has an electromechanical oscillation analysis module. This paper describes the oscillation detection tool for historical data with an aim to develop real time oscillation detection system for potentially unstable events in real-time.

Keywords—*electromechanical oscillations, Prony analysis, synchrophasors, WAMS*

I. INTRODUCTION

Basic concept for Wide Area Monitoring Protection And Control (WAMPAC) system has been known for a while but implementation in Transmission System Company (TSO) has happened when technology and theoretical background for specific disturbances in power system have been mature enough. Wide Area Monitoring system has been used as a basis on synchrophasor measurement and it is an example of technology use which gives completely new concept for monitoring, protection and control of power system in real time.

WAMPAC system with Phasor Measurement Unit, PMU placed across whole transmission network or power system is a data source for synchrophasor values of voltage and current. Those data have unique importance. Because of that WAMPAC system is able to produce dynamic insight in power system in real time. Results of this new technical solution are greater precision of measurements, faster data exchange thus making it possible to design and implement new algorithms for protection and control in power system.

WAMPAC system can be divided into three main modules:

- Phasor Data Concentrator, PDC for collecting data from PMUs.
- Processing of synchrophasor measurements in various applications in control room or functions in WAMPAC system.

- Presentation of processed data which can be used for the following.
 - Decision making tool for dispatcher assistance in control room.
 - Automatic sequence for prepared control actions in power system.
 - Offline processing and post-mortem analyses.
 - Using synchrophasor data in System Integrity Protection Scheme (SIPS).

Each application in WAMPAC processes electrical synchrophasor values using optimal mathematical analyses, depending on requirements for those applications. In developing new applications [1] – [3] which would detect and predict complex disturbances in system, additional mathematical analyses according to their advantages or abilities, have to be deployed processing raw WAMPAC data into useful information that can be presented to network operator.

II. ALGORITHMS FOR DETECTION AND ANALYSES OF ACTIVE POWER AND FREQUENCY OSCILLATIONS

Nature of active power swing phenomena in power system is caused by oscillatory interaction of generators or group of generators responding to different changes in power system. Power system have many oscillatory modes because of numerous different components operated. There are different mathematical methods which can be used in analyses of oscillations in power system according to [4] – [6]. Usually active power and frequency oscillations are monitored as they are of great importance.

A. Type of oscillations

Characteristic frequencies of oscillations connected to disturbances in power system are in Table I., generally divided in three categories.

TABLE I. FREQUENCY RANGE FOR OSCILLATIONS IN TRANSMISSION NETWORK

No.	Frequency range	Type of oscillations
1.	0.002-0.1 Hz	Turbine governor oscillations
2.	0.1-4.0 Hz	Interarea and local electromechanical oscillations
3.	4-46 / 56 Hz	Sub-Synchronous Oscillations - SSO

1) *Turbine governor oscillations*: Low frequency oscillations were influenced by turbine governor control and mechanical performance of generators in power plants. Decreasing inertia capabilities of power system strongly influences and raises frequency instability and sensitivities in power system during active power changes. Very low frequency oscillations usually are common oscillations in whole power system. Research and praxis pointed that in some cases those oscillations can be up to 1.0 Hz with period of 30 seconds in power system with dominant hydro power plants. In European power system those oscillations are revealed in small and middle-sized system like Island, Ireland and Nordic countries.

2) *Interarea and local electromechanical oscillations*: Interarea electromechanical oscillations include oscillatory interaction of generators connected to the network with other rotors (generators) in the network. In a case of oscillations between areas one group of machines will oscillate in one direction while other group of machines on far end will oscillate in opposite direction. Electromechanical oscillations can be categorized as local oscillations if those oscillation appears only in one power plant while oscillations in rest of the power system can be neglected. Local oscillations modes usually have higher oscillations frequencies than the interarea oscillations because of smaller inertia of one machine. However, in some cases it is hard to have clear distinctions between those two categories.

3) *Sub-Synchronous Oscillations - SSO*: For bigger frequency oscillations, the cause is natural oscillations inside power plants (turbine governance control) with power system. This phenomenon can be distinguished in three variants; subsynchronous resonance, subsynchronous interaction with governance and subsynchronous torsion interaction.

The main goal is to find the most appropriate mathematical method for determining the amplitude, frequency and damping for active power oscillations. Several methods were studied to select the methods which will be implemented for on line detection in WAMPAC system:

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

FFT and Prony analyses were chosen for detection and analyses those type of oscillations [7] – [11].

B. Fourier Transformation

Fourier transformation is a method of decomposition and signal approximation through sum of multiple sine waves. Applying Fourier transformation with observation window corresponding to frequency of disturbance oscillation it is possible to track the origin of disturbance. The Fourier transform is interesting when looking for oscillations because there are no problems with numerical instability, and with

certain trade-offs in resolution it is in practice algorithmically less complex than the Prony method. However, Fourier transformation gives only amplitude and frequency values, without information for signal damping. Still damping can be calculated by tracking amplitude variations of some harmonics in time. Second weakness of this method is relative frequency resolution. In theory procedure allows to have some small growth in frequency in decomposition spectra. This growth is inversely proportional to observation time window. For spectral decomposition for fine granulation window needs to be long (window of 100 seconds for resolution of 0.01 Hz) or it is needed to extend the signal in time domain using zero-padding technique. This can help to increase resolution for isolated frequency spectral component, nevertheless it still impossible to increase resolution and separate the near spectral component.

C. Prony Analyses

Using classical methods like Fourier transformation to define frequency specter and signal amplitude, for electromechanical oscillations additionally damping or changes in amplitude oscillations and phase of oscillations must be defined. Some additional key indicators make it easier to find location of oscillations source. The most often mathematical methods used for signal analyses and identification systems with synchrophasor measurements is Prony analysis. Prony analysis has advantage in comparison with other mathematical methods because original measured signals were decomposed in way that gives information about frequency, amplitude and phase of oscillatory modes and also gives damping value for each mode.

Prony analysis directly estimates parameters structure of eigenvalues (left and right eigenvalues) and made up the following set up. Complex damped sine wave was equally deployed in observed time period (1):

$$\begin{aligned}
 y(t) &= \\
 &= \sum_{i=1}^L c_i e^{\lambda_i t} = \sum_{i=1}^L c_i e^{(\sigma_i \pm j\omega_i)t} \\
 &= \sum_{i=1}^L A_i e^{(\sigma_i t)} \cos(\omega_i t + \varphi_i) \\
 &= \sum_{i=1}^L A_i e^{(\sigma_i t)} \cos(2\pi f_i t + \varphi_i)
 \end{aligned} \tag{1}$$

Parameters from (1) are:

- A_i Amplitude for component i .
- λ_i Eigenvalues for system.
- σ_i Damping coefficient for component i .
- ω_i Angle frequency of component i .
- φ_i Phase angle of component i .
- f_i Frequency of component i .
- L Total number of exponential components.

Damping ratio for exact oscillatory mode that has been used for defining the stability of power system is determined like (2):

$$\xi_i = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (2)$$

Damping values define instantaneous stability (3):

$$\begin{cases} \xi > \xi_0 \rightarrow \text{System is stable} \\ 0 < \xi < \xi_0 \rightarrow \text{Weakly damped system} \\ \xi < 0 \rightarrow \text{Undamped system} \end{cases} \quad (3)$$

Damping ratio (or relative damping) of 5% means that in three oscillation periods, amplitude is damped for approximately 32% of initial value. Minimal value for damping is not quite exactly defined but damping of less than 3% may be considered as insufficient. Total system damping can be satisfied and correct, and power system is stable if all oscillatory modes have damping of minimally 5%.

