Setup of the Laboratory for Synchronized Measurement for PMU's Testing

Vladimir Terzija, *Senior Member, IEEE*, Shawn Shihao Wu, *MIET*, John Fitch

***Abstract*— Phasor Measurement Units are one of the main building blocks of the Synchronized Measurement Technology, which is technologically enabler of the Wide Area Monitoring, Protection and Control (WAMPAC) system. The existing IEEE Std C37.118-2005 standard, determines how phasors' information should be forwarded to Data Concentrators, in where data obtained from PMUs are visualized, analyzed and used for specific WAMPAC applications. This standard defines steady-state performance, sampling frequency and frame format requirements for PMUs. However, this standard does not define the transient performance of PMUs. It is expected, that WAMPAC system should support the system operation particularly during transient conditions, so that the understanding of transient performance of PMUs is critically important. In this paper, a new concept for synchronized testing of PMUs and WAMPAC applications during steady state and transient conditions will be presented. An attempt to define standardised voltage and current signals will be given, as well. Furthermore, an example how to improve the quality of existing simulation tools for testing applications based on synchronized sampling will be described. A methodology for accessing the accuracy of time synchronization will be demonstrated using real testing devices and GPS synchronizing clock.**

***Index Terms*— Phasor Measurement Units, Synchronized Measurement Technology, Wide Area Monitoring Protection and Control, Global Position System, Transient Testing**

I. INTRODUCTION

The concept of Wide Area Monitoring, Protection and Control (WAMPAC) is enabled through the usage of Synchronized Measurement Technology. The main building blocks of the SMT are [1]:

- phasor measuring units (PMUs)
- communication infrastructure
- data concentrators (DC) and
- different applications.

A successful WAMPAC application depends on the quality of all above mentioned blocks. PMUs are processing input voltages and currents, sampled with the preselected sampling frequency (e.g. 3.2 kHz) and determining voltage and current phasors and frequency. The determined variables are sent over communication channels to data concentrators (DC), in which WAMPAC applications are carried out. Different applications can be classified in two main groups:

- off line applications and
- on line applications

The speed of data transfer over communication channels is less critical in the case of the off line applications. Contrary, the on line applications require faster data transfer and it is different from application to application. For example, the voltage stability application is less critical from e.g. frequency stability application, in which essentially faster response is expected.

The phasor measurement technology has a unique capability of sampling analogue voltage and current signals in synchronism with the Global Positioning System, GPS, as well as converting the analogue signals into phasors (synchrophasors). The IEEE Standard C37-118-2005 [3] determines how information about phasors should be forwarded from PMUs to phasor data concentrators (DCs), where they are analyzed, visualized, or used for specific applications. This standard also defines the steady-state performances, sampling frequency and frame format requirement for PMUs. However, this standard does not define the conditions and accuracy under transient conditions. This important aspect is currently under consideration at different IEEE working groups level.

The purpose of PMU testing is to ensure the required accuracy and performance [4]. This is particularly important for TNO/DNO users. PMUs are expected to be a part of the existing technical support enabling a secure and reliable system exploitation and operation. Dynamic testing approach has been recently addressed by the performance and standards task team (PSTT) of the North American Synchrophasor Initiative (NASPI) [5]. Here a simple assessment of the PMU response to step a change of some of parameters of the input signal is used as a criterion for the quality of PMU. An important accuracy criterion defined in C37.118-2005 standard is the Total Vector Error (TVE) [3]. However, it is suitable for steady state PMU performance assessment.

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Transient testing based on the injection of realistic voltage and current waveforms seems to be vital during testing of Intelligent Electronic Devices (e.g. protection relays) [6]. In order to assess the performances of PMUs involved in a specific application, a synchronized testing platform, capable of generating synchronized realistic test signals is needed.

The ultimate goal of this paper is to present the setup of the Manchester Laboratory for Synchronized Measurement and to demonstrate opportunities for testing WAMPAC solutions and main building blocks of the Synchronized Measurement Technology.

II. DESCRIPTION OF THE MANCHESTER LABORATORY FOR SYNCHRONIZED MEASUREMENT

A unique property of PMUs is their capability of achieving high accuracy synchronized measurement. In order to test PMUs used for a specific WAMPAC application, a laboratory testing platform including the use of GPS signal is needed. The platform should be capable of testing the PMUs' behaviour under transient conditions. One of critically important feature of the platform is that test signals must be synchronized. The required synchronization accuracy can be validated by simulating an arbitrary system transient and by using two different simulated signals with known properties (e.g. amplitude, phase angle, frequency, etc.) in the testing procedure: two signals are forwarded to two different test devices, synchronized by GPS. The hardware should have the capability of achieving synchronism using GPS. The simplest way to check the quality of the synchronization is to generate simulated (and synchronized) test signals, and to check if they are also synchronized at the output of the test devices used for PMU testing. The phase difference of the signals in the measuring device can be compared with the phase difference of simulated signals.

