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Simple method for calibration of PMU calibrators

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***Abstract* – The number of Phasor Measurement Units (PMU) is growing rapidly. The metrological institutes and calibration laboratories has to calibrate not only PMUs, but also calibrators of PMUs. To achieve this goal, several reference PMU systems have been built. These systems use costly time synchronization units. The paper shows another method to trace a digitizer to a standard of time. The advantage of the method is removing a need to obtain a time synchronization unit. Setup of a reference PMU system using the method is described and uncertainty budget is shown. The budget shows out the presented method achieved sufficiently low uncertainties required for calibration of PMU calibrators.**

I. INTRODUCTION

The number of Phasor Measurement Units (PMUs) installed around the world and the number of vendors have been growing rapidly. The industry recognized that phasor measurements and wide-area monitoring have significant impact on the power system security. The PMU device measures synchrophasor of alternate voltage and current at a high sample rate (up to 1 phasor per cycle), thus providing the transmission system's dynamic observability. Every PMU is equipped with a GPS (Global Positioning System) receiver, so that all the measurements in the system can be time-aligned.

The measurement of synchrophasor requires measurement of amplitude and phase of an alternate voltage or current signal. The phase has to be referenced to a time standard, thus results in a measurement of absolute phase. PMU consists of a transducer and an analogue to digital converter (ADC) to record a waveform. The sampled data is processed by data processing algorithm, a synchrophasor value is calculated and usually reported to a Phasor Data Concentrator (PDC). PDC can collect streams from multiple PMUs using chosen communications network technology and it is responsible for providing data to analyse.

Calibration of a PMU is a task accomplished by generating a waveform with defined properties of amplitude and absolute phase in both static and dynamic modes. Typical PMU calibrator (e.g. a Fluke 6105A with Fluke 6135A) is a phantom voltage and current generator tied to the control system, standard of time and frequency, control computer and network hub. A PMU calibrator can generate various waveforms to test and validate multiple properties of the PMU according the IEEE standard C37.118.1-2011 [1].

The error of a PMU is expressed as a Total Vector Error (TVE). Maximal TVE of a PMU, as specified by IEEE standard, should be 1 %. So uncertainty of PMU calibrator should be (by using a rule of a thumb 1 to 4) less than 0.25 %.

A calibration of the PMU calibrator is a typical task for National Metrological Institute (NMI) and it is more complex than the calibration of a PMU. A reference PMU is required, and all reference PMU components must be traceable to the national standards. The target uncertainty of the synchrophasor should be less than 0.025 %. Several such PMUs have been developed, e.g. [2], [3]. These reference PMU systems are composed of transducer, digitizer, time standard, time synchronization unit, data processing algorithms, control computer, and control software. The time synchronization unit is used to trace the absolute time of ADC samples. Most of the listed components are common in every NMI. Several international projects aim at calibration of the transducers and digitizer with utmost precision using quantum standards. Contrary the time synchronization unit is not common. It must handle complex time synchronisation signals (e.g. IRIG-B) and can be expensive. However, every NMI own a time standard generating one-pulse-per-second signal (1PPS).

This paper shows a method to trace digital samples to the absolute time and use it for the calibration of synchrophasor without using costly time synchronization unit. A two channel digitizer is used to sample both the voltage signal and a 1PPS signal. This was used to calculate the absolute time of the samples, calculate the synchrophasor and calibrate a PMU calibrator. The advantage of this method is decreased requirements to establish a new calibration service in a NMI.

II. SYNCHROPHASOR CALIBRATION METHOD

The presented calibration method relies on the properties of a two channel digitizer with a time base common to both ADCs. Because of the common time base, time errors of samples acquired by first channel are almost the same as the time errors of the samples acquired by second channel. The first channel is used to calibrate the time base and the second channel is used to sample the synchrophasor waveform.

The method was tested on a measurement setup consisting of:

- transducer,

- two channel digitizer,
- time standard,
- data processing algorithm,

The schematic diagram of the measurement setup is shown in Fig. 1. PMU calibrator Fluke 6105A and 6135A served as a device under test and was set to generate synchrophasor waveform. Selected PMU calibrator cannot work without a connected PMU, thus a PMU was part of the setup. The values measured by the PMU were not taken into account. The transducer of CMI own design scaled the voltage down to the full scale range of the digitizer National Instruments 5922. The digitizer was powered by external DC battery to prevent ground loops. A time standard Stanford-Research FS740 traceable to national standard of time was used to generate 1PPS signal. Both Fluke 6135A and FS740 used dedicated independent GPS antenna.