III. COMPARISON OF MATHEMATICAL CALCULATIONS WITH MEASURED SYNCHROPHASOR VALUES

This chapter describes conducted signals processing from real synchrophasor values for specific event in power system. Comparison of two methods from chapter II was carried out with results from those methods also compared. Measurements of active power and frequency in two sample per second values, 20 ms and 100 ms were processed with a data set of 3000 and 1200 sample. One generator oscillation in hydro power plant Zakučac at 14 November 2014, was chosen from archive [12] – [13] to be processed in this study work. Oscillations in this case were induced by combinations of two facts. During that time maintenance work on generator was being done, and for that purpose some set up and parameters changes in turbine governor and voltage regulators were made. Hydro power plant has complex switchyard with two voltage levels, 220 kV and 110 kV, and two busbar systems in each voltage level. Circuit breaker at coupler bay failed during operations and provoked busbar protection to operate and trip some circuit breaker.

This sudden changes in both switchyards was the reason to initiate oscillations for generator No. 1 and No. 4, which at the time were producing 120 MW and 136 MW. Both generators have significant amplitude oscillations even up to ± 70 MW. Operating personnel in power plant followed the procedure and tried to stabilize generators operations. Ultimately generators had to have been switched off from network making the oscillations disappear.

Those oscillations propagated up to highest voltage level and were recorded with WAM system on 400 kV level in whole network, Fig. 1.

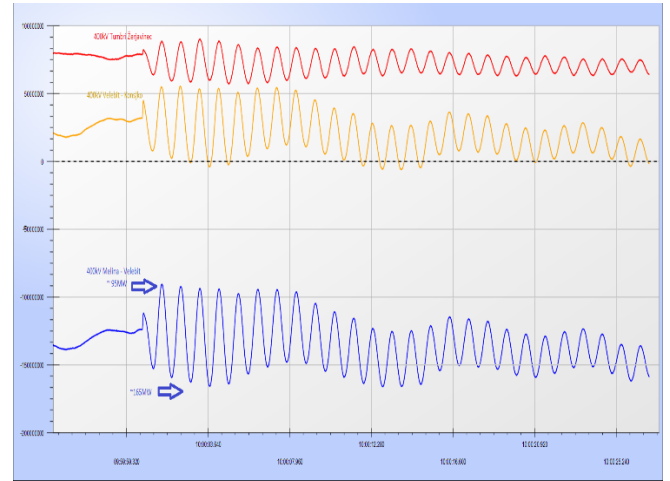


Fig. 1. Active power oscillations detected on three 400 kV line

Blue and yellow line on Fig. 1 represent oscillations on 400 kV line in vicinity of hydro plant. Red line is for 400 kV line few hundred kilometers away from hydro plant.

Oscillations continued almost 10 minutes and changed during the disturbance because the switching state of network also changes. Fig. 1 presents only the start of these oscillations.

The result of Prony algorithm applied to oscillation records captured on 400 kV line Melina-Velebit is presented on Fig. 2. The diagram presents line power processed by Prony method, amplitude and frequency of detected modes.

