Laboratory Test Set-up for the assessment of PMU Time Synchronization Requirements

Ravi Shankar Singh
Dept. of Electrical Engineering
Aalto University
Espoo, Finland
Email: ravi.singh@aalto.fi

Hossein Hooshyar
Electrical Power Systems
KTH Royal Institue of Technology
Stockholm, Sweden
Email: hossein.hooshyar@ee.kth.se

Luigi Vanfretti
KTH Royal Institute of Technology
Stockholm, Sweden
Statnett SF, Oslo
Oslo, Norway
Email: luigi.vanfretti@ee.kth.se

***Abstract*—This paper presents the construction of a Hardware-in-the-loop laboratory test set-up designed to assess time synchronization requirements of Phasor Measurement Units (PMUs). The test set-up is also used to investigate the effects of signal phase shift caused by current and voltage transformers on the time synchronization requirements of PMUs. The paper also describes the structure of the IRIG-B time-sync code which was simulated in real-time and then fed to a PMU as a high-accuracy timing source.**

***Index Terms*—Phasor Measurement Unit (PMU), Real-Time Simulation, Hardware-in-the-Loop (HIL), IRIG-B.**

I. Introduction

Phasor Measurement Units (PMUs) are nowadays being used to generate time synchronized phasor measurements used in wide-area monitoring, control and protection systems for the modern power grid [1]. Logged synchrophasor records also help in event reconstruction in case of a disturbance or failure of the grid. This helps in detailed examination of the events leading up to a disturbance [2]. To obtain reliable phasor estimates from a PMU, the instrument should be supplied with a high-accuracy timing source. The timing source should accurately synchronize the PMU's clock with the Coordinated Universal Time (UTC) which serves as a common reference for all PMUs in the grid [3]. Inaccuracies in PMU timing will degrade the PMU phasor estimates. A timing error of $5ms$ can cause an error of $\pm 90^\circ$ in the estimated phasor at a system frequency of 50Hz. The estimated phasor error of a PMU is quantified in terms of the Total Vector Error (TVE). The TVE is an expression of the difference between the theoretical value and the PMU's estimate of the signal at the same instant of time [4]. So PMU timing errors will effect in increased TVEs. As stated in the IEEE Standard C37.118.1-2011 for Synchrophasors Measurements for Power Systems, the timing source should be accurate enough to keep the TVE within 1% [4].

Previous works have focussed on assessing the TVE compliance criteria of PMUs under steady-state conditions [5], [6]. However, these tests were performed using stand-alone relay

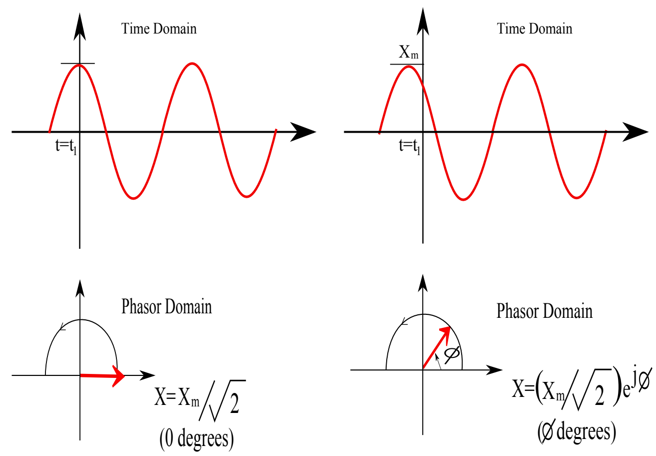


Fig. 1: Importance of time in correct phasor estimation

test kits. These test kits supply current and voltage signals directly to the PMUs. In practical applications of commercial PMUs, these signals are fed to the PMUs via instrument channel consisting of current and voltage transformers (CTs and VTs). This instrument channel introduces ratio and phase errors in the voltage and current signals before feeding them to the PMUs [7]. The errors in phase of the signals will affect the final TVE of the PMU. It is known that the timing errors also affect the TVE. As the total TVE should be less than 1%, the share of TVE due to timing source inaccuracy will decrease in presence of phase errors caused by the instrumentation channel. This will require the reassessment of the timing requirements for PMUs. However, the test set-up mentioned above did not include CTs and VTs and hence will only be suitable for the ideal case if it is assumed that the PMU is getting error free original signals.

