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Time synchronization for synchronous measurements in Electric Power Systems with reference to the IEEE C37.118™ Standard – selected tests and recommendations

***Abstract**. Time-stamped synchronized measurements offer tremendous benefits to electric power system applications. Synchrophasors require high-accuracy time-stamping of all the measurements in the power system. This paper discusses direct and indirect type of synchronization and presents hardware implementation of the time-source solution which can be used for precision time-stamping in Phasor Measuring Units (PMUs) to meet the rigorous requirements of the IEEE C37.118™2011 Standard. In addition, functional testing is performed to verify the practicality of the proposed solutions.*

***Streszczenie.** Zsynchronizowane w czasie pomiary oferują wiele możliwości zastosowań w systemie elektroenergetycznym. Urządzenia, które je realizują wymagają precyzyjnych źródeł czasu. W artykule omówiono bezpośredni i pośredni sposób synchronizacji czasu oraz przedstawiono sprzętową implementację źródła czasu dla urządzeń PMU spełniającą restrykcyjne wymogi standardu IEEE C37.118™2011. Przeprowadzono również wybrane badania funkcjonalne dla weryfikacji poprawności tego rozwiązania. (**Synchronizacja czasu dla potrzeb pomiarów synchronicznych w Systemie Elektroenergetycznym z odniesieniem do wymagań normy C37.118™ – wybrane badania i propozycje rozwiązań**).*

Keywords: Time synchronization, synchronous measurements, Electric Power System, IEEE C37.118™.
Słowa kluczowe: Synchronizacja czasu, pomiary synchroