Real Time Operation of Synchrophasor Data Functions in Transmission System Control Room

Igor Ivanković
Croatian transmission system operator
HOPS
Zagreb, Croatia
igor.ivankovic@hops.hr

Renata Rubeša
Croatian transmission system operator
HOPS
Zagreb, Croatia
renata.rubesa@hops.hr

Igor Kuzle
University of Zagreb
Faculty of Electrical Engineering and Computing
Zagreb, Croatia
igor.kuzle@fer.hr

Marko Rekić
Croatian transmission system operator
HOPS
Zagreb, Croatia
marko.rekic@hops.hr

***Abstract*—Rare events and disturbances in transmission network can occur in some time frames or with some electrical values which are not fully covered with relay protection and SCADA systems. This gap can be fixed with Wide area monitoring system in control room. WAM system collects synchrophasor data from all 400 and 220 kV transmission lines. Inside WAM system special functions, based on synchrophasor data, were developed for these purposes. That way total monitoring for power oscillations in transmission network is established. These functions are in testing phase and will be connected to SCADA system in control room. New generations of Phasor measurement units send to control room values for all three phase values and positive, negative and zero components. Function for early warning also was developed based on negative and zero components. Special attention was put on communication channels and delay aspects. Special algorithms were implemented to override those aspects in communication channels. Few examples for those new functions will be elaborated and presented.**

Keywords—synchrophasor data in control room; monitoring of oscillations in transmission network; monitoring of negative and zero component in transmsission network

I. Introduction

Synchrophasor data, standards

Two types of phasor measurement units are in operation in transmission network, which send data to phasor data concentrator in control room. Old types generated data stream with positive sequence of voltage and current. New types generated full range of values, positive, negative and zero sequence [1], and all three values for phase voltage and current.

WAM system in control room operated in monitoring mode with basic functionalities. Data collected were extensively used for off line analyses and study work.

New project have been launched to upgrade the existing system with new functions. One part of project has goal to connect existing WAM system to SCADA system, Fig. 1. Conclusion from many analyses pointed that this connection should be established because there is a group of events, which can effectively be detected with WAM functionalities. In some circumstances those events and disturbances will hardly be noticed without relay protection or WAM system.

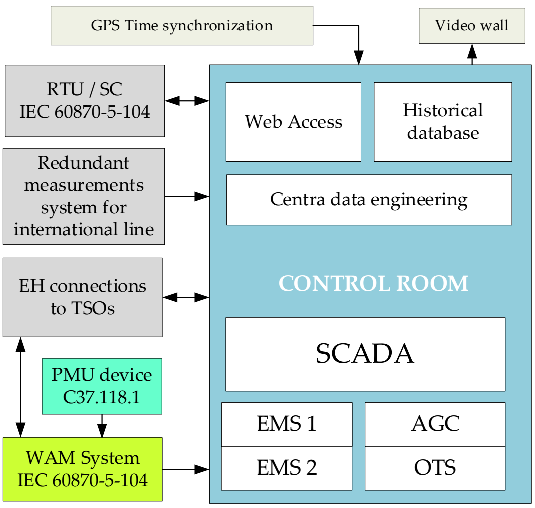

Fig. 1. SCADA system with basic block scheme and future WAM system connection

New PMU devices in this system use protocol C37.118.1 and older type of device use IEEE 1344. Newer protocol offers much more data from PMU devices and is more suitable for developing advanced functionalities. Today RTU system used protocol IEC 60870-5-104 as default solution. WAM system

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will implement these functionalities in SCADA system using that protocol.

II. Undetctable Events in Control Room

A. *Time frame and events in transmission network*

Majority of events and disturbances will be detect and monitored with two older systems, SCADA and relay protection system. Some gap exists between them in time domain because both have some limitations. WAM system [2] can overlap this gap with some automatic algorithms, Fig. 2. In future WAM system will be upgraded with protection and control function, WAMPAC system [3], [4].