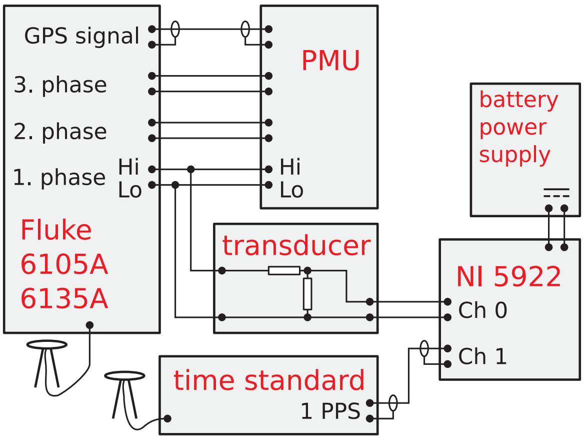

Fig. 1. Schematic diagram of the calibration setup. Both Fluke 6135A and reference time standard are connected to its own GPS antennas.

The generated 1PPS signal consists of rectangular pulses of 20 µs duration, one puls every second. The pulses were used for two purposes.

First purpose was to calibrate the sampling frequency of the ADC. Digitizers usually can lock to a reference frequency signal, typically of 10 MHz frequency. Yet the 1PPS gave clear information on the correctness of the lock.

Second purpose was to identify start of a real time second and thus providing the absolute time of the samples. Unfortunately, such a simple 1PPS signal can not provide information which second is observed. This problem was solved by recording the time of start of the sampling in the control computer. The maximal clock error of the computer had to be less than 0.5 s. Such precision can be obtained using Network Time Protocol (NTP).

III. REQUIREMENTS FOR THE CALIBRATION METHOD

Using the TVE definition, requirements for the calibration method can be found. TVE is estimated as:

$$TVE = \frac{|X_{\mathrm{meas}} - X_{\mathrm{ref}}|}{|X_{\mathrm{ref}}|}, \tag{1}$$

where X_{meas} is value of a measured synchrophasor, X_{ref} is value of a reference synchrophasor. A synchrophasor is defined as a complex number with X_{r} real and X_{i} imaginary part: $X = X_{\mathrm{r}} + iX_i$. For a reference, dependence of the TVE on the error of the amplitude and phase measurement is shown in figure 2.

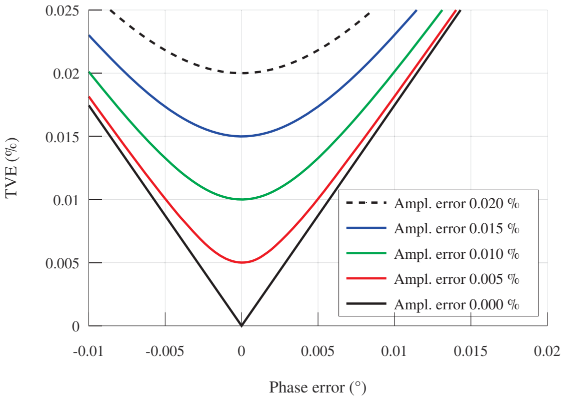

Fig. 2. Dependence of TVE on the errors of the amplitude and phase according Eq 1 for nominal amplitude 1 V and nominal phase 0 °.

To obtain the TVE less than 0.025 % (250 parts per million), the combined relative errors of amplitude and phase measurement must be less than this value. Typical CMCs of NMI for voltage amplitude calibration at range 10 to 300 V is about 10 to 30 µV V^{-1}. This is about one order less than required error of TVE. Because TVE is composed from both amplitude and phase uncertainty, and because the uncertainty is added as square root of sum of squares [4], the uncertainty of amplitude can be the minor component. Thus the uncertainty of phase can be up to 250 µrad (0.0143 °). For typical signal frequency of 50 Hz this results in a maximal possible uncertainty of time measurement 0.8 µs.

IV. ABSOLUTE TIME RESOLUTION USING 1PPS

The 1PPS signal, as generated by a standard of time, usually has got a short transition time in order of nanoseconds. Identification of the beginning of the second depends on the transition time of the signal, resolution and sampling rate of the digitizer and error of the algorithm identifying the actual start of the signal.

The digitizer used in the setup can sample with various rates from 50 to 15 000 kSa s^{-1}. To achieve error less than

0.8 µs, the sampling rate has to be at least 1250 kSa s^{-1}. Sampling rate of 15 MSa s^{-1} was selected during the measurements.

To calculate absolute time of samples, a simple algorithm have been used. The sampling duration was selected to sample at least three pulses of the 1PPS signal, i.e. the length of the record was greater than 3 s. An algorithm found the maximum of the signal, selected voltage at half of the maximum and identified rising slopes of the pulses. Example of identification of a pulse rising slope is shown in Fig. 3. Fig. 4 shows a series of four pulses in one record with marks denoting real time second after 16:21:00 of local time.

