Analyses of Phasor Measurement Unit Estimation Algorithms for Protection Functions inside WAMPAC System

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***Abstract*—Transmission system operators utilize phasor measurement unit devices from different vendors. Those devices are basic parts of Wide Area Monitoring Protection and Control system installed in control center. Detail study work needs to be obtained in order to have deep analyses of data generated from those devices. Data gathered in WAMPAC system is used as input for protection and control functions. Extensive laboratory and field test procedures have to be carried out for whole chain of phasor data. Complete testing from substation to control center is presented.**

***Index Terms*—phasor measurement unit, estimation algorithm, protection function, WAMPAC system.**

I. Introduction

Current status of Phasor Measurement Unit (PMU) in Croatian Transmission System Operator (TSO) matches requirements of Wide Area Monitoring system (WAMS) which was a target application in mid 2000 when pilot devices were deployed [1], [2]. Implementation of particular protection functions within Wide Area Monitoring Protection And Control (WAMPAC) system based on phasor data imposes additional study work and extensive testing activities [3], [4].

There are two PMU models installed in high voltage transmission network (400 and 220 kV) delivered from different vendors. Phasor estimation algorithms [5], [6], [7] on both models work according to standards valid at the moment of deploying. First generation PMU device, in further text denoted as PMU_A is based on IEEE 1344 standard [8]whereas newest PMU device, denoted as PMU_B, has estimation algorithm according to IEEE C37.118 standard class P recommendation [9], [10].

Different phasor estimation algorithms in PMUs can have significant impact on phasor data process in WAMPAC system. Therefore, comprehensive analyses have to be carried out before protection function in WAMPAC system [11], [12], [13], [14] will be released to production phase. For instance, protection function which is implemented only on one transmission line side are far less sensitive to PMU algorithms differences than protection function which acts upon phasor data from both transmission line sides.

Study work includes laboratory [15] and field testing of protection loop that embeds PMUs from different vendors.

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II. Laboratory and Field Testing Set Up

The goal of this study work was to precisely determine behavior in static and dynamic conditions for phasor estimation algorithms in PMUs from different vendors. Basic testing scheme is on Fig. 1. Testing was done with two sets of time synchronized testing apparatus. Synchronization was done by GPS antenna. Different simulation scenarios were prepared and started simultaneously on both apparatuses and PMUs. In the first phase of the study tests were performed in laboratory and resulting synchrophasors were collected by laboratory Phasor Data Concentrator (PDC).

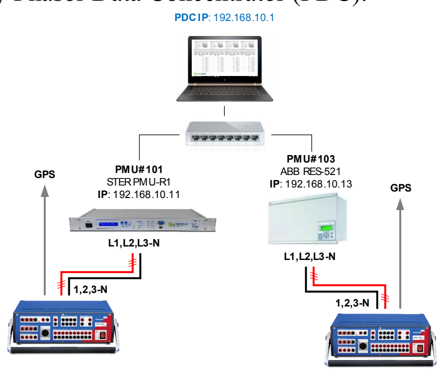

Fig. 1. Basic scheme for PMUs and WAMPAC testing

Testing simulations were based on collecting the PMUs response for ramping and continuous changes for three phase voltage input. The following changes were tested:

- Positive sequence voltage amplitude step,
- Positive sequence voltage phase angle step,
- Single phase voltage amplitude and phase step,
- System frequency step,

- System frequency ramping,
- Voltage angle modulation.

All test signals were generated using two professional calibrated apparatuses which were capable to simulate voltage and current suitable for these purposes. There were synchronized on UTC time by GPS receiver in micro second range. Simulations scenarios were:

- Step changes of voltage amplitude to 90% and 110%,
- Step changes of voltage phase of 1°, 5° and 10°,
- Step changes of voltage frequency of 0.1, 0.5, 1.0 and 2.0 Hz,
- Voltage amplitude and phase change in 1 ms step during one period (20 ms),
- Simulation of one phase fault,
- Frequency modulation checks and,
- Frequency ramping check.

For each test performed, PMU_A model was set in three different setups:

- "PMU_AA" - default setup on devices in TSO network, adaptive sampling enabled with group delay of output filtering 73.7ms.
- "PMU_AB" - adaptive sampling enabled, output filtering disabled,
- "PMU_AC" - adaptive sampling disabled, output filtering disabled.