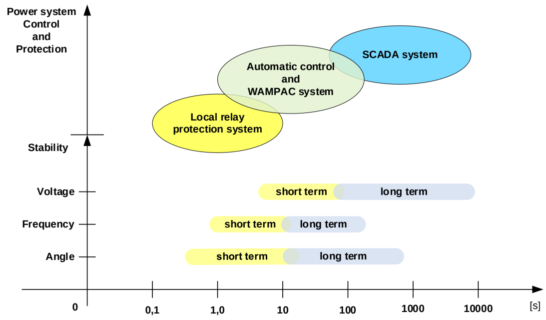

Fig. 2. Power system control and protection, and events in power system in time frame scale

Disturbances in power system can be divided in three groups by value with each being short term or long term. Experience from operating with WAM system shows that complete range of events can be covered by this system.

B. *Prefaults and predamages events*

SCADA systems have resolution of sampling rate with few seconds and some dead zones for various signals. Issues for current signals connected on metering core of instrument transformer have certain limitations. Relay protection system are dominantly parametrized for high current which occur during short circuit. For that reasons some slow evolving fault and other specific fault usually will not be detected in correct way. Those faults and events happen from time to time and are listed in Table I.

TABLE I. Transmission Elements and Events Effective Traceable with WAM System

	Element	**Event**
1.	Line	Phase and ground wire issues, High resistance fault
2.	Transformer	Power transformers issues, Metering transformers issues
3.	Circuit breaker	Faults inside breaking chamber, Motion parts issues
4.	Measurement	Auxiliary source for SCADA measurement and validation

Positive sequences are limited to detect some events in the network. Negative sequence can detected almost any specific faults (high impedance fault, specific fault in power transformer (turn to turn fault), and metering transformer). For that reasons, new PMU devices have significant advantage in use in transmission network operations [5], [6].

Prefault conditions and start of failures on overhead line, for example, damages on phase wire and jumper can be effectively detected. Problems with equipment in switchyards (circuit breaker operations, contacts not completely opened or closed, or problems in breaker chamber) will be discovered in early phase. WAM system is highly sensitive and can detect failures with very low operations load (current), such events cannot be detect with modern numerical protection without dedicated settings for protection purposes.

Measurements from WAM system can be used in some validation processes for supervising measurement in SCADA system and other applications (accounting).

C. *Low and medium oscillations*

Even strong and mesh transmission network can suffer from oscillations of active and reactive power [7]. Detection systems for those events are still only relay protection system. Relay protection devices on line can recognize in some rough manner those power oscillations. Parameters setting in this function focus only on line protection functionality (short circuit). That is why relay functions are rarely sensitive enough to detect small oscillations. Those oscillations are usually categorized in four groups, Table II.

TABLE II. Active Power Oscillations Range in Continental European Transmission Network

	Type of oscillations	**Frequency**
1.	Interarea oscillations	0.2 Hz to 0.4 Hz
2.	Regional oscillations	0.5 Hz to 0.8 Hz
3.	Machine oscillations	0.9 Hz to 2.0 Hz
4.	Large disturbance [a]	more than 2 Hz, even to 10 Hz

[a] Large oscillations will trigger line relay protection system

Other applications in control center were also not designed and developed to have ability to detect oscillations in transmission network. SCADA system can collect data but in real time, it cannot detect oscillations. Only in off line analyses some anomaly in power flow can be detect.

Information for detection of active power flow oscillations will be generated in control room and dispatcher can activate adequate measure. It is important to have early detections of generator in irregular operation, (failure in regulations circuit of turbine or voltage control), triping of some generation unit in transmission network which caused swinging in transmission network in real time. With those alarm functionalities additional data for study works and analyses for network operations, validations for control and parameter setting (primary regulations, PSS parameters), relay protection setting will be collected.

III. Available WAMS Functions for Control Room

WAM system in control room has several implemented functions for different purposes. Those functions were intensively tested through FAT and SAT phases before they passed to production phase inside applications. Basic functionalities where created for voltage, current, frequency and oscillations monitoring, Table III.

