Croatian Academic Research Wide Area Monitoring System - CARWAMS

S. Skok[1], D. Brnobic[2], V. Kirincic[3]

Abstract – *Paper describes start-up of Croatian Academic Research Wide Area Monitoring System (CARWAMS), which is intended to support involvement of small R&D teams into fast developing synchronized measurement technology (SMT). Low voltage synchrophasors are collected by platform called WAMSTER, including handheld Phasor Measurement Units (PMUs) and GPRS data transfer to a dedicated served. Measurements are available on-line. CARWAMS uses previously developed Phasor Data Concentrator (PDC) with added pseudo real time monitoring applications such as angle and frequency instability. Archived measurements and calculated results are used for post mortem analysis and further development of applications.*

***Keywords**: Angle instability, frequency instability, GPRS, phasor measurement unit, pseudo real time, post mortem analysis, synchronized measurement technology, wide area monitoring*

I. Introduction

Synchronized measurement technology (SMT) with its benefits is already recognized as an important enabler of next generation power systems [1]-[4]. From its origin with Phasor Measurement Units (PMUs), over numerous deployments all over the world [5], to development of sophisticated System Integrity Protection Schemes (SIPS), it evaluated to a powerful tool for power system monitoring, protection and control.

Heart of a Wide Area Monitoring system (WAM) is Phasor Data Concentrator (PDC). Most of the PDCs have been custom built by researchers and manufacturers of the PMUs, in accordance with industry synchrophasor standards. Majority of pilot projects and early implementations of the WAM systems has been realized with the commercial PMUs and PDCs. As the experience in the WAM grew, R&D teams related to academia and/or power utilities created solutions suited to the specific power system.

As the first WAM system for the Croatian TSO is realized with a commercially available of-the-shelf application, some drawbacks of the current system and new requirements for a more open and adoptable system arise. The current system architecture was additionally equipped with a new commercially available PDC from a different vendor, with new characteristics and additional applications than the adjacent one. The two PDCs were put into parallel operation, gathering data from the same PMUs. In parallel with implementation of the second PDC, a multi-purpose and open system architecture, with configurable and custom made interface for different user types, was developed by an academia R&D team in collaboration with power utility experts. The originally developed algorithm is able to communicate and collect data from different sources such as the already existing PDC, virtual PMUs, SCADA and the new PDC; filter data if required; provide real time monitoring of the 400 kV network; create record of outages and errors; record and store data [6].

Confidentiality of measured data regarding the energy trading and power system security issues presents a major obstacle for involvement of academia in direct monitoring of the transmission network for research and development purposes. Consequently, just low voltage (LV) measurement points with general purpose Ethernet in vicinity can be used for PMU data collecting purposes in independent, short term or low cost R&D projects. Upon authors' opinion, a solution to remedy mentioned difficulties and to ease the academia and small R&D teams getting involved in the synchrophasor highway should be provided. In example of a socket phasor measurement system [7], single 230 V phase measurements from remote locations are coordinated via the Internet and used to detect events that are also visible at the 400 kV level.

The idea of Croatian Academic Research Wide Area Monitoring System (CARWAMS) is based on two main characteristics: deployment simplicity and communication infrastructure independence. In project's initial phase, synchrophasors at Croatian universities located in different transmission areas are measured by using WAMSTER system measurement and communication layer [8]. The WAMSTER does not aim to be a tool for real-time control and protective applications because of GPRS data transfer speed insufficiency and unreliability. It can be declared as the pseudo on-line monitoring tool that is expected to be recognized by the TSOs as the efficient disturbance detection and localization tool based on the voltage and frequency excursions measurements.

The CARWAMS applications are deployed within the enhanced PDC architecture [6]. The calculation results are visualized and stored for post mortem analysis, together with the measurement data. Primary intention of the CARWAMS is pseudo real time monitoring of transmission network, but it could easily be extended to power quality and disturbance recording applications.