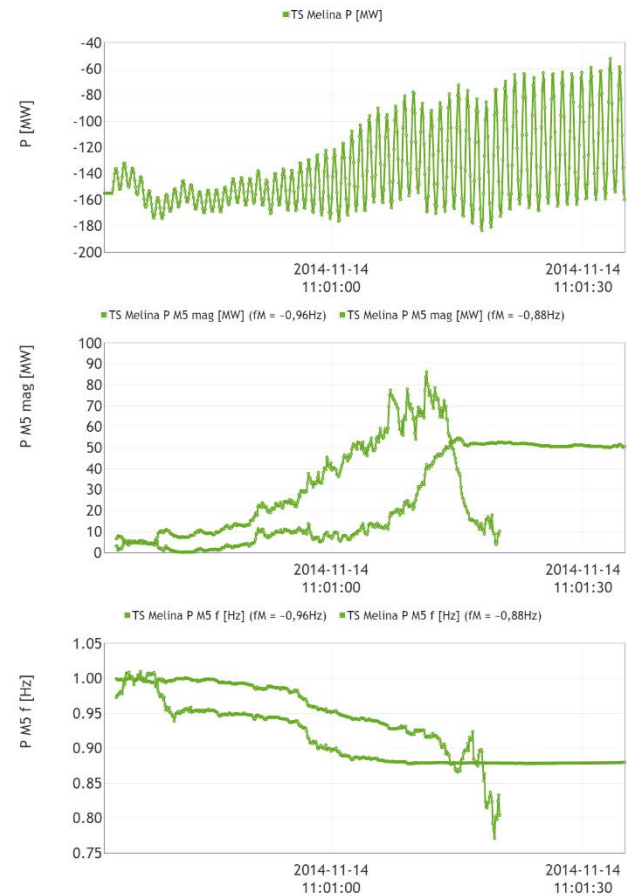


Fig. 2. Line power processed by Prony method, amplitude and frequency of detected modes at 400 kV Melina-Velebit

At the beginning of the oscillation event two modes with frequencies close to 1 Hz were detected. After a change in the system (probably change of switching state in hydro power plant) which is manifested in a change of the mean value of power at 11:00:38, mode frequencies were separated by 0.05 Hz with a simultaneous decrease in frequency towards 0.96 Hz and increase in amplitude. With the further development of the oscillatory event mode frequencies shifted towards 0.9 Hz with an additional increase in oscillation amplitude. Another change in system that happened at 11:01:11 resulted with the abrupt decrease of frequency and amplitude of one mode. After approximately seven seconds an amplitude of that mode was reduced below the detection threshold. The second mode kept its frequency and amplitude unchanged at 0.88 Hz and 51 MW until the end of the observed period.

During this observation period, damping calculations was successfully calculated, Fig. 3.

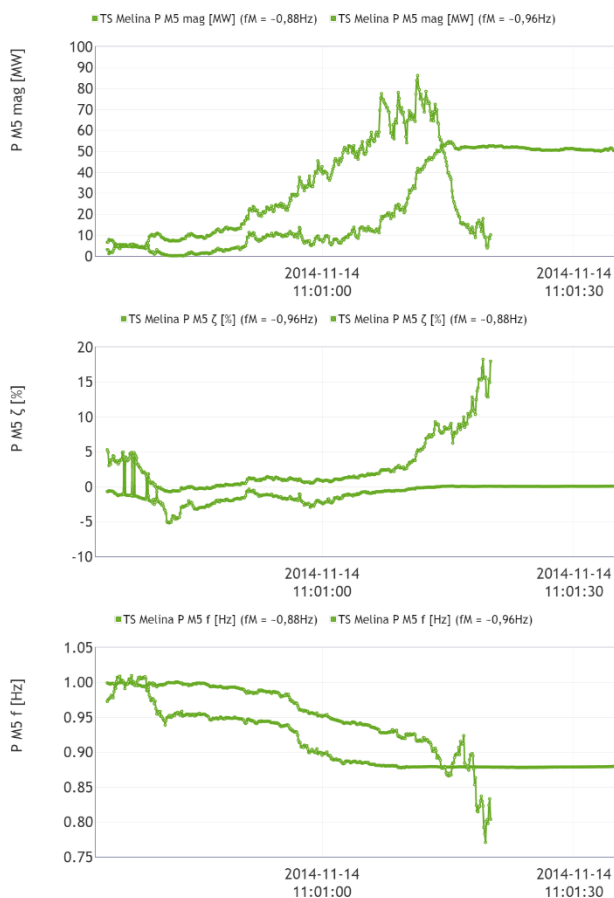


Fig. 3. Amplitude, damping ratio and frequency of detected modes at 400 kV Melina-Velebit

Proposed method processes in good and precise manner three main values important for oscillation detections in power system and respectively in transmission network in real time, which raise capabilities of TSO for control.