TABLE III. FUNCTION IN WAM SYSTEM FOR DETECT EVENTS

	Element	Alarm level
1.	Voltage monitoring	High level in 2 stage and 1 stage in low level
2.	Frequency monitoring	1 stage for high and low level
3.	Current monitoring	High level in 2 stage
4.	Oscillations monitoring	High level in 4 stage

A. Voltage and current monitoring

Using that electrical value it is possible to trace many disturbances in transmission network. Alarm levels are set using experience from relay protection setting. Time delays (10 and 5 seconds for voltage and 20 seconds for currents) are set for some level and other levels will operate without time delay.

B. Frequency monitoring

This value is important for controlling the transmission network and WAM system can be used very effectively for tracing the frequency. Each PMU device continuously gives information for frequency and no time delays were set on.

C. Oscillations monitoring

Currently in this phase of project, oscillations monitoring function uses voltage angle values. It uses values from both line ends through installed PMUs. Study work for synchrocheck function define values for alarms in four stage (5°, 10°, 20° and 180°), without time delay.

IV. ANALYSES OF CHARACTERISTIC EVENTS FROM OPERATIONS

In this chapter four characteristic events will be analyzed in order to present real and full potential of synchrophasor data. All of those events are record without some automatic action from system or dispatcher, but each case shows that some automatic action (alarm rise in SCADA or breaker triping) will help.

A. Sensitve monitoring for low profile line fault

Full potential of synchrophasor data use is presented in case when transmission network is not fully covered with PMU devices, Fig. 3.

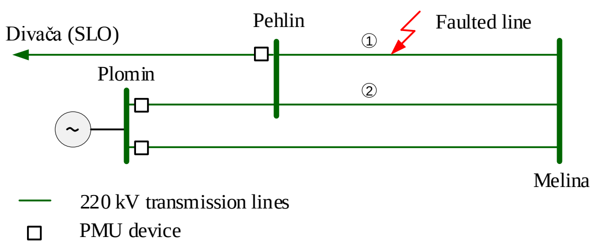

Fig. 3. Singl line diagram for 220 kV transmission network affected with fault on line Pehlin-Melina 1

Very specific fault starts too develop on line 1 without PMU, but on other three lines, enough data is collected from PMUs, to make correct conclusion that something happened in neighboring network. In one phase jumper was broken on tension tower, Fig. 4.

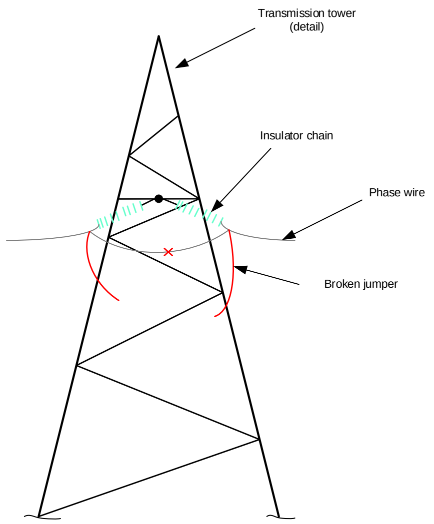

Fig. 4. Type of phase fault on line tension tower

Line to Divača (SLO) has significant load, average value for current were more than 450A, other two lines only 50A. Fault started on date 04.03.2018, at 21:16:57 hours, Fig. 5.

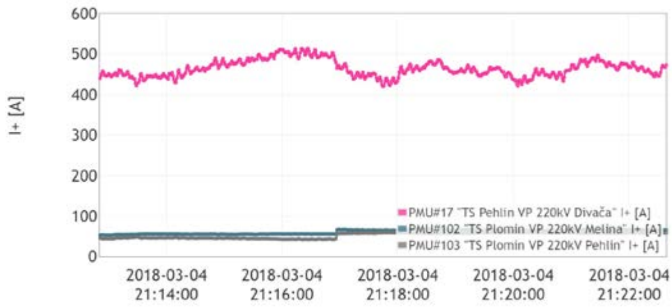

Fig. 5. Current positive value for three transmisison lines with fault appears on fourth non PMU monitored line

Using only positive value for current it is hard to recognize that anything happened but with negative sequence, Fig. 6 and zero sequence Fig. 7, it is clear that the fault is there.