II. WAMSTER overview

The WAMSTER project was started at “Studio elektronike Rijeka” (STER) (eng. studio of electronics) at the end of 2009 as a coordinated work with Department of Power Systems Faculty of Engineering, University of Rijeka (RITEH). The concept established by the WAMSTER can be considered as a “wireless worldwide data” PMU source and concentrator. The WAMSTER system is targeting to solve practical obstacles for “a small R&D team” involved in the PMU surveys worldwide. It uses the globally available GPRS network and the Internet accessible server as a data collecting channel. Prevention of the data loss due to large and highly unpredictable communication delays and high probability of the GPRS communication interruption are resolved by an adaptive communication scheme, along with a battery backup and dedicated flash memory on each PMU.

Modification of a modest, but robust and proven PQ measuring platform into a handheld PMU lowers development and production costs. Therefore, the developed PMU can be used by itself as a “low cost PMU generator”, or can be integrated with the WAMSTER system as a source for “a self-sufficient PMU data collecting & archiving system”. The WAMSTER system is consisted of:

- multiple easy-to-use handheld PMUs, equipped with the GPS and the GPRS modem (Fig. 1);
- dedicated server for the R&D hosting purposes and serving of the real-time and historical data to web clients;
- system administration and data archiving, presentation and export application.

The developed PMU provides measurement of four voltage synchrophasors. A voltage range selector provides 3 ranges: 150 V suitable for 100 V systems and VT connection, 300 V for 230V systems and 1000 V for large industrial LV installations. The measurement data creates synchronous stream for the four voltage synchrophasors. Additional four current inputs are currently used for development purposes, and will be re-included in data stream after completion of the development phase. Instrument’s front-end consists of dual 4-channel 16-bits synchronous sampling ADC. ADC sampling frequency is adapted to mains frequency in order to form 64 samples-per-period windows. Windows are formed and tagged according to the IEEE C37.118 standard. The synchrophasors are calculated by FFT calculation performed on non-overlapping, rectangular window of data and saved to instrument’s flash memory at synchronous speed. The instrument has a battery backup sufficient for 8 hour operation.

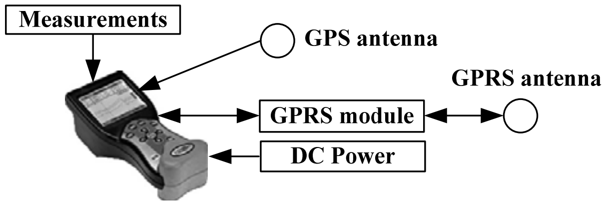

Fig. 1. WAMSTER handheld PMU

In normal PMU reporting operation, most recent packet of the phasors is reported at synchronous speed (50 frames per second) to the WAMSTER server through the GPSR link as soon as possible, from the each connected PMU. In a case of the interruption in communication link, this can result in the packets being dropped from the PMU data stream. When the missing packet is detected in the incoming stream, the WAMSTER server immediately issues a command that collects the missing data from the instrument’s flash memory. The missing data will be reported to the server after the communication channel regains its full speed profile.

In a case of permanent reduction of communication capability, a missing data alarm will repeatedly activate regaining procedure and a list of missing packets at server will start to increase. To deal with this situation, the server will issue a “sub-synchronous reporting speed” command that will reduce the PMU reporting to 25, 10 or 1 frame per second (for 50 Hz systems). This will allocate more communication resources for collection of the missing data because the instrument’s flash memory of 32GB permits more than 5 months of data storage autonomy. After that time, any non reported data will be overwritten and permanently lost. When the communication link has been fully reestablished, the server will increase the speed to its nominal value.

There is also an alternative reporting scheme provided by the WAMSTER that is particularly useful in cases when the WAMSTER serves as the PDC for the superior WAM system. In condensed mode, a single PMU frame is sent to the server each second for system health check purposes. In case of a detected disturbance, or upon user request, the WAMSTER server will issue requests to all the PMUs to start collecting the data from the instrument's flash memory stored at synchronous speed (50 frames per second), for the requested time span only. In this way, the communication and data storage requirements are significantly reduced during the normal operation.