IV. IMPLEMENTATION OF PRONY METHOD IN WAM SYSTEM

Wider spectra of electromechanical oscillations is a goal to be detected and the Prony methods which will be implemented must be able to detect oscillations from 0.1 Hz to 2.5 Hz. Also dimension of time window must be defined

that capture all wanted oscillations but in the same time must have shot enough window to be able to have right reaction for detection in real time.

First step was to test the chosen Prony set up on historical PMUs data. Adjustment and fine tuning is in the following direction. Synchrophasor data stream in full resolution (50 synchrophasor per second, with time resolution of reporting every 20 ms) gives comparable results to having the same data stream decimated on 10 Hz (reporting rate of 100 ms), but with far less computation steps. Next step in decimation on 1.0 Hz (reporting rate of 1000 ms) show that can be useful only for frequency form 0.05 Hz to 0.01 Hz. For frequency higher than 0.1 Hz these decimations cannot be applied. After analyses for optimal ratio between quality and numerical computation decimation of 10 samples per second and window with 200 samples (time period of 20 second) is selected. This set up allows for detecting oscillation modes in frequency range from 0.1 Hz to 2.5 Hz.

A. Signal preparation and calculation

Decimations of 10 sample per second is set before to start Prony decomposition. Window with 200 samples firstly goes through detrending process removing the DC component and linear changes in input signal (increased or decreased trend) during observation window. After that, the window is processed with Prony method: building the Toeplitz matrix with input signal, then calculating pseudoinverse matrix (Moore-Penrose inverse matrix). Characteristic polynomial is a result of matrix operations. Prony method as a result gives different modes, which were categorized by amplitude. Modes, which were not fit in the boundaries, were discarded. Usually those modes were high frequency with short duration, as a deficiency of numerical calculations. At the end, modes with great damping also were discard. Modes with damping greater than 20% is set like parameter to throw away this mode. This parameter is chosen as experiential parameter and usually does not represent stabile oscillation in power system.

B. Oscillation modes tracking in time

Goal is to detect permanent oscillations and present them in time, and because of that, results of Prony analyses from particular windows were traced through time and grouped in trends.

Algorithm for mode tracking through time has two lists for modes: list of active modes (those modes that have in last results of Prony, damping coefficient < 20%), and list of inactive modes (those modes were detected during the tracking, but were not detected during last two windows of Prony).

After each calculation of Prony methods on a new window, results were firstly compared with a list of active modes. Algorithm calculates matrix of probability to locate the modes (matrix = [number of detected modes] * [number of active modes]). Calculations for probability of affiliations to some of existing modes is inversely proportional to distance from mode frequency, which has been increased for average frequency of last 10 modes for tracking mode. Frequency deviation from tracking mode must be less than 0.01 Hz.

In a case that in a list of active modes there are no matching modes, then the same procedure is applied to the list of inactive modes. If the mode frequency finds a match in

the list of inactive modes, then this particular mode is switched to the list of active modes, otherwise a new mode is created and added to the list of active modes.

This algorithm gives priority to active mode during the phase, which groups the modes. In case of gradually frequency slipping from a mode frequency we can get that, some other inactive modes can be recognized. In such case continuous mode tracking will be terminated.

In our case, mode tracking is organized in eight groups (window), Table II.

TABLE II. FREQUENCY FOR MODE TRACKING IN RANGE 0.1 Hz – 2 HZ IN EIGHT GROUP

1	2	3	4	5	6	7	9
0.1Hz	0.2Hz	0.3Hz	0.7Hz	1.0Hz	1.15Hz	1.5Hz	2.0Hz

Results of Prony analyses were classified in the nearest window.

C. GUI for Prony algorithm

Special GUI was designed for the analyses of historical and real data in WAM system. GUI has many possibilities: to organize and present data and detect oscillations in power system. The four main display were organized for Prony presentation:

- PRONY TREND: simple use of Prony method for any set of historical synchrophasor data with few values and several measurement points, Fig. 4.
- PRONY ANALYSES: simple graphical, table and vector display of Prony results for comparison of detected mode in different locations, Fig. 7.
- PRONY DECOMPOSITION: gives possibilities of Prony decomposition for order of 200. Display offers details for each calculation mode and is possible to analyses each mode in time, Fig. 5.
- LIST FOR DETECTED OSCILLATIONS: List gives detail data for oscillations comparing the historical database. Those data were; basic data for oscillations, locations, time of events, durations, values when the oscillations were detected, frequency, damping, maximal and average amplitude and energy, Fig. 6.