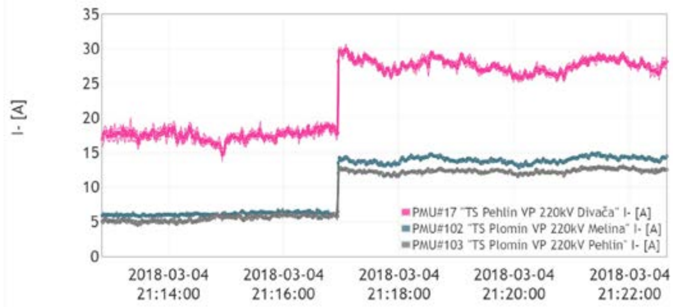

Fig. 6. Current negative value for three transmisison lines with fault appears on fourth non PMU monitored line

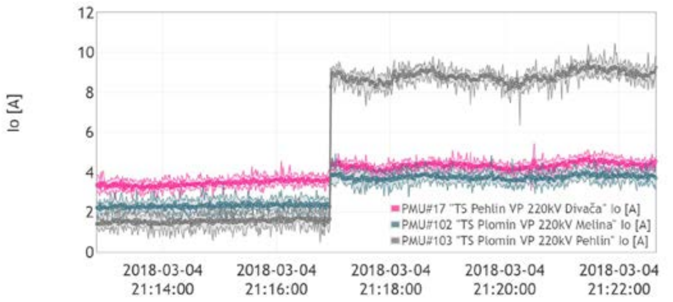

Fig. 7. Current zero value for three transmisison lines with fault appears on fourth non PMU monitored line

Negative and zero sequences have increased immediately and pointed that there is fault in network. Unfortunately, fault lasted until 07.03.2018 at 08:56 hours when the line 1, switched off from operations, Fig. 8 and Fig. 9. Before that, first signal from relay protection appears at 08:38 hours. From fault occurrence and first signal from relay protection too much time has passed.

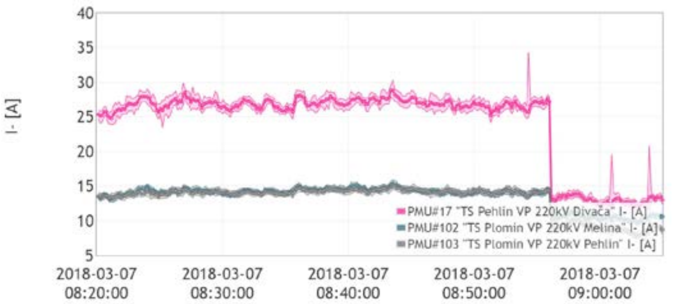

Fig. 8. Current negative value for three lines with fault disconected on fourth non PMU monitored line

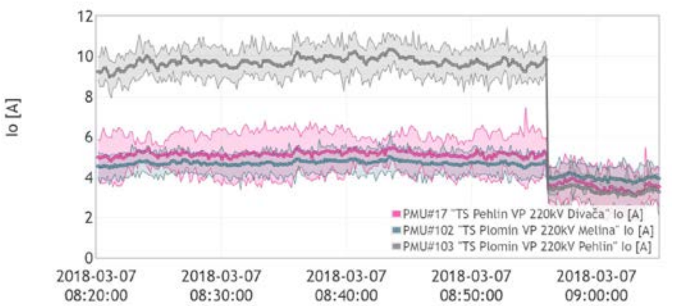

Fig. 9. Current zero value for three lines with fault disconected on fourth non PMU monitored line

After switching the faulty line 1, negative and zero sequence decreased significantly. Same day, on 07.03.2018. at 14:06 hours, fault on line was fixed and switched in operations. Negative and zero sequence components have again assumed their "natural" values, Fig. 10 and Fig. 11.

Analyses show that in EMS (Energy management system) system in control room (EMS1 and EMS2) also found errors on faulty line 1, which operated on two phase only.