III. CARWAMS architecture

Due to the specific shape of the Croatian power system, there are four transmission areas with the important power stations in the vicinity of bigger cities. The CARWAMS uses the WAMSTER as the measuring platform while the applications are implemented within the originally developed PDC, Fig. 2.

The PMU measurements are collected by the WAMSTER and processed to a Data Acquisition and Exchange Server where are routed to the applications and finally the results are visualized. There is also a History Server that enables post disturbance analysis by archiving measured and calculated data, as well as an Alarm & Event Server (including Database). Measurement locations are strategically chosen to cover the whole Croatian power system, Fig. 3.

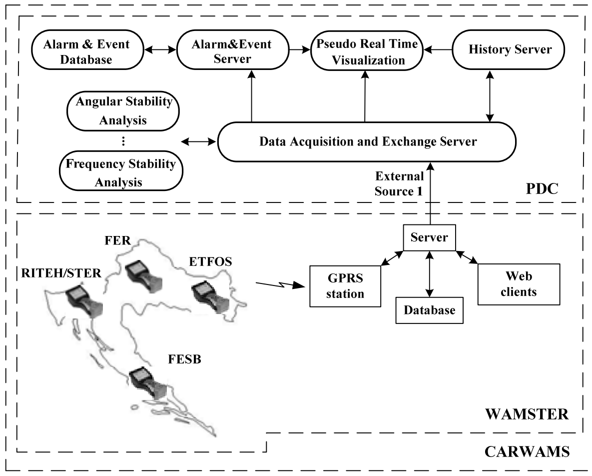

Fig. 2. CARWAMS architecture

At present (July 2011), the system is at its mature pre-release phase [9]. Several units are used for field measurement and protocol development. Five units are permanently used in the CARWAMS project (four units at the universities and one at the development center).