For the purpose of testing PMUs, a suitable library of computer simulated test signals was established. Such a library can be particularly important for a formal assessment of PMU transient properties. Let us select one of typical signals' example, from the above mentioned library:

$$s(t)=V_1\sin\left(2\pi f_1 t+\varphi_1\right)+V_2\sin\left(2\pi\left(f_1+\Delta f\right)t+\varphi_2\right) \tag{1}$$

where the first sine wave is the fundamental one, and the second one plays the role of the modulation. For an arbitrary set of input parameters from Equation (1): voltages, phase angles, frequency and delta frequency, the signal presented in Fig. 1 can be obtained. The signal presented represents transient processes typical for the slow, electromechanical transients, characteristic for oscillations between generators after an imbalance in active power.

The next important element of the Manchester Laboratory for Synchronized Measurement is the library of signals obtained through a simulation of a power system. The simulation software tool used here is the ATP-EMTP. Here it is critical to simulate realistically transient processes in networks relevant for the assessment of PMUs.

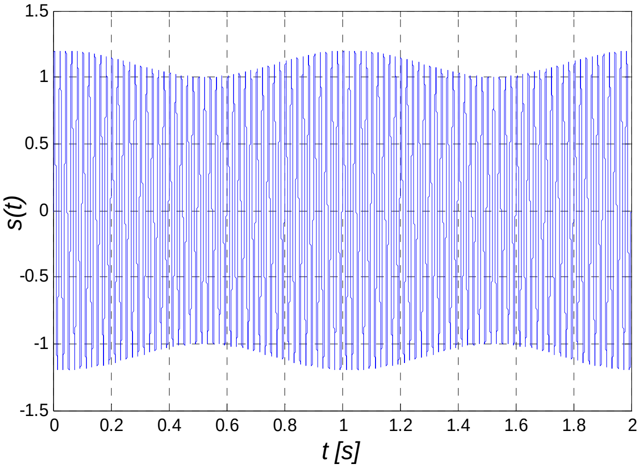

Fig. 1. Test signal, from the Library of simulated test signals.

The test signals must be amplified in order to be used for PMU synchronized testing. In order to synchronize amplifiers, two sets of Omicron CMC-256 test set with GPS functions are used. Furthermore, the following measuring equipment used for basic testing are: laboratory oscilloscope and the National Instrument's Data Acquisition System.

In Fig. 2 a global block diagram of the synchronized testing is presented. Here two typical software packages (ATP-EMTP and Digsilent) are used for the purpose of system simulation. The simulated signals (voltages and currents) are transferred to the Omicron test set according to the Comtrade format. The Omicron test set was consisting of two GPS synchronized amplifiers, which amplified simulated signals and were forwarded to PMUs, Data Acquisition System and Oscilloscope. One of critical issues here is to check the accuracy of the synchronized laboratory setup from Fig. 2.

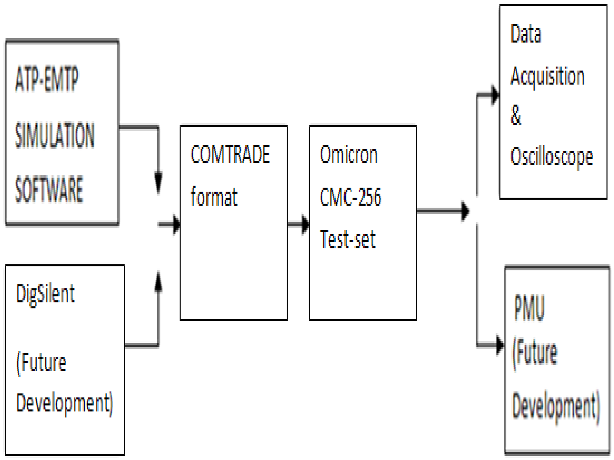

Fig. 2: Global block diagram of testing

In Fig. 3 a 2 busbar system, modelled and simulated in the ATP-EMTP software package is presented. The simulated system was subjected to a single phase to ground resistive fault. The two busbar system model was used to test the synchronization accuracy of the laboratory setup. It was also used for future research into the development of new transient testing methodologies.