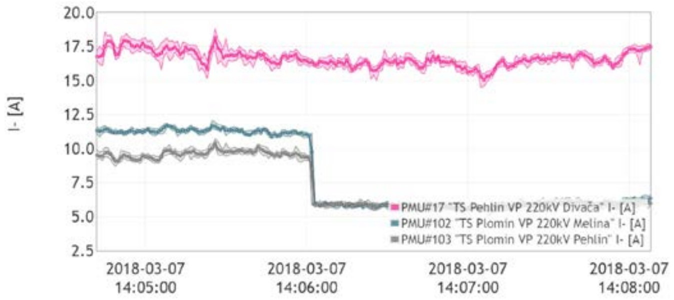

Fig. 10. Current negative value for three lines after switched on the fourth non PMU monitored line after repair

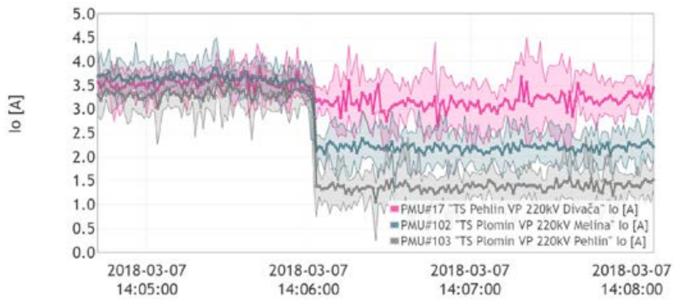

Fig. 11. Current zero value for three lines after switched on the fourth non PMU monitored line after repair

This case shows that signals from EMS system can also be combined for alarming purposes. Monitoring all lines connected on one bus with algorithm, such kind of faults would be effectively detected. Negative and zero sequence currents can be defined for each line in different loading conditions. In that way, characteristic footprint will be added to the transmission lines. Also some key performance indices for PMU monitored and not monitored lines could be defined.

B. Monitoring of generators electromechanical oscilaltions

Oscillations of single generators are possible events for each transmission network. Significant event was on 14th November 2014, with oscillations of 0.96 Hz, Fig. 12. Detail analyses are in [8] and analyze was done with Prony [9].

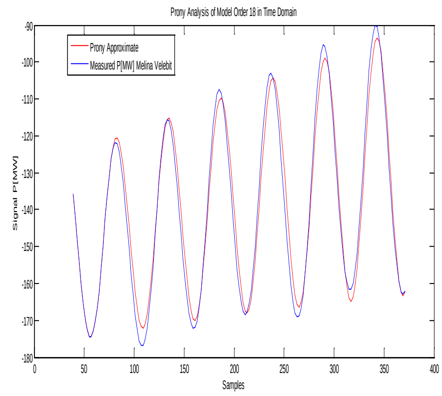

Fig. 12. Measurement and Prony analysis of line active power on 14th November 2014

Causes for such events, most of the time, are failures in generator regulation circuits. In such conditions, oscillations of active power have frequency of 1-2 Hz. Those oscillations propagate to transmission network. SCADA system have recording functionalities, but without alarm. More detail and precise recording were in WAM system. Second event with the same cause and active power oscillations on 400 kV line, Fig. 13, happened on 18th April 2008.

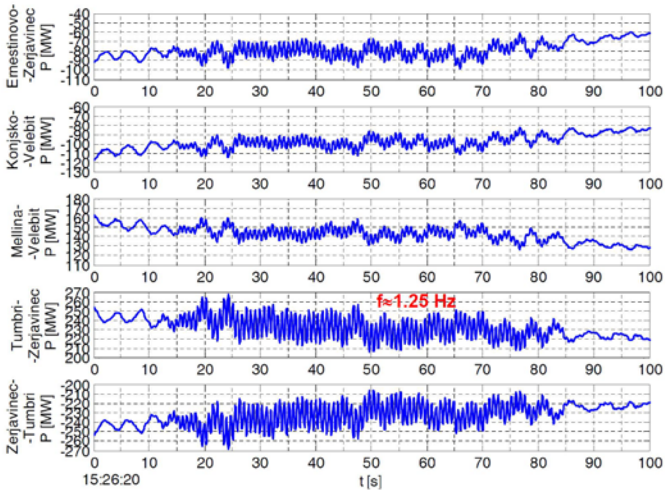

Fig. 13. WAM system recording on 18th April 2008 for line active power

Analyses show characteristic oscillations frequency of 1.37 Hz and interarea oscillations from 0.22 Hz, Fig. 14.