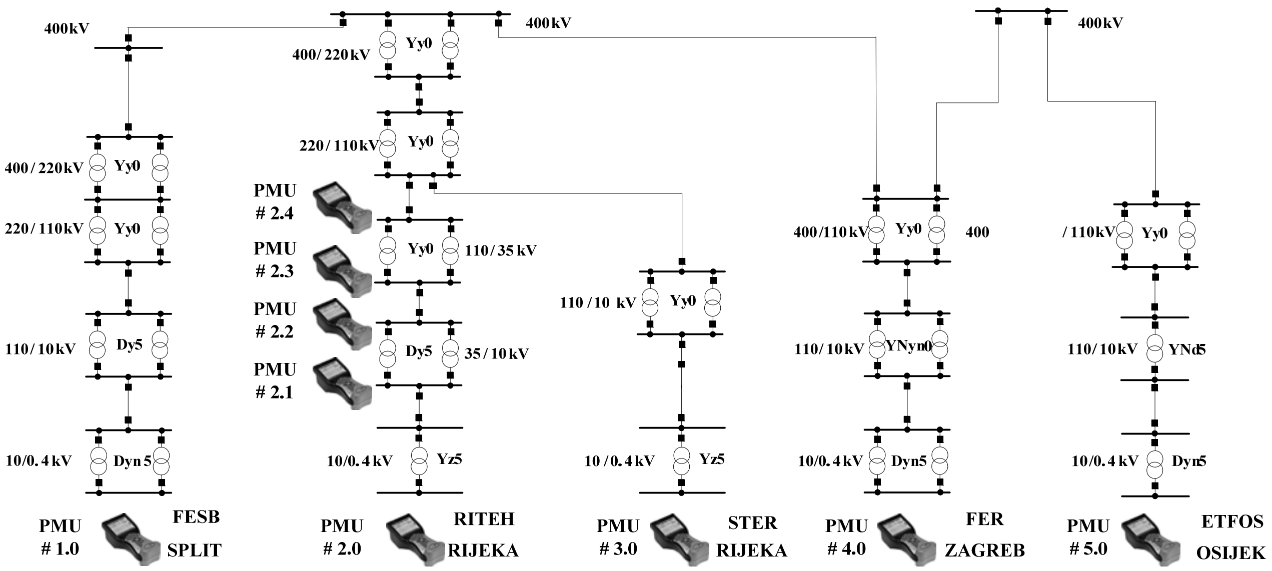

Fig. 3. CARWAMS measurement locations in the Croatian power system

IV. CARWAMS pseudo real time applications

Due to modern trends such as energy trading market and renewable energy sources integration, with the economic aspect in front of the technical one, the power system is running on the edge. Applications based on the synchronized phasor measurements are intended to ensure the dynamic, real-time capture of system operating conditions. This information, provided to the system operator, allows increased operational efficiency under normal system conditions and allows the operator to anticipate, detect and correct problems during abnormal system conditions. There are numerous examples of tools using the synchrophasors [10]-[14].

CARWAMS pseudo real-time applications are implemented within the developed and previously described PDC architecture. After recalculating the phase displacement due to transformers and power lines [15]-[16], LV phasor measurements can be used for transmission network monitoring. The main focus is on the pseudo real time monitoring applications and post-mortem analysis as there is a delay in the GPRS data transfer. So far developed applications include: Angle Instability (Power Oscillations) Monitoring, Frequency Instability Monitoring and Post-Mortem Analysis.

IV.1. Testing WAMSTER

To verify the WAMTER stability and accuracy, as a first phase of the CARWAMS research project, the WAMSTER units were installed at several locations inside the Croatian power transmission and distribution network, from 0.4 kV to 110 kV level, Fig. 4.

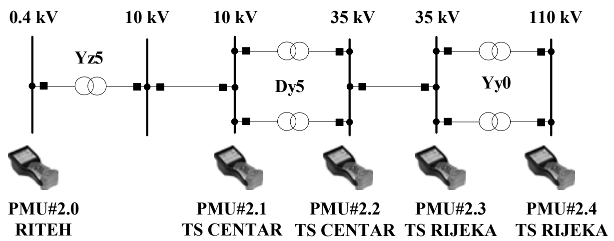

Fig. 4. Initial test system

Table I gives theoretical phase angle difference and daily phase variation (Fig. 5), with PMU#2.0 taken as the reference.

TABLE I
THEORETICAL PHASE ANGLE DIFFERENCE AND DAILY PHASE VARIATION

Nr.	Theoretical phase angle difference [°]	Daily phase angle variation [°]
PMU#2.0 - PMU#2.1	150	0.5 .. 1.5
PMU#2.1 - PMU#2.2	150	1.5 .. 3.1
PMU#2.2 - PMU#2.3	0	0 .. 0.2
PMU#2-3 - PMU#2.4	0	1.8 .. 3.5

IV.2. WAMSTER measurements

The on-line application enables visualization of the synchrophasors, with comparison of magnitudes and angles difference in all three phases. On-line statuses are used mainly for presenting a brief history of synchrophasor data.

In order to a get more data one has to log into WAMSTER system. A control panel is used for setting a database request: a (sub) set of PMU devices, time range and reporting speed must be specified and compressed achieve is created with requested data. Once created, file can be downloaded and analyzed with specialized tools or general purpose program packets.

Example of data collected with portable WAMSTER PMU devices for a typical winter day can is shown in Fig. 5. A 24h log of 1second synchrophasor data is filtered with 1 minute moving average filter. It can be seen that the major phase shift between 110 kV and 0.4 kV level is induced by a 110/35 kV transformer (3.5° at peek consumption) and a 35/10 kV transformer (3.1°). The phase shift variation at 10/0.4 kV transformer is lower and reaches up to 1.5°. Angle at cable connecting two 35 kV busses can be neglected.