In further analysis PMU_A will be named as PMU_AA, PMU_AB and PMU_AC according to active settings.

III. RESULTS AND ANALYSES FOR LABORATORY AND FIELD TEST

A. Voltage amplitude stepping

The main goal of this test procedure is to check the PMU response to 90% and 110% voltage amplitude stepping at nominal frequency. Diagram on Fig. 2 presents comparison between PMU_AA and PMU_B. Amplitudes of positive sequence component voltages are presented on upper part whereas phase angles are on lower part.

Fig. 3 shows responses to step change for all PMUs. PMU_B exhibits the fastest response. PMU_AB and PMU_AC have similar responses within transition period of one reporting cycle. More detailed testing not presented in this work exposed that there could be none or one transition reading between two steady states in PMU_B algorithm. Algorithms PMU_AB and PMU_AC exhibit one or two intermediate measurements. This leads to a conclusion that PMU_A has estimation window length of 2 cycles whereas PMU_B has shorter, single cycle estimation window length.

PMU_AA response is delayed by additional filtering. Transition period ends eight reporting cycles after step change.

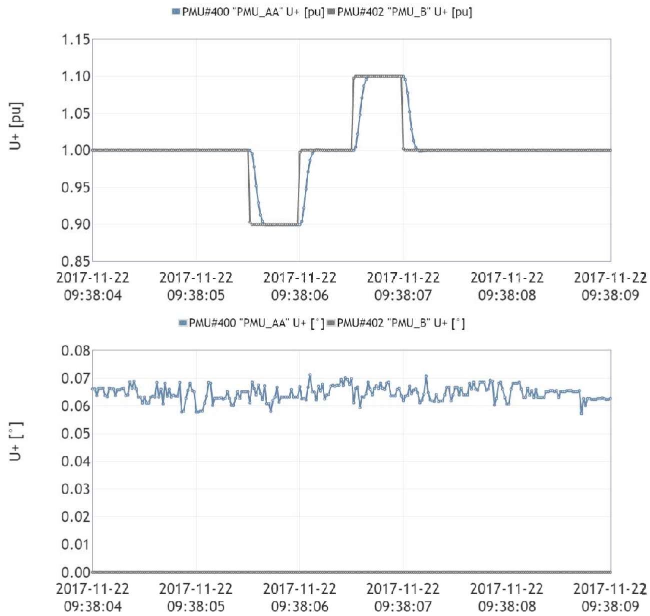

Fig. 2. PMU_AA and PMU_B response to step voltage amplitude change

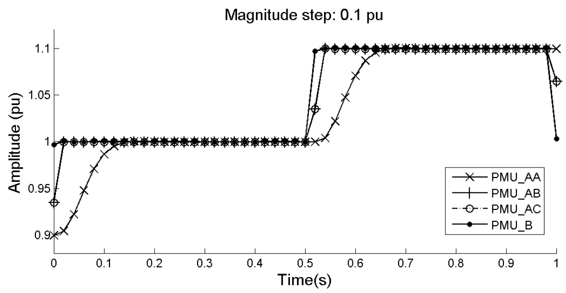

Fig. 3. PMU_AA, PMU_AB, PMU_AC and PMU_B responses to amplitude voltage step change

B. Voltage phase angle stepping

Comparison between PMU_AA and PMU_B responses to 1°, 5° and 10° phase step changes at nominal magnitude and frequency is presented on Fig. 4. It is authors' opinion that variation in PMU_AA amplitude can be neglected in protection algorithm. On the other hand, angle errors in PMU_AA exhibits significant delays and overshoot and were examined more closely. Fig. 5 presents angle response to +10° and -10° steps in 2.5 and 3 s. On this figure, angle reported by PMU_B is used as an angle reference. Negative values in PMU_AA, PMU_AB and PMU_AC responses for 2.5 s disclosure that PMU_B has the fastest response. Filtering in PMU_AA results with the slowest response, similar to amplitude step response.