This paper proposes a method and presents a real-time, Hardware-in-the-Loop (HIL) test set-up to assess the timing requirements of commercial PMUs and tries to show that the timing requirement in terms of accuracy, of commercial PMUs could be much more strict than the limits set in the IEEE Standard C37.118.1-2011. The paper is organized as follows. Section II presents the tests carried out in previous works using stand-alone relay test kits. Section III discusses the idea of

This work is supported by the FP7 IDE4L project funded by the European Commission, the STandUp for Energy Collaboration Initiative and by Statnett SF, the Norwegian TSO).

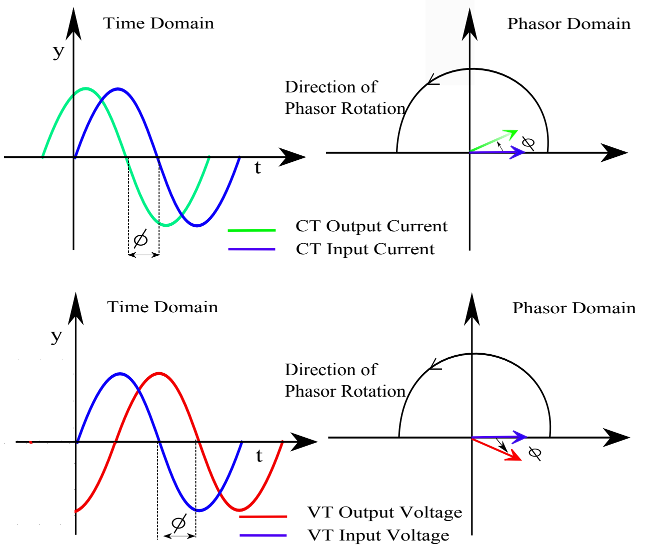


Fig. 2: Phase errors in current and voltage signals due CTs and VTs

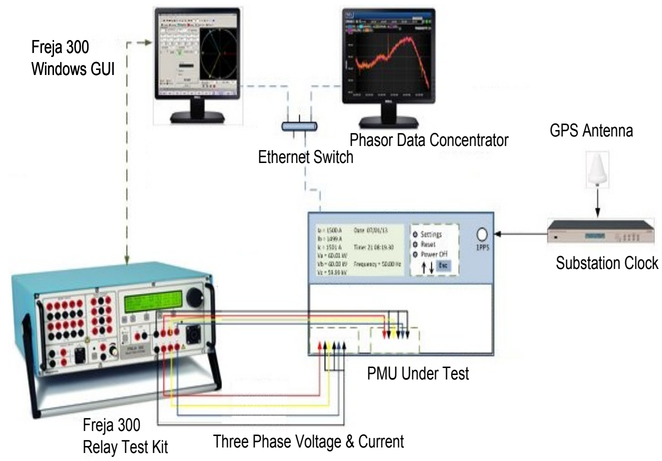


Fig. 3: PMU test using stand-alone relay test kit

the proposed test and then discusses the set-up for real-time HIL test to access the PMU timing requirements in laboratory. Some results in brief are presented in IV and conclusions are drawn in section V.

II. Stand-alone PMU Test

This section briefly outlines the Stand-alone test set-up to test the steady-state compliance of PMUs. To estimate phasors reliably, a PMU requires two inputs, power system signals (V & I) and a high accuracy timing source. To test the performance of a PMU in the laboratory, sources to generate both inputs are required. In this stand-alone test, high power voltage and current signals are injected in the PMUs using stand-alone relay test kits like Freja 300 [8]. A high-accuracy time signal is supplied using a Global Positioning System (GPS)-assisted substation clock (Arbiter 1094b [9]). Phasor estimates generated by the PMUs are sent to Phasor Data Concentrator (PDC) computer. The set-up is shown in Fig. 3.

The measured values of the signals are compared by the original signal and the TVE is calculated from the logged PMU data. This TVE includes the effect of the PMU's signal processing unit (which includes Analog to Digital converters and step down transformers) [2]. This test set-up does not include the instrumentation channel and hence the PMU estimate is not affected by any kind of external phase errors caused by CTs and VTs. It is known that Phase angle error for VTs is in the range of $\pm 4°$ and for CTs in the range of $\pm 2°$. In high accuracy instrument transformers, the phase angle varies between $\pm 0.1°$ [10]. The output voltage from the VTs lags the original volatge signal and the current output form the CTs leads the original current signal as shown in Fig. 2. These phase shifts will affect the accuracy of phasor estimates generated by a PMU, thus increasing the TVE.