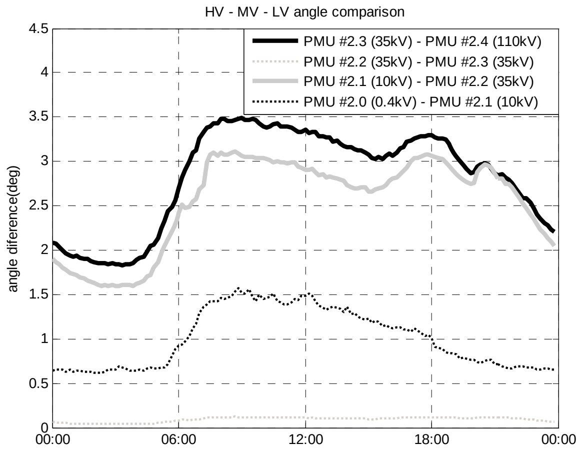

Fig. 5. 24 hour log of phase variation measured from 110 kV to 0.4 kV voltage busbars

Phase difference variation due to change of consumption (Fig. 5) as well as phase shift caused by the power transformer group (Table I) can be taken into account, as shown in Fig 6, which gives phase shift between PMUs installed at universities at different parts of Croatia. A change of phase angle variation between winter (light line) and summer (bold line) times is the smallest in Fig. 6a), as it presents angle difference within single transmission area, or more precisely within the same urban area. The change of phase angle variation is the most evident in Fig. 6c), where phase angle differences measured in vicinity of large hydro power plants can be explained by change of hydrological conditions that caused reduction of amount of generated power in southern part of county.

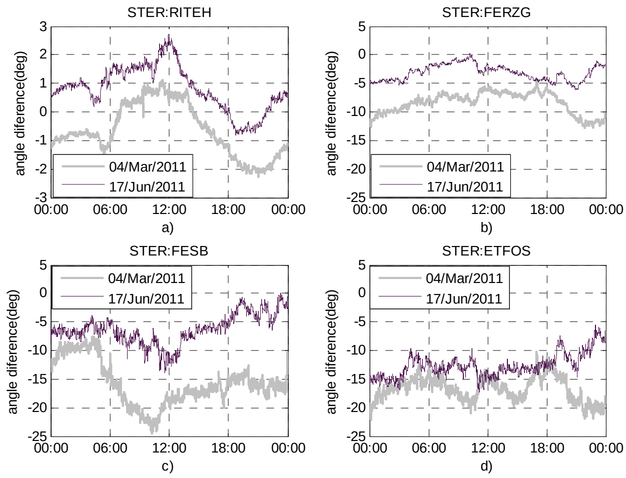

Fig. 6. A log of phase difference between CARWAMS PMUs

Fig. 7 gives the total phase angle difference for a typical winter day between PMU#2.4 (110 kV) and PMU#2.0 (0.4 kV) as well as between PMU#2.0 (0.4 kV) and PMU#3.0 (0.4 kV). If Fig. 6a) and Fig. 7 are compared, it can be concluded that the majority of the angle difference appears in both measurement points on LV level, regardless of the topology and power consumption.

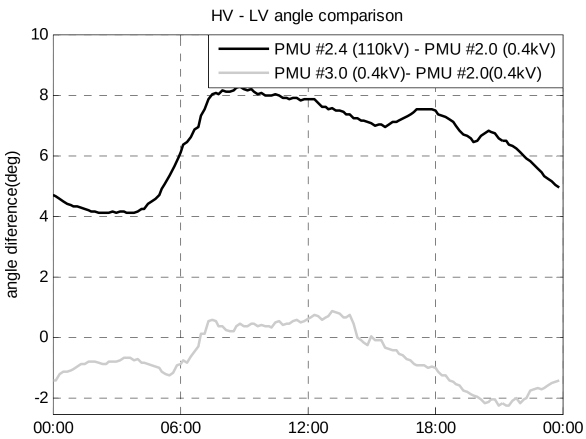

Fig. 7. 24 hour log of total phase difference between 110 kV and 0.4 kV voltage busbars

IV.3. Angle Instability – Power Oscillations

The fundamental phenomena appearing in the power system in a case of angle instability are power oscillations. Depending on their severity and origin they are categorized as transient angle instability or small-signal angle instability [16].