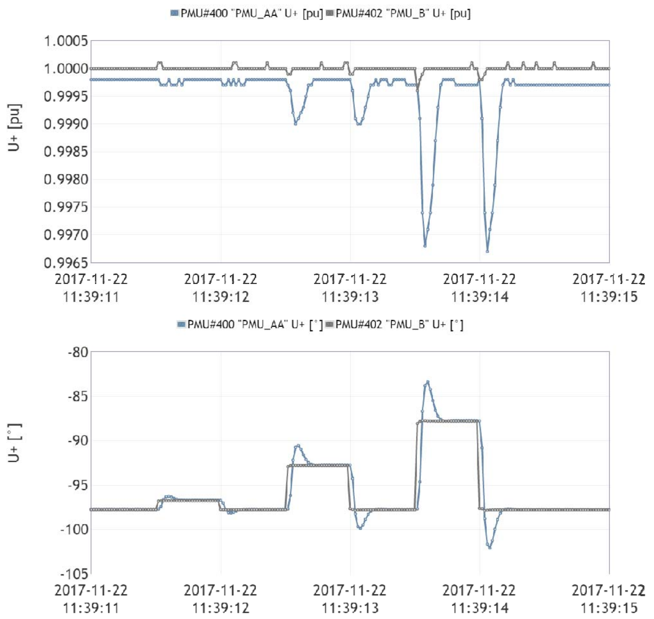

Fig. 4. PMU_AA and PMU_B responses on voltage phase step changes

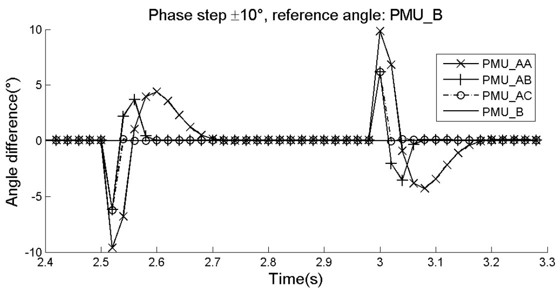

Fig. 5. Voltage angle difference between reference PMU_B and PMU_AA, PMU_AB and PMU_AC

Response lag at PMU_AC lasting one reporting interval (20 ms) can be seen on Fig. 5. A slower response is caused by longer phase estimation window. PMU_AB response difference lasts three reporting intervals (60 ms). Additional two intervals are introduced by adaptive sampling algorithm which lessens PMU_A angle error of at stationary non-nominal frequencies condition.

PMU_AA responses shown on Fig. 3 and 5 confirms that PMU_AA setting is inadequate for tracking of dynamic events in transmission network due to slow response time and overshoot. In following pages responses from PMU_AB and PMU_AC are compared with PMU_B used as reference PMU.

C. *Frequency stepping*

To determine PMU_A adaptive sampling ability to correct measurement errors, responses on several frequency steps up to ±2 Hz from nominal frequency were checked. Results showed that deviations of amplitude are negligible. Estimated angle differences between PMU_AB and PMU_AC compared to reference PMU_B are shown on Fig. 6.

PMU_AC has permanent error in angle reporting that changes at slope -4.5° per +1 Hz deviation from nominal frequency. Adaptive sampling algorithm enabled in PMU_AB suppresses angle error in steady state. Transition period lasts three reporting intervals i.e. 60 ms after frequency step.

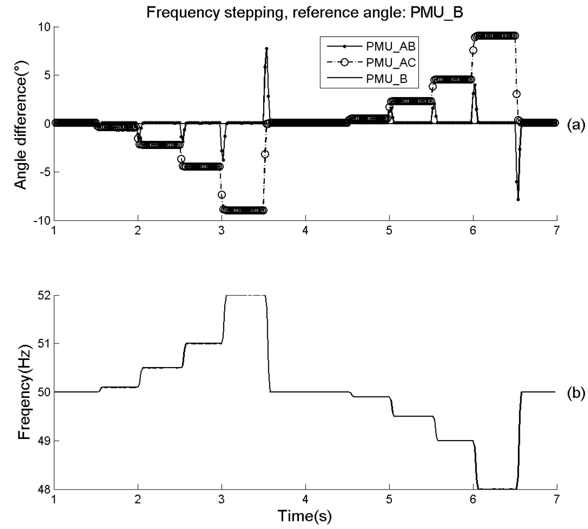

Fig. 6. PMU_AB and PMU_AC responses to frequency stepping, (a) angle differences to PMU_B reference, (b) frequency change in steps

D. *Frequency ramping*

Evaluation of response to linear frequency change was simulated using ±1 Hz/s frequency ramp. Readings of voltage amplitude are shown on Fig. 7a.