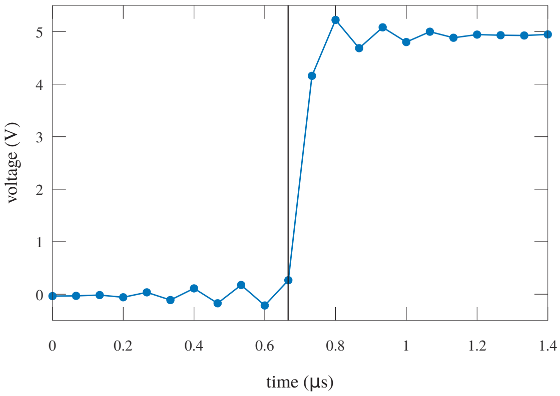

Fig. 3. Rising slope of one pulse denoting start of second as sampled by the digitizer. Vertical line denotes identified start of pulse.

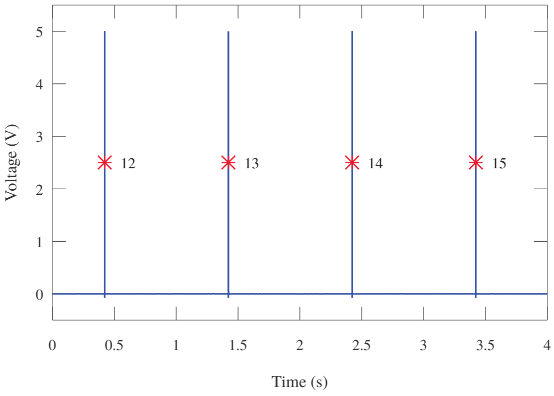

Fig. 4. Record with four pulses per second with marks denoting real time second after 16:21:00 of local time.

Simple linear regression was used to fit the sample indexes of the rising slopes and to obtain information both on the absolute time of every single sample using intercept of the fit and on the sampling rate using slope of the fit. The errors of the linear regression were smaller than 1×10^{-15} s for the case of the digitizer locked to a reference 10 MHz signal. The value of regression errors is at the level of rounding error, see figure 5. This was a good indication and check of proper detection of the rising slopes and of working algorithm.

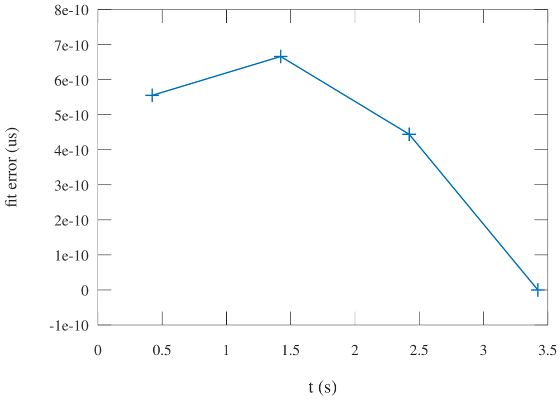

Fig. 5. Linear regression errors of the rising slopes.

Start of the sampling process was recorded by the control computer and the information was used to identify the first pulse of the 1PPS signal and relate it to the actual absolute second of Universal Time Coordinated (UTC). Although operating system Microsoft Windows contain a native tool providing time synchronization using NTP, the reliability was bad with errors repeatably greater than several seconds. Therefore software NetTime [5] was used to synchronize the computer time and the time errors decreased to 100 ms or less. However, any error of computer time smaller than 0.49 s was sufficient to correctly identify the actual seconds of the absolute time.

V. UNCERTAINTY BUDGET

The uncertainty budget of the described setup is shown in following tables.

The first table 1 shows uncertainty components affecting estimation of the phase. The second table 2 shows uncertainty components affecting estimation of the amplitude.

A. *Time standard*

The uncertainty contributions of the time standard FS740 are: the error of the time standard, pulse transition time, jitter, phase accuracy and cable delay. Values of errors were based on the specifications and uncertainty, if not stated in the specifications, was selected as half of the maximum error.