As the synchrophasors provide the angle information, various aspects regarding the angle instability including the PMU measurements have been discussed [17]-[18]. The Italian blackout investigation [19] indicates that the operator did not have information about the angle difference, which was too large for successful reclosing. Such situation could have been avoided if the PMU measurements were available.

SMT applications bring benefits in three specific areas:

- Angular separation analysis and alarming – enables operators to assess stress on the network.
- Measurement of phase angle separation - allows early identification of potential problems both locally and regionally.
- Monitoring of long-duration, low frequency, inter-area oscillations – accurate knowledge of inter-area oscillations allows operators to adopt a power transfer limit higher than the limit currently in use.

Voltage and angle roses are visually effective representations that help the operator to easily monitor the power system. The voltage and angle roses give a static stress assessment, while angles trend provides information about dynamics in the power system. Related to appropriate thresholds, these data could be used as instability indicators, Fig. 8. The application recalculates angles according to chosen reference bus.

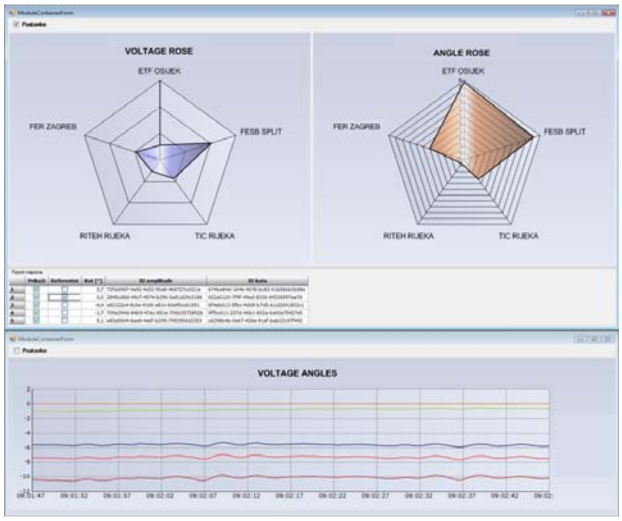

Fig. 8. The operator console – the voltage and angle roses

IV.4. Frequency Instability

Frequency stability describes the ability of the power system to maintain the system frequency within an acceptable range during normal operating conditions or after severe disturbances [20]. Thus the frequency instability occurs when there is a mismatch between load and supply and the system cannot compensate for this mismatch before the frequency reaches an unacceptable value.

The system frequency determined from the PMU measurements can be used as an indicator of the supply/load balance and its deviation is valuable information about the size of supply/load loss or about the system integrity during separation or islanding [10]. The frequency measured by PMUs can also be used to indentify where the fault occurred, as shown in a post-mortem analysis section. The developed application gives the operator simple overview of the power system, including the frequency, voltage levels and angle differences, Fig. 9.

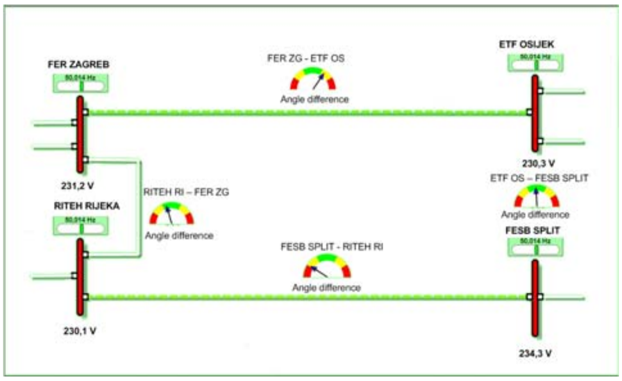

Fig. 9. The operator console – the power system frequency, voltage levels and angle differences

IV.5. Post Mortem Analysis – Disturbance Experience

The synchronized phasor measurements can be utilized for a post mortem analysis as the data is recorded and archived. The CARWAMS measurements could effectively be used for pseudo real-time monitoring of the transmission network regarding the angle and frequency stability, but the main benefit is the data archiving for the post-mortem analysis. An example of a recorded disturbance is a failure of 110 kV power transformer, which caused blackout in a part of Croatian capital. The disturbance was archived, with greatest frequency and voltage sags in the vicinity of the faulted area, Fig. 10 and Fig. 11, respectively.