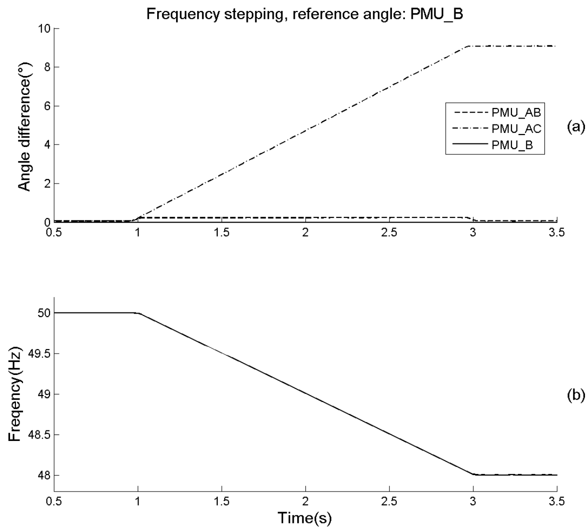

Fig. 7. PMU_AB and PMU_AC responses to frequency ramp -1 Hz/s, (a) angle differences to PMU_B reference, (b) frequency ramp

Amplitude deviations recorded during the test are negligible in terms of protection algorithms.

Angle difference comparing to PMU_B angle reference is shown on Fig 7a. Delay of 3 reporting intervals in correction algorithm exposes PMU_AB inability to compensate angle error while frequency is changing. .Previously detected deviation of -4.5°/Hz in PMU_AC algorithm is visible on Fig 7a.

E. Voltage angle modulation

To compare different PMUs algorithm responses on oscillations that can appear in transmission system a test signal with modulated voltage angle was generated. Frequency modulation of 1 Hz was chosen as adequate for mimicking oscillations recorded in transmission network of Croatian TSO [16].

Angle voltage amplitude modulation of 5.7° creates frequency amplitude oscillation of ±0.1 Hz. Results of testing confirmed that deviations in estimated voltage amplitude are negligible, Fig 8.

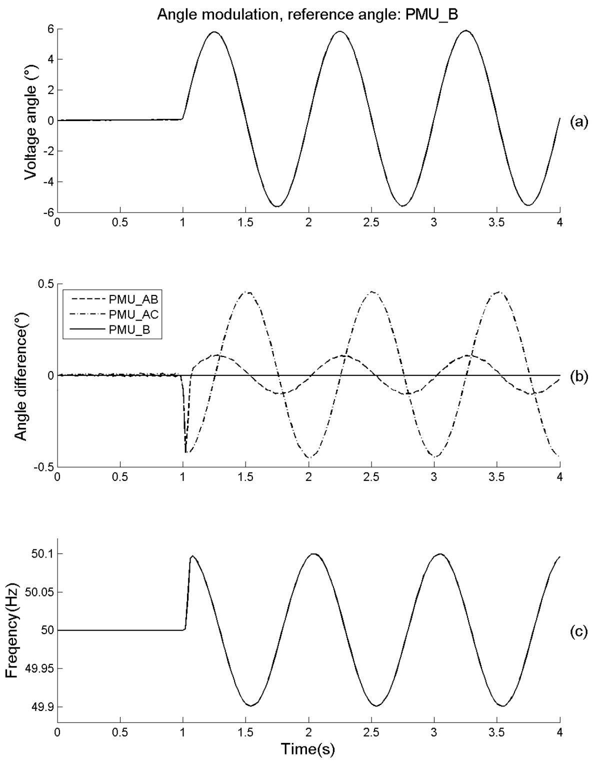

Fig. 8. Angle modulation test – (a) input voltage angle, (b) PMU_AB and PMU_AC angle difference to PMU_B reference, (c) resulting frequency

Maximum angle deviation of PMU_AB algorithm in transient period is -0.42°. After initial period, difference is limited by ±0.1° amplitude. Angle difference peak is in phase with input angle amplitude peak. Deviation at the beginning of transient period of angle in PMU_AC is same as in PMU_AB with value -0.42°. Amplitude deviation is ±0.45° and angle deviation is in phase with frequency in steady-state.

F. PMU_A type device paramater set sellection

After conducted simulations and analysis responses on Fig. 5 and 8, "C" settings for PMU_A type are selected as optimal because of following conclusions:

1) No overshoot in PMU_AC reposonse on step change.

2) Setlling time after step response for PMU_AC algorithm is 40 ms thus shorter than PMU_AB settling time which is 80 ms.