1% TVE corresponds to a phase angle error of $0.573°$, provided no other errors are present. This is about $31.8\mu s$ at a power system frequency of 50Hz (or $26\mu s$ at 60Hz). The presence of phase errors in input signals reduces the margin for time source inaccuracies to be less than the $31.8\mu s$ limit specified in IEEE C37.118.1-2011 [4]. The next section presents a method and laboratory test set-up to study and assess the time synchronization requirements of commercial PMUs in a controlled laboratory environment.

III. Test set-up for Assessment of PMU Time Sycnhronization Requirements

This method assesses the timing requirements of PMUs based on the required accuracy of the timing source. For a fair assessment, it is necessary to to test the PMU in an environment emulating the on field implementation of commercial PMUs. On field, the PMU is supplied signals via an instrumentation channel. Also, to see the effect of varying timing errors on the TVE and hence estimate the acceptable accuracy limits of the timing source, a controllable PMU timing solution is required. This timing solution would be able to supply time with varying accuracy as required. In the case of above mentioned stand-alone test, there is no instrumentation channel and also the time clock supplying the time to PMU is assisted by GPS and hence uncontrollable. The test set-up discussed in the paper tests the PMUs in presence of an emulated instrumentation channel and using a user controllable time source.

To emulate the instrumentation channel, Megger amplifiers SMRT1 were used in between the current and voltage signals generation source and the PMU under test. Amplifier's phase angle accuracy of the output current and voltage signals could be up to $\pm 0.25°$ at 50Hz [11]. This accuracy range was found suitable to be used as a substitute for high accuracy instrument transformers whose phase angle accuracy varies between $\pm 0.1°$.

To be able to control the PMU timing signal, it was decided to simulate the time signal in real-time and then feed it to the PMU. Basic control blocks from SIMULINK's library can be

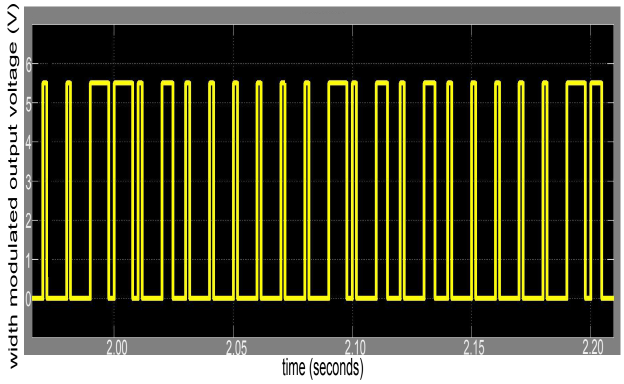


Fig. 4: IRIG-B pulses simulated in SIMULINK

used to vary the accuracy of the time signal supplied. An Inter-Range Instrumentation Group Code B (IRIG-B) time signal was chosen as the high accuracy PMU timing source [12]. It distributes time to PMUs with an accuracy of $\pm 500ns$ [13] and can be simulated and controlled using SIMULINK. The PMU under test also requires balanced three-phase voltage and current signals as inputs. Both signals required, i.e. IRIG-B timing signal and the three-phase voltage and current (V and I) signals, can be simulated in SIMULINK. These signals can be sent in real-time as inputs to the PMU. The structure of IRIG-B time code which was simulated in real-time for PMU time synchronization is briefly discussed below.

A. IRIG Overview

IRIG-B is a serial time code developed by the Telecommunication Group of IRIG. IRIG has six different encoding formats labelled `A, B, D, E, G and H`, out of which IRIG-B is most commonly used to distribute time to Intelligent Electronic Devices (IEDs) [12]. IRIG-B can be distributed in two ways, one as a DC Level Shifted (DCLS) pulse width coded signal (unmodulated) or as an amplitude modulated signal based on a sine wave carrier with a frequency of $1kHz$ [14]. GPS based clocks can generate IRIG-B coded timing signals which can be distributed to many IEDs in single substation. Unmodulated DCLS IRIG-B can achieve accuracies in the range of $\pm 500ns$., which is better than the accuracy of $\pm 10\mu s$ achievable by its amplitude modulated counterpart [13]. This makes the DC shifted, unmodulated form of IRIG-B the most suitable format for time distribution in PMU applications.