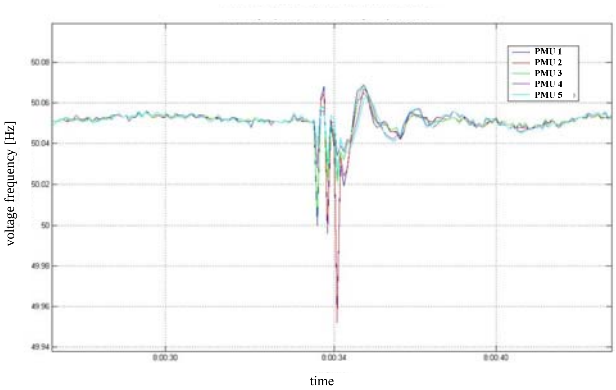

Fig. 10. The PMU frequency measurements

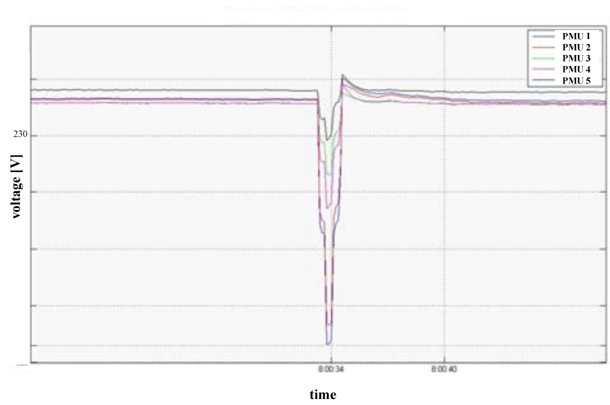

Fig. 11. The PMU voltage measurements

V. Recommendations

The CARWAMS project based on the WAMSTER measurement platform in the Republic of Croatia can be easily used as a key model for other academia and utility R&D teams in starting-up their WAM systems. Therefore, a proposed methodology includes:

- identification of characteristic buses in the power system, in accordance to an observability analysis;
- deployment of PMUs;
- development of system tailored applications based on PMU measurements;
- exchange of measured and calculated data with other TSOs.

VI. Conclusion

The CARWAMS presents the WAM system established on the synchrophasor measurements at the Croatian universities, located in the four different transmission areas. Due to the obstacles for involvement of academia in direct monitoring of the transmission network for research and development purposes, the solution has been found in the LV phasor measurements. The phasors are collected by the WAMSTER platform that uses the handheld PMUs with the GPRS data transfer.

Using the WAMSTER measurements as inputs, the previously developed PDC is a base for development of pseudo real time transmission network monitoring applications, such as the angle and frequency instability monitoring. Another important segment is the post mortem analysis based on the selectively archived measurements and calculated data.

The CARWAMS based on the WAMSTER platform is about to be used in the transmission power system mathematical model verification, in order to get power system elements' characteristic in pseudo real time. Also, future work comprises further development and deployment of the pseudo real time monitoring applications based on synchrophasors, as well as sophisticated SIPS for part of transmission system in an urban area. Another area of interest is the development of a hybrid power system state estimator, which uses both SCADA and PMU measurement.

The archived data is intended to be used for the post mortem analysis and case studies, where LV frequency changes can be indicator of disturbances in the transmission network. As the CARWAMS is still in testing phase it will be thoroughly analyzed and compared to the WAM system deployed in the Croatian National Dispatching Center.

References

[1] A. G. Phadke, J. S. Thorp, *Synchronized Phasor Measurements and. Their Applications* (New York: Springer, 2008).