Single phase voltages and currents from each busbar are simultaneously and synchronously amplified by the amplifiers. The phase angle difference of the amplified signals are compared with the simulated phase angle differences. In this way, the quality of synchronization was verified.

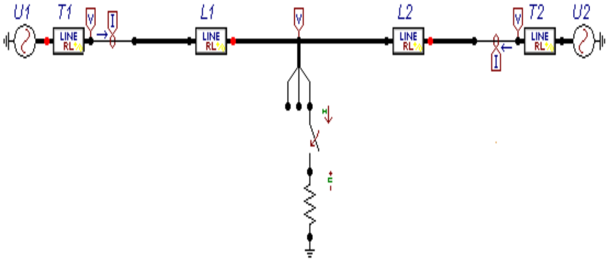

Fig. 3: The ATP-EMTP 2 busbar system model.

Each Omicron amplifier was used to amplify the simulated busbar voltage/current waveforms. Two sets of synchronized Omicron CMC-256 are here used. The synchronization was achieved by using Omicron CMGPS system, which can synchronize the internal time of the both test sets, thus achieving the PMU functionality.

The file format that was imported into Omicron CMC-256 is COMTRADE [7], created by ATP-EMTP. The COMTRADE is the standard format for transient data exchange.

In Fig. 4 the elements of the Manchester Laboratory for Synchronized Measurements are presented.

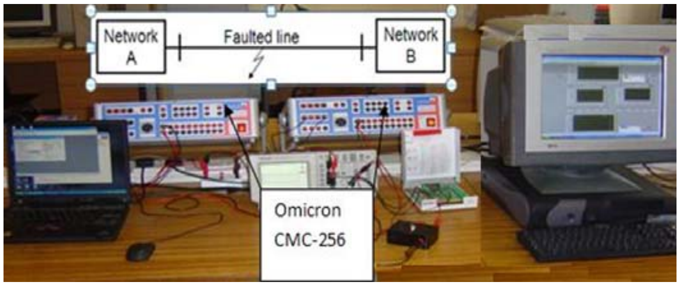

Fig. 4: Synchronized Laboratory at University of Manchester.

III. THE TESTING CONCEPT

Two Omicron CMC-256 testing devices, which are capable of achieving synchronism through the use of Omicron CMGPS, were used to verify the concept of testing the synchronized laboratory setup. Steady state and transient conditions in a real system were simulated using the ATP-EMTP and DigSilent software packages. The simulated waveforms were saved in the COMTRADE format. The COMTRADE files were further amplified by the Omicrons. The results were then analyzed by the National Instrument Labview (see Fig. 5).

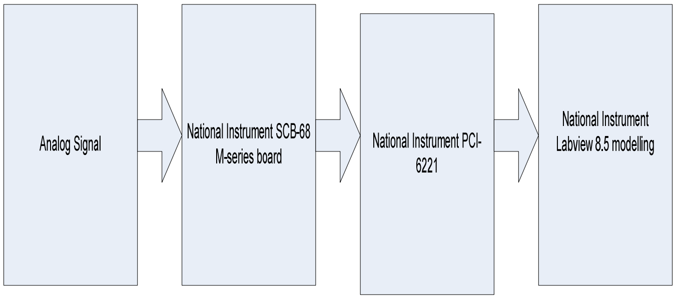

Fig. 5: National Instrument Labview Sequence.

Steady state and faulty conditions on the transmission line were modelled and simulated using the ATP-EMTP software package. The following three types of testing were proposed to test the accuracy of the synchronized laboratory setup:

1. Two identical steady-state waveforms are simulated and amplified by using synchronized Omicrons. The phase angle difference of the two waveforms was zero.

2. Steady state waveforms at busbar 1 and 2 are simultaneously amplified. The phase angle difference of the two waveforms was 11.25^0.

3. Transient waveforms from busbar 1 and 2 are amplified. Visual inspection of phase angle differences during pre-fault period and after the fault are analyzed. Here the FFT method was used to analyze the signals archived in Labview.

In Fig. 6 the above described testing is presented.