3) Angle error of PMU_AC on not nominal frequencies can be corrected with measuerd frequency and correction of +4.5° for one Hz differntial from nominal frequency.

Complex and extensive analysis of laboratory testing was completed with the final setting selected for PMU_A device. All PMU_A devices in transmission network were set accordingly including the device used in the field test carried out on 400 kV line.

G. Field test for overhead line 400 kV Melina - Tumbri

The whole path for phasor data was rechecked in field test in the second phase of project. TSO has done for the first time this complex PMUs field testing in two different 400 kV substations and control center. The topology of test setup was similar as one presented at Fig. 1. PMUs were on each side of 400 kV line generating synchrophasor data and sending it to WAMPAC PDC in control center. Line length is 127 km and the nearest substation is 20 km farther from control center. Relay outputs on PMU devices were used for a closed PMU-PDC-PMU loop response time measurement.

Synchronized angle steps of 10° were generated to check stationary states. At each stationary state (0°, 10°,…, 340°, 350°) one PMU was subjected to step change of ±20°.

Primary trigger mechanism on PDC server is set to instant firing when voltage angle difference is greater than 15°. Activation of triggering mechanism initiated command for binary output change on PMU_B device in substation. Binary output transition was used for PMU-PDC-PMU loop total response time measurement. Secondary triggering mechanism is set on voltage angle difference of 3° and time delay of 40 ms. Role of secondary triggering mechanism was to check the hypothesis that with 40 ms delay the difference between estimation algorithms of PMU_AC and PMU_B can be suppressed.

Step response of ±20° on PMU_B is presented on Fig. 9 and for PMU_AC on Fig. 10. Purple shaded field on figures marks periods of triggering mechanism activation. Presented diagrams confirm the preposition that chosen 40 ms delay suppresses the difference between PMU_AC and PMU_B algorithms. Furthermore, it is visible that triggering is faster when difference is induced on PMU_B device, which can be attributed to faster response time of the device.

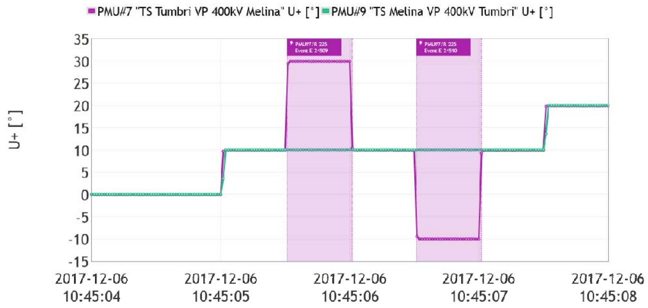

Fig. 9. Detail step change of voltage phase angle for PMU_B in Tumbri substation

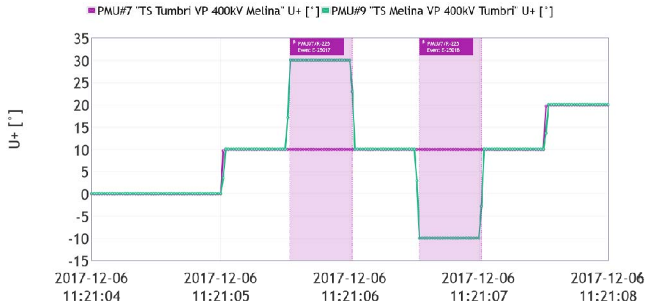

Fig. 10. Detail step change of voltage phase angle for PMU_AC in Melina substation

Four test sequences on each transmission line end were conducted during field testing. As each sequence generates 72 triggering impulse, 288 reaction of closed PMU-PDC-PMU loop were recorded for closing binary output on different PMU devices, Table I.

TABLE I. TIME MEASURMENT FOR STEP RESPONSE IN CLOSED LOOP

No.	PMU type	Minimal time[a]	Maximal time[a]
1.	PMU_B	25 ms	35 ms
2.	PMU_AC	45 ms	55 ms

[a] Closed loop PMU-PDC-PMU measured on PMU binary output

Summarized presentation of whole study work was done in table from step voltage response until binary output in PMU was closed.