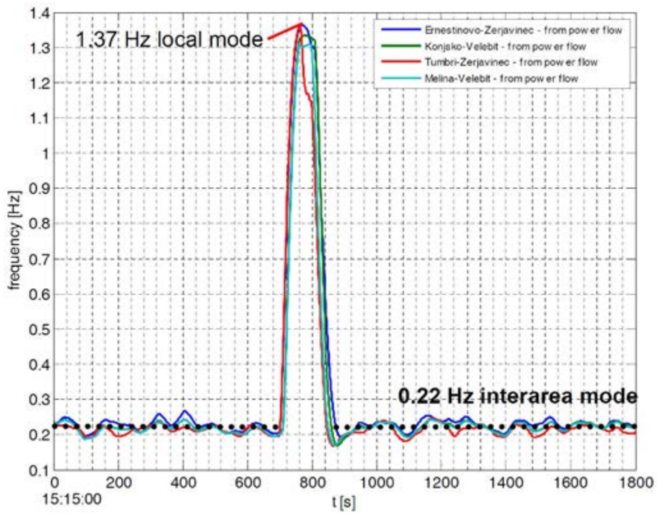

Fig. 14. Frequencies of line active power flow oscillations in Croatian transmisison network on 18th April 2018

In this case generator unit was connected to 110 kV network and unit had relatively small rated power (less than 100 MW). WAM system continuously recorded power flow on 400 kV transmission lines. Interarea oscillations are constantly present in European continental transmission with frequency of 0.22 Hz. After few days, second failure happened at 28th April with same characteristic frequency footprint, Fig. 15. Event was recorded in WAM system from 400 kV PMU.

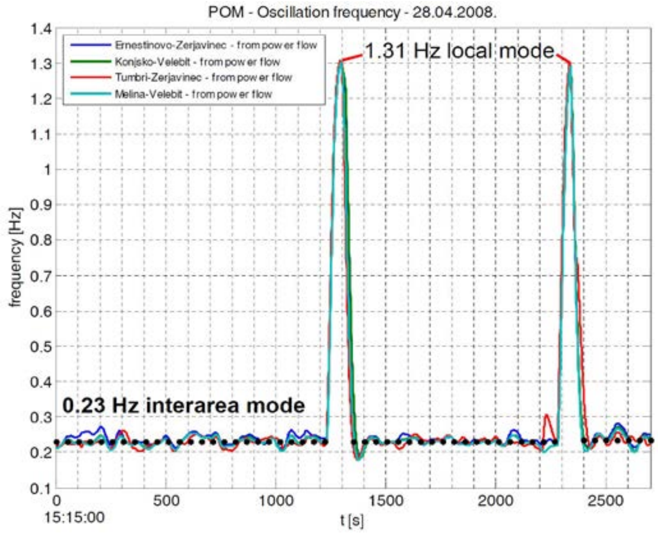

Fig. 15. Frequencies of line active power flow oscillations in Croatian transmisison network on 28th April 2018

In those two cases undamped electromechanical resonance of one unit in hydropower plant appeared.

C. Freuquency tracking in continental Europe network

It is common to have data exchanged between TSOs, also PMUs data can be exchange for various specific tasks. Frequency tracking with PMU data through WAM system should be conducted in real time in the future. European network could be monitored that way. Disturbance in one part of network would be detected across whole network. Example of one disturbance in southern part of Italy is covered with Croatian WAM system and with PMUs in other European country, Belgium and Germany, on different voltage levels, Fig. 16.