Fig. 4. GUI for Prony Trend for disturbance in south part of Italy on 03.12.2017.

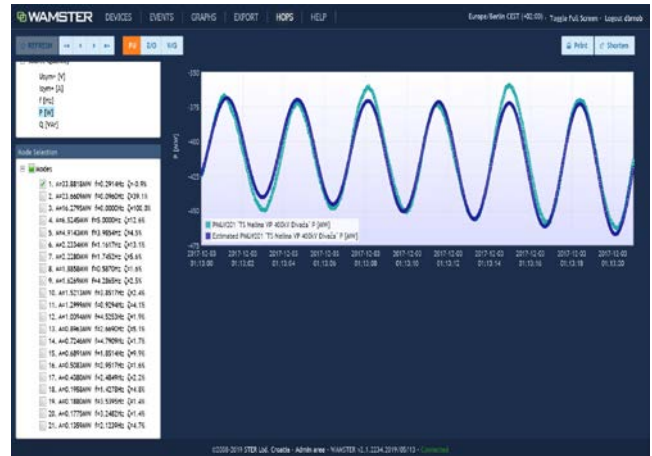


Fig. 5. GUI for Prony decomposition for comparison of input signal and calculated mode, 0.291 Hz; 0.9%; 33.9 MW

D. Analyses of oscillations detected on line 400 kV Konjsko-Mostar

In addition the detected oscillations on 400 kV line Konjsko-Mostar are presented. Processing of synchrophasor data detected one event, with duration of 1 minute and 16 seconds, with frequency oscillations 0.17 Hz and median power oscillations of 10.72 Mw, Fig. 6.



Fig. 6. Oscillations detected on line Konjsko-Mostar in substation Konjsko

Fig. 6 presents few information from this event. For the same event, eight PMU devices from all over transmission network also tracked oscillations. Some of them were in same substation and others a several hundred kilometers away. Detailed results of Prony analyses and phase for each mode are on Fig. 7.



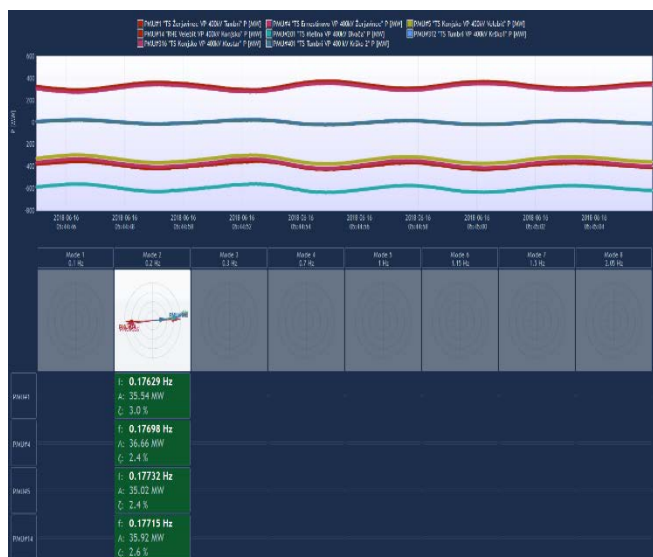


Fig. 7. GUI for Prony Analyse during oscillations on line Konjsko-Mostar, which were detected from 8 PMU devices on 400 kV transmission network

During this oscillations period some changes in amplitudes, frequencies and damping factor were persistent, Fig. 7. Data from PMU#14 (substation Velebit) and PMU#316 (substation Konjsko) were opposite in phase. It can be concluded that between those two PMUs is some imaginary center of oscillations in east-west direction in European interconnection and the cause of oscillations are somewhere outside of Croatia.