IV. CONCLUSION

Short summary indicates the following conclusions. Synchrophasor estimation algorithm in PMU_A can be influenced by several user settable parameters. Precise testing shows that differences in synchrophasor flows exist when non-stationary input stimulus is applied to PMUs. Depending on estimation parameters settings, delays in range from 40 ms to 160 ms can be observed. By enabling so called "frequency adaptive" settings exhibit different levels of overshoot in phasor estimation and time needed to reach final values after stimulus step change. On the other hand, algorithm without frequency adaptation exhibits faster response and no overshoots but with phase estimation error of 4.5°/Hz difference between actual and nominal frequency.

Detail analyses determined the most appropriated setting for PMU_A type for utilization in WAMPAC system in control center. Algorithms for protection purposes in that system should use some suppressed time delay. In case for Croatian TSO and two type vendor, 40 ms delay were set in WAMPAC system.

REFERENCES

[1] A. G. Phadke, P. Wall, L. Deng, V. Terzija, "Improving the performance of power system protection using wide area monitoring systems", Journal of Modern Power System Clean Energy, (2016), 4(3):319-331, DOI:10.1007/s40565-016-0211-x.

[2] E. Grebe, J. Kabouris, S. López Barba, W. Sattinger, W. Winter, "Low Frequency Oscillations in the Interconnected System of Continental Europe", Power and Energy Society General Meeting, 2010 IEEE, 25-29 2010, Providence, Rhode Island, USA, DOI: 10.1109/PES.2010.5589932.

[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", Invited paper, Proceedings of the IEEE, Vol. 99, No. 1, January 2011.

[4] I. Ivanković, I. Kuzle, N. Holjevac, "Multifunctional WAMPAC system concept for out-of-step protection based on synchrophasor measurements", International journal of electrical power & energy systems (0142-0615), Vol. 87, May 2017, pp 77-88, DOI:10.1016/ijepes.2016.11.005.

[5] D. Gallo, C. Landi, M. Luiso, P. Tosato, D. Macii, D. Brunelli, "A Testbed for the Experimental Characterization of Estimation Algorithms for Phasor Measurement Units", 2017 IEEE International Workshop on Applied Measurements for Power Systems (AMPS), Liverpool, UK, 20-22 September 2017, pp 1-6.

[6] G. Barchi, D. Macii, D. Petri, "Phasor measurement units for smart grids: Estimation algorithms and performance issues", AEIT Annual Conference 2013, Palermo, Italy, 3-5 October 2013, pp 1-6.

[7] P. Tosato, D. Macii, M. Luiso, D. Brunelli, D. Gallo, C. Landi, "A Tuned Lightweight Estimation Algorithm for Low-Cost Phasor Measurement Units", IEEE Transactions on Instrumentation and Measurement, Year: 2018, Volume: PP, Issue: 99, pp. 1-11.

[8] IEEE Std 1344-1995, IEEE Standard for Synchrophasors for Power Systems.

[9] IEEE Std C37.118.1-2011, IEEE Standard for Synchrophasor Measurements for Power Systems.

[10] IEEE Std C37.118.2-2011, IEEE Standard for Synchrophasor Data Transfer for Power Systems.

[11] A. Guzmán, V. Mynam, G. Zweigle, "Backup Transmission Line Protection for Ground Faults and Power Swing Detection Using Synchrophasors", 10th annual Automation and Integration Seminar at WPDAC, Spokane, Washington, USA, April 7, 2008.

[12] M. M. Eissa, M. E. Masoud, and M. M. M. Elanwar, "A Novel Back Up Wide Area Protection Technique for Power Transmission Grids Using Phasor Measurement Unit," *IEEE Trans. Power Deliv.*, vol. 25, no. 1, 2010, pp. 270–278.

[13] B. Kasztenny, N. Fischer, K. Fodero, A. Zvarych, "Communications and Data Synchronization for Line Current Differential Schemes," Schweitzer Engineering Laboratories, Inc. 20110906, TP 6492-01, 2011.

[14] H. Elghazaly, A. Emam, A. Saber, "A Backup Wide-Area Protection Technique for Power Transmission Network", IEEJ Transactions on electrical and electronic engineering, IEEJ Trans 2017; 12: 702-709, Published online in Wiley Online Library (wileyonlinelibrary.com). DOI:10.1002/tee.22456.

[15] www.wamster.net

[16] R. Rubeša, "HOPS Wide Area Monitoring System recordings of Oscillations on the 14th November 2014," Report for the ENTSO-e System Protection and Dynamics Group, HOPS, Croatia, February 2015.