B. *Transducer*

The selected transducer was used to convert PMU calibrator voltage amplitude from 50 to 240 V to a value smaller than 5 V range of the digitizer by means of a resis-

Table 1. Uncertainty budget for absolute phase estimation

Uncertainty source	Error or specifications	*TVE*	$u(TVE)$
Contributions of the time standard:			
Traceability to national standard of time	0 ± 10 ns	0	3.1×10^{-6}
Pulse transition time	1 ± 1 ns	0.31×10^{-6}	0.31×10^{-6}
Jitter	25 ± 25 ps	0.79×10^{-9}	0.79×10^{-9}
Phase accuracy	1 ± 1 ns	0.31×10^{-6}	0.31×10^{-6}
Cable delay, 0.1 m	0.5 ± 0.1 ns	0.173×10^{-6}	0.031×10^{-6}
Contributions of the transducer:			
Phase error	12.61 ± 0.11 m°	220.1×10^{-6}	1.9×10^{-6}
Contributions of the digitizer:			
Interchannel phase difference	0 ± 0.1 m°	0	1.7×10^{-6}
Contributions of data processing:			
Pulse start detection	0 ± 33 ns	0	10×10^{-6}
Phase estimation error	0 ± 0.1 mrad	0	100×10^{-6}
Total phase uncertainty contribution			101×10^{-6}

Table 2. Uncertainty budget for amplitude estimation

Uncertainty source	Error or specifications	*TVE*	$u(TVE)$
Transducer ratio error	$17 \pm 22\ \mu\mathrm{V\,V^{-1}}$	17×10^{-6}	22×10^{-6}
Digitizer gain error	$-263 \pm 42\ \mu\mathrm{V}$	404×10^{-6}	64×10^{-6}
Digitizer gain stability (10 minutes)	$0 \pm 10\ \mu\mathrm{V\,V^{-1}}$	0	10×10^{-6}
Algorithm error	$0 \pm 10\ \mu\mathrm{V\,V^{-1}}$	0	10×10^{-6}
Total amplitude uncertainty contribution			69×10^{-6}

tive divider. The transducer was built in Czech Metrology Institute. Calibration of a transducer was already described in several papers and is out of focus of this paper [6]. The transducer was calibrated for amplitude ratio at expected signal frequency (approx. 50 Hz) and at defined impedance load at the output. The impedance was determined by the input impedance of the digitizer and a cable connecting the transducer and the digitizer. The error and uncertainty of the transducer was based on the calibration certificate.

C. *Digitizer*

Amplitude error of the digitizer was calibrated using methods already published [7]–[10]. The error and uncertainty of the digitizer was based on the calibration certificate. Stability of the digitizer was based on [9]. Because the time of the samples was estimated using the first digitizer channel, and the synchrophasor was estimated using the second channel, the phase error between both channels had to be estimated. The error was measured by using a signal of an AC source. The signal was split using T cable connection and lead to both digitizer channels at once. Next a phase of the AC waveform was calculated for both channels. Difference between the two phase values resulted in the inter-channel phase error.

D. *Data processing*

Sampled ac waveform had to be processed by an algorithm to obtain amplitude and phase and to calculate the synchrophasor. Three main groups of algorithms exists. Based on the algorithm comparisons [11], [12], the PSFE algorithm have been selected to process the sampled data. Using simulations and studies already presented in [13], [14] and tests published in [15], [16] the algorithm error of phase estimation is expected to be less than 0.1 mrad and for amplitude estimation less than $10\ \mu\mathrm{V\,V^{-1}}$ for sampling frequency $15\ \mathrm{MSa\,s^{-1}}$, records longer than 10 periods of the signal, and coherent sampling.

VI. CALIBRATION OF PMU CALIBRATOR

The PMU calibrator was set to generate simple three-phase sine waves of nominal amplitude 230 V and nominal frequency 50 Hz. The signals were sampled one phase after another. Tab. 3 shows the measured phase errors and TVE values. Specifications of the Fluke system for TVE is 0.1 %, so the PMU calibrator is well in the specifications. The total uncertainty of the measurement setup is well below required 0.025 % (250×10^{-6}) so the target uncertainty was achieved. The measured data were published in [17].

Table 3. Measured TVE of a three phase PMU calibrator.

	TVE ($\times 10^6$)
Phase 1	192 ± 122
Phase 2	4 ± 122
Phase 3	133 ± 122

VII. DISCUSSION

The presented paper shows an easy method to trace the sampled records to the absolute time. Simple reference PMU system was set up and the presented method was used to calibrate a PMU calibrator. The system and the method circumvents the need to buy costly time synchronization time units used in other reference PMU meters. The uncertainty contribution to the TVE caused by phase errors was estimated to be 101×10^{-6} (0.0101 %).

The presented system does not implement full online reference PMU meter because of the many complexities of the real PMU meter fulfilling whole IEEE standard. The purpose of the system was only to measure synchrophasor using fully traceable methods and devices and to establish a direct traceability link between national standards of time, voltage and PMU calibrator.

VIII. ACKNOWLEDGEMENT

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