Fig. 7 present relatively small oscillations in active power on all 400 kV lines in transmission network and those oscillations were changed during the event. Prony analyses gives exact information about magnitude and frequency of oscillations. Frequency of oscillations are around 0.18 Hz and this clearly points out interarea oscillations.

Damping factor was also tracked efficiently during the whole disturbance.

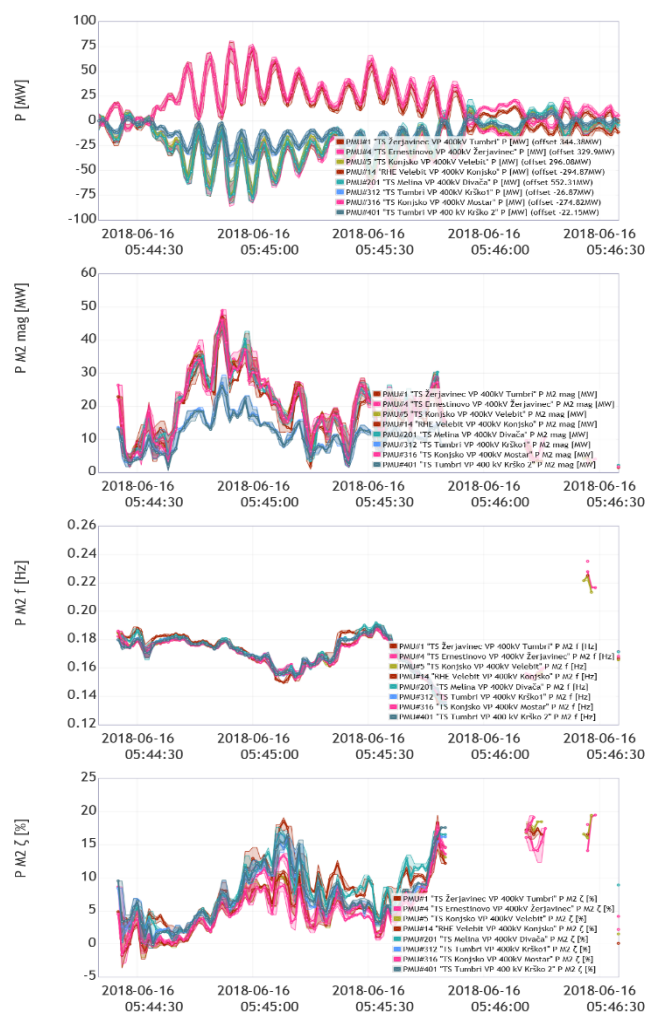


Fig. 8. Amplitude, frequency and damping mode for all 400 kV line in transmission network in Croatia

V. CONCLUSION

Paper extensively presents work and results to implement on line detection of active power oscillations in power system and transmission network in WAM system, which is located in, control room of Croatian TSO. Once more is clearly visible that using synchrophasor data has unique values in power system applications. Deep insight in power system in area of oscillations has been established using synchrophasor data.

Prony method was chosen to be implemented in new applications in WAM system. Output from these new functionalities are values of amplitude, frequency and damping for each oscillation in power system.

Method was tested on archive data from well documented oscillatory events in transmission network with WAM system.

Numerical calculations were stable and adequate ratio between time resolution of results and number of modes was found, which was calculated during estimation process of electromechanical oscillations, between length of time window for processing and request for numerical calculation. New applications were used to present the main results and benefit on real oscillations in one hydro power plant and for one interarea oscillation in European continental interconnection of high voltage transmission network.

Future work will be in two directions. Continuing the work on archive data in order to define key point indices for such oscillation events and disturbances in transmission network. Second part will be in direction to realize full real time functionality in WAM system in control room. That means intensive testing and setting up final parameters so that WAM system can raise alarms to operating personnel.

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