B. Unmodulated DCLS IRIG-B

Unmodulated DCLS IRIG-B is distributed in frames. Each frame is one second long and has a pulse rate (or a bit rate) of 100 pulses per second (pps). The 'on-time' for each bit refers to the leading edge of the pulse. Each bit has an index count identification number. The Index count interval is the time interval between the leading edges of two consecutive pulses. Each bit has an index interval of 10ms. [14]. The index count ranges from 0 to 99 and then rolls over to 0 for the next second. Each frame uses five types of pulses: logic zero, logic one, position markers P_0-P_9, a reference bit P_r and index markers. Reference bit P_r indicates start of a new frame. Position identifiers from P_0 through P_9 are placed every ten bits. Index markers occur between decimal digits in each sub-word to provide visual separation. The width of these pulses are pulse width coded where the width of logic zero is set to be 20% of the index interval ($2ms$), the width of logic one is 50% of the index interval ($5ms$). Position markers and the reference bit are 80% of the index interval ($8ms$) and index marker bits are 20% of the index interval ($2ms$). Every new one-second time frame is identified by two consecutive $8ms$ pulses, P_0 and P_r. The structure of an IRIG-B frame is presented below:

<synch>SS:MM:HH:DDD<Control><Binary Seconds>
where:

SS	The second of the minute [00 to 59 (60 during leap seconds)] in Binary Coded Decimal (BCD)
MM	The minute of the hour (00 to 59) in BCD
HH	The hour of day (00 to 23) in BCD
DDD	The day of year (001 to 366) in BCD
Control	Informations like leap second, daylight saving, quality information and a parity bit included in a block of 27 bits
Binary Seconds	Second of the day in 17 bits

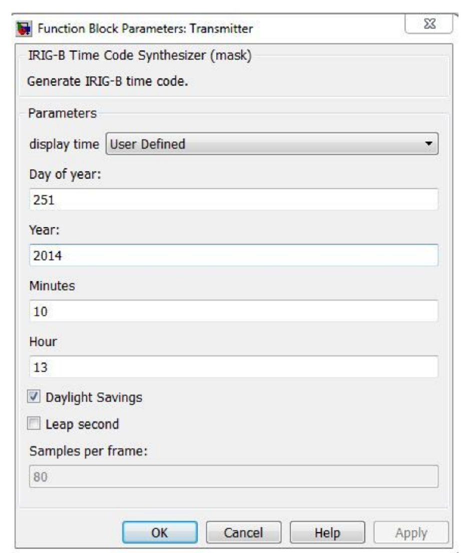


Fig. 5: Initial parameters for IRIG-B generator block in SIMULINK

To be able to use IRIG-B as a controllable timing source for PMUs under test, MATLAB code was written to generate pulse width modulated IRIG-B signals in the DCLS format specified above. The code was embedded in a SIMULINK model as a MATLAB function. The code includes an option to set the initial time from which time starts rolling. Other control parameters like daylight saving, leap seconds and time quality can also be set and changed. The parameters giving initial time of the IRIG-B time block can be set as shown in Fig. 5.

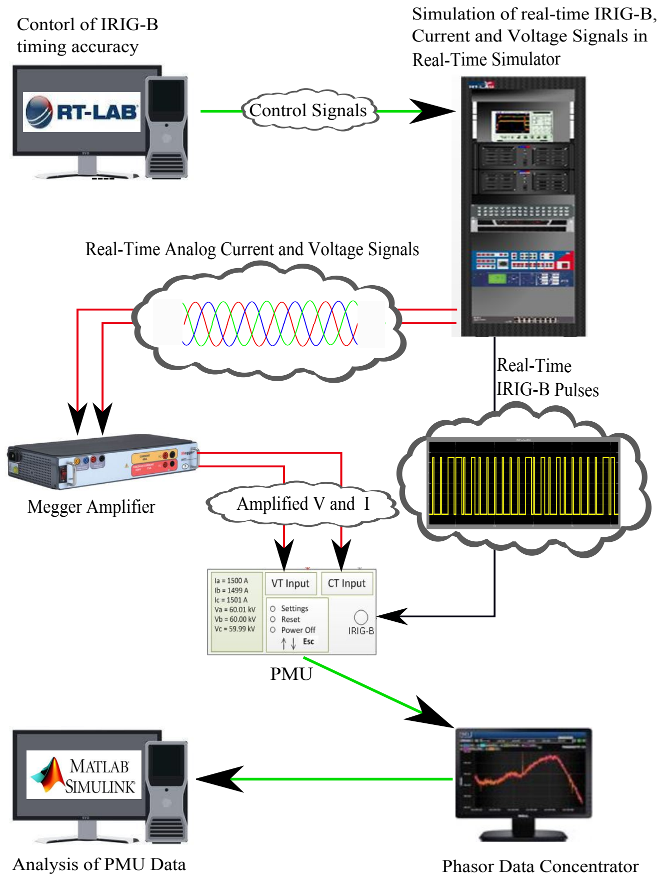
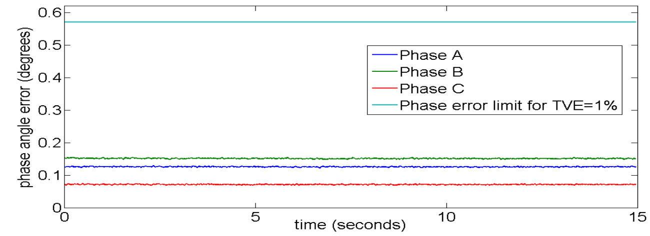