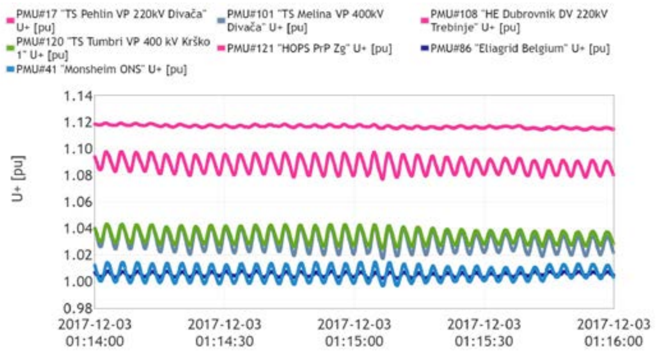

Fig. 16. Volatge from PMU installed in Croatian transmission network and Europe for oscillations in south Italy on 3rd December 2017

PMUs in Croatian transmission system, No. 17, 101 and 120, nearest to the disturbances recorded largest oscillations. PMU No. 108, situated on east part of the transmission network had negligible oscillations. PMUs on the north part of the system, No. 41 and 86 had lower oscillations. Frequencies are perfectly record and derived from voltage PMU data on Fig. 17.

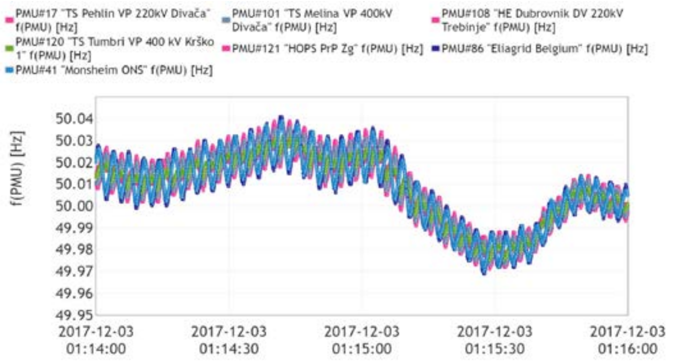

Fig. 17. Frequency from PMU installed in Croatian transmission network and Europe for oscillations in south Italy on 3rd December 2017

Usually, frequency fluctuations are around ± 20-30 mHz in European system and are not sine wave shaped like in this incident. Using many PMUs data it is possible to detect and locate in which part of the network oscillations source is.

D. High voltage circuit breaker unspecific fault

WAM system has applications for monitoring the high voltage equipment. This very specific failure inside the high voltage circuit breaker was completely recorded with PMU data. After triping command, one pole of the breaker still remained closed. WAM system using only voltage positive sequence data recorded 1/3 of nominal voltage, Fig. 18. These analyses are done after incident.

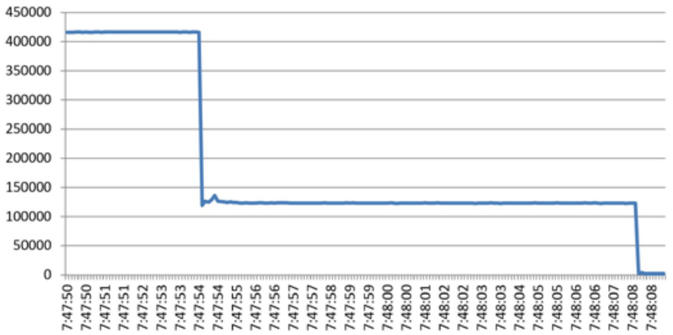

Fig. 18. Volatge from substation Ernestinovo, line Zerjavinec for fault in circuit breaker on 30th August 2012

Fault lasted for 14 seconds before it was removed. This case pointed that line back up protection function can be designed inside WAM system [10], [11].

V. Conclusion

Experience in WAM system operations gives new basis for improving this system and connecting them to SCADA system in control room. In first phase few selected alarms would be connected to SCADA. These alarms will be generated in basic function inside WAM system.

Analyses of four different disturbances in transmission network based on synchrophasor data present full potential of WAM system when upgraded with functionalities for alarming and protecting. Those analyses were done in off line and in next phase of project should be implemented in some automatic manner.

New algorithm for alarming and protecting will be developed and implemented. It can be based on traditional relay protection knowledge or it will use some new technic like machine learning. New algorithm will use all sets of data from new PMU devices, phase voltage and current, and positive, negative and zero sequence values in different combinations.

It is important to define others key performance indices for different purposes in transmission network. At the end for it to be used in every day TSO operations, full attention must also be placed on communications issues.

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