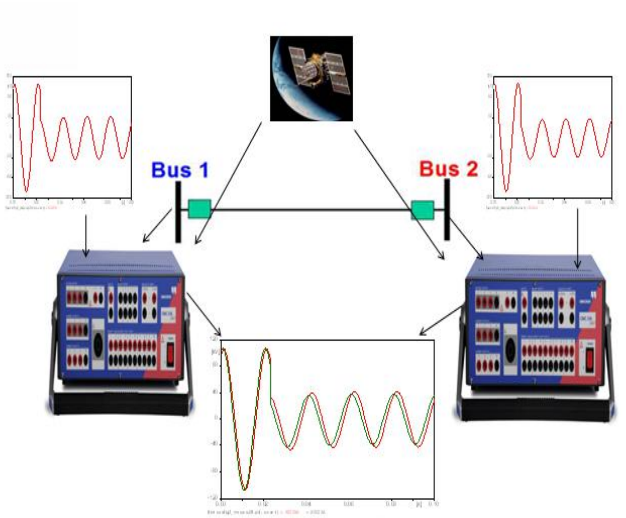

Fig. 6: Overview of transient testing of synchronized laboratory setup.

A. *Test 1*

In this test two identical signals, presented in Fig. 7, are processed. They are obtained under steady state conditions at busbar 1. Both signals are synchronously amplified by Omicrons and presented in Labview. Obviously, in Labview a single signal was obtained, confirming that no phase difference was introduced from the test devices.

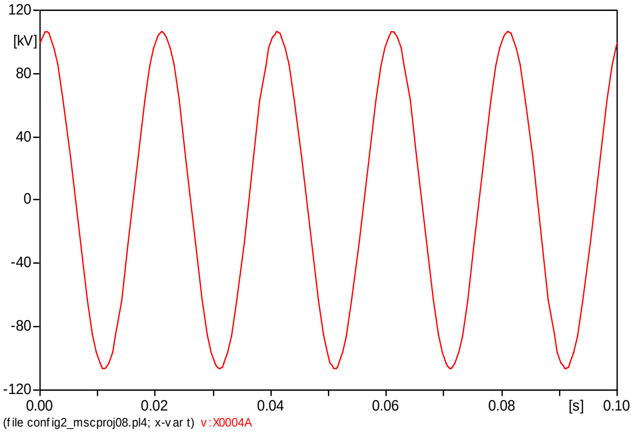

Fig. 7: Steady-steady waveform of ATP-EMTP model busbar 1

B. *Test 2*

In this test, the steady state conditions, in which two signals with different phases (phase difference 11.25^0) are processed, are presented. Two signals are presented in Fig. 8. This test also confirmed that no errors are identified in Labview, i.e. the same phase difference as in the original simulated signals were detected.

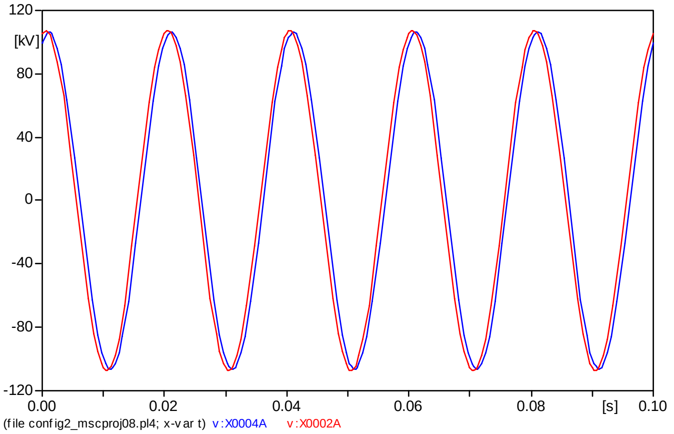

Fig. 8: Steady-steady waveform of ATP-EMTP model of busbar 1 and 2

C. *Test 3*

The current practice of the testing of Intelligent Electronic Devices (IEDs) such as protection relays and disturbance fault recorders involves steady state condition testing only. For example, the relay testing under steady state condition involves injecting a fixed voltage and ramp current until the relay operates [9]. The injected voltage has a fixed sinusoidal waveform and the injected current has a linearly changed amplitude. However, this testing is obviously not adequate to evaluate the protection relay under abnormal transient conditions. Therefore, the transient testing should be used for the purpose of the relay characteristics evaluation.

Transient testing [6] is an important method for validation of relay logic and settings. Transient testing are more accurate than steady-state testing because it uses waveforms which are closer to reality. The IEEE power system relaying committee has developed a standard model for the purpose of testing relay under transients [10].

The IEEE Standard C37.118 [3] defines PMU requirements during steady state conditions. The Manchester Laboratory for Synchronized Measurements has the capability of simulating realistic network transients under which real PMU have to operate. However before starting with procedures for testing PMUs, the accuracy of the laboratory setup, in terms of the quality of the synchronization must be carried out.