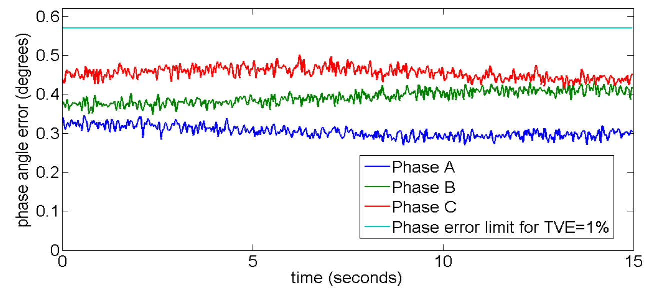
Fig. 6: Real-Time, Hardware-in-the-loop set-up to determine timing accuracy requirements

C. Real-Time Hardware-in-the-loop set-up

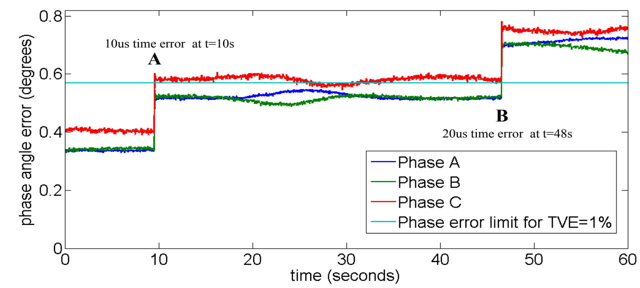
For this test, real-time voltage and current signals and real-time and controllable IRIG-B timing signals were required as inputs to commercial PMU under test. All these signals should use a same time reference. These signals were obtained by executing the IRIG-B and balanced three phase current and voltage signals SIMULINK blocks on the Opal-RT's eMEGASIM real-time simulator platform [15]. Analog pulses of IRIG-B and analog voltage and current phases were obtanind from the simulators output terminals. The simulator can produce analog outputs up to $\pm 16V$. The PMUs required IRIG-B time code pulse of amplitude 5.5V. So analog IRIG-B pulses were generated in real-time with amplitude of $5.5V$ and were directly sent to the PMU IRIG-B input. This synchronises the PMU to the time according to the initial parameters set by the user. For correct operation, the PMU required higher amplitude voltage and current signals. So the three phase voltage and current signals generated by the real-time simulator were amplified using the Megger SMRT1 amplifiers and were fed to the VT and CT inputs of the PMU. Due to the associated phase angle errors, these single phase Megger amplifiers were also representing CTs and VTs in this set-up. The whole channel from the real-time simulator's output to the PMU's current and voltage input including the amplifiers and the connection cables represented the instrumentation channel. Simulink model-to-data analysis work-flow for this test is shown in Fig. 6 The green wires in the the figure indicate transfer of data over Ethernet. The instrument channel is shown connected using the red arrows.



(a) Phase error in measured voltage signals in stand-alone tests



(b) Phase error in measured voltage signals in presence of Instrumentation Channel



(c) Phase error in measured voltage signals in presence of Instrumentation Channel and varrying time error in steps of $10\mu s$ at point A and B

Fig. 7: Phase angle variation in measured voltage for a commercial PMU for different test cases;

The PMU makes phasor estimates of the signals received. The timing signals can be manipulated by the user during the test. Basic blocks like 'Transmission Delay' from SIMULINK's library can be used to delay the time signals for a few microseconds to a few milliseconds. In the experiment, the time errors were varied in the steps of $10\mu s$. Continuously generated synchrophasor estimates by the PMU for different timing errors were sent to the Phasor Data Concentrator (PDC) and stored there. This logged data was analysed using MATLAB. The effect of timing errors on the phase errors of the measured signals and hence on the over all TVE of the estimated phasor was studied and plotted on the graphs.