[2] J. De La Ree, V. Centeno, J. S. Thorp, A. G. Phadke, Synchronized Phasor Measurement Applications in Power Systems, *Smart Grid, IEEE Transactions on , vol.1 n.*1, June 2010, pp. 20 - 27.

[3] V. Terzija, G. Valverde, D. Cai, P. Regulski, V. Madani, J. Fitch, S. Skok, M. Begovic, A. G. Phadke, Wide-Area Monitoring, Protection, and Control of Future Electric Power Networks, *Proceedings of the IEEE , vol. 99, n.* 1, January 2011, pp. 80 – 93.

[4] D. Novosel; K. Vu; V. Centeno; S. Skok, M. Begovic, Benefits of Synchronized-Measurement Technology for Power-Grid Applications, *System Sciences, 2007. HICSS 2007. 40th Annual Hawaii International Conference on*, January 2007, Hawaii.

[5] A. G. Phadke, R. M. de Moraes, The Wide World of Wide-area Measurement, *Power and Energy Magazine, IEEE, vol. 6, n.* 5, September-October 2008, pp. 52 – 65.

[6] S. Skok, I. Sturlic, R. Matica, Multipurpose open system architecture model of wide area monitoring, *PowerTech, 2009 IEEE Bucharest* , 28 June - July 2 2009, Bucharest, Romania.

[7] B. C. Pal, K. Görner, T. Babnik, Large-Scale WAMS, *Recent Trends in Power Grid Monitoring*, April 2010, Imperial College London.

[8] Available: http://www.naspi.org/toolRepository/ [3rd April 2011].

[9] Available: www.wamster.net [7th April 2011].

[10] Real-Time Application of Synchrophasors for Improving Reliability. Final Draft. Draft report on phasor technology for grid reliability. Available: www.naspi.org/news/rapir_final_draft_20100603.pdf [2nd April 2011].

[11] C. Martinez, M. Parashar, J. Dyer, EIPP Real Time Task Team, White Paper Draft 3: Wide Area Monitoring-Control Phasor Data Requirements, December 2004. Available: http://www.naspi.org/resources/archive/rttt/eipp_realtime_group_data_requirements_draft_120105.pdf [5th April 2011].

[12] SCE Synchronized Measurement and Analysis in Real Time. Available: http://www.naspi.org/toolRepository/ [5th April 2011].

[13] Phasor Real Time Dynamics Monitoring System. Available: http://www.phasor-rtdms.com/ [7th April 2011].

[14] G. Zhang, P. Hirsch, S. Lee, Wide Area Frequency Visualization using Smart Client Technology, *Power Engineering Society General Meeting, 2007. IEEE*, 24-28 June 2007, Tampa, FL, USA.

[15] M. J. Heathcote, *The J & P Transformer Book: A Practical Technology of the Power Transformer* (Oxford: Elsevier, 2007).

[16] P. Kundur, *Power System Stability and Control* (Electric Power Research Institute, McGraw/Hill, 1994).

[17] D. Hu, *A Wide-Area Control for Mitigating Angle Instability in Electric Power Systems*, M.Sc. Thesis, School of Electrical Engineering and Computer Science, Washington, 2006. Available: http://www.dissertations.wsu.edu/Thesis/Fall2006/d_hu_091406.pdf [4th April 2011].

[18] M. V. Venkatasubramanian, M. Sherwood, Ve. Ajjarapu, B. Leonardi, Real-Time Security Assessment of Angle Stability Using Synchrophasors Real-Time Security Assessment of Angle Stability, PSERC Final Project Report, May 2010. Available: www.pserc.wisc.edu/ [2nd April 2011].

[19] Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy, UCTE, 2004. Available: www.rae.gr/cases/C13/italy/UCTE_rept.pdf [7th April 2011].

[20] M. Larsson, C. Rehtanz, Predictive frequency stability control based on wide-area phasor measurements, *Power Engineering Society Summer Meeting, IEEE*, 25-25 July 2002, Chicago, IL, USA.

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