Using the ATP-EMTP model, the A-phase voltages were imported to both synchronized Omicron test devices. The amplified signals are forwarded to Labview and analysed from the synchronization viewpoint. In Fig. 9 the simulated voltages at both busbars are presented.

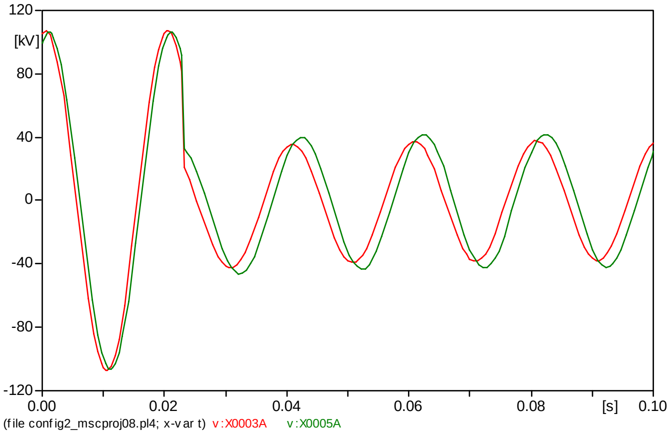

Fig. 9: Simulated voltage transient waveforms from busbar 1 and 2.

From Fig. 9 it is obvious, that different phase angle differences exist before and during the fault. Therefore, the phase difference of two signals cannot be simply compared. The Fast Fourier Transform (FFT) can be used to analyze the phase angle of each signal. Based on the calculated phase differences, the quality of the synchronization was assessed. According to the results obtained, it was concluded that the phase difference during the fault was 19.2631^0, what was exactly the phase difference obtained at the simulation level.

Using the above methodology, the 100% synchronization between the signals has been confirmed.

The methodology for phase difference calculation based on the usage of the FFT is valid it the system frequency is constant. It is known, that if the fundamental frequency of the signals processed is not equal to the rated frequency, the leakage effects in the FFT deteriorate the quality of the phase differences calculation. Under these circumstances, some alternative methods must be developed. Authors are currently developing methods for phase differences determination based on the implementation of the estimation theory, particularly on the use of the recursive optimal estimators. A typical example of such estimators is the Extended Kalman Filter (EKF), suitable for the estimation of unknown parameters of non-linear signal models. In Fig. 10, a block diagram for phase difference calculation/estimation is presented.

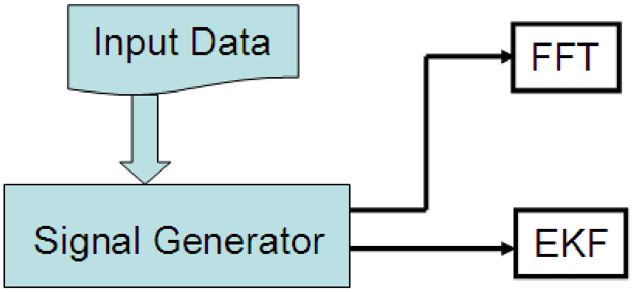

Fig. 10: General Block Diagram of procedures for phase angle calculation / estimation (FFT suitable for signals with nominal frequency; EKF suitable for signals with off-nominal frequency).

The above concept is currently under testing and validation.

IV. CONCLUSION

In the paper the main components of the Manchester Laboratory for Synchronized Measurement are presented. Typical examples of synthetic test signals are presented. The methods for generating and amplifying test signals is presented. A general concept for transferring simulated signals over a synchronized amplifier to PMUs is presented. The methods for the synchronization accuracy assessment during steady state and transient conditions are presented. The issues related to the assessment of transients during which the system frequency is not constant, has been addressed, as well. By this, methods based on the implementation of non-linear recursive estimators (e.g. Extended Kalman Filter) are proposed. In the next stage, authors plan to move forward, starting evaluating some of developed WAMPAC applications.

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VI. BIOGRAPHIES

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Shawn Shihao Wu was born in Singapore in 1981. He was an Artillery Officer in Singapore 9th Division Artillery from 2001 to 2004. He received his BEng (Hons) degree in Electrical Engineering from the University of Sheffield in 2006 and MSc with distinction in Electrical Power Engineering from the University of Manchester in 2008.. From 2006 to 2007, he worked in Guthrie Engineering Singapore which is the representatives of Siemens AG power transmission and distribution division (PTD) as a project engineer where his roles and responsibilities include designing, installing and commissioning of High Voltage Switchgear and Protection LCC. His current research areas are High Voltage testing, protection and WAMPAC. He is current pursuing his PhD at The University of Manchester.

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