IV. Results

After analysing the phasor data recorded, it is realized that the phase error due to the instrumentation channel can cause major rise in the final TVE of the measurement system including PMU and instrumentation channel. The plots of phase angle errors for measured voltage signals by a commercial PMU is shown in Fig. 7. It is seen that in presence of instrumentation channel errors the time error of $10\mu s$ caused the voltage phase angle errors cross the $0.573°$ mark which effects in 1% TVE. So it can be asserted that the errors due to instrumentation channel should be considered while examining the timing requirements for commercial PMUs.

V. Conclusion

This paper has detailed the construction of a real-time test set-up to determine the timing accuracy requirements for PMUs. A generic hardware-in-the-loop set-up was constructed around OPAL-RT's real-time simulation platform using commercial PMU units. Brief overview of IRIG-B as PMU time source was also discussed. Tests were performed using a controllable simulation of a timing source to explore the effects of timing errors on the Total Vector Error. The results for a commercial PMU were discussed and it was observed that phase angel errors due instrumentation channel and can significantly affect the final TVE of the PMU measurement system and hence this should be taken into account while determining the PMU timing requirements.

References

[1] B. Vandiver,A, Apostolov, F. SteinHauser, "Testing of Phasor Measurement Units," in *2010 63rd Annual Conference for Protective Relay Engineers* , pp. 1-5, Apr. 2010.

[2] B. Dickerson, *"Time in the Power Industry:How and Why We Use It"* available online at:http://www.arbiter.com/files/product-attachments/TimeInThePowerIndustry.pdf

[3] *IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control*, C37.242-2013 , March 2013.

[4] *IEEE Standard for Synchrophasor Measurements for Power Systems*, C37.118.1-2011 , Dec 2011.

[5] G. Y. Yang, K. E. Martin and J. Østergaard, "Investigation of PMU Performance Under TVE criterion", in *Proc. 5th International Conference on Critical Infrastructure (CRIS, 2010)*, pp. 1-7.

[6] M. S. Almas, J. Kilter and L. Vanfretti, "Experiences with steady-state PMU compliance testing using standard relay testing equipment", in *Proc. Electric Power Quality and Supply Reliability Conference (PQ), 2014*, pp. 103-110.

[7] Z. Wu, K. Thomas, R. Sun, V. A. Centeno and A. G. Phadke, "Three-phase instrument transformer calibration with synchronized phasor measurements", in *Proc. 2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, pp. 1-6.

[8] Megger, Freja 300 - Relay Test System, [Online]. Available: http://www.megger.com/eu/products/ProductDetails.php?ID=861&Description=.

[9] Arbiter, GPS Substation Clock Model 1094B, [Online]. Available: http://www.arbiter.com/catalog/product/model-1094b-gps-satellite-precision-time-clock.php

[10] Z.Huang; B. Kasztenny; V. Madani; K. Martin et al, "Performance evaluation of phasor measurement systems", in *Proc. Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,2008*, pp. 1-7.

[11] Megger, SMRT1, Single Phase Relay Tester, [Online]. Available: http://www.megger.com/us/products/ProductDetails.php?ID=1529

[12] Jin-kai Huang, Liang Du, Qun-ying Liu, "Application of IRIG-B Code in Phase Measurement Unit", in *2012 Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 1-3, Mar 2012.

[13] Jackie Peer, Eric Sagen, Shankar Achanta and Veselin Skendzic, "The Future of Time: Evolving requirements for Precize Time Synchronization in the Electric Power Industry," Schweitzer Engineering Laboratories, Inc., 2011, [Online]. available: https://www.selinc.com/WorkArea/DownloadAsset.aspx?id=9995

[14] IRIG Standard 200-98,*IRIG Serial Time Code Formats*, May 1998. [Online]. Available: http://www.irigb.com/pdf/wp-irig-200-98.pdf

[15] Opal-RT Technologies, "OP5600 off-the-shelf Hardware-in-the-Loop (HIL) simulator," [Online]. Available: http://http://www.opal-rt.com/product/op5600-hil-hardware-in-the-loop-computer-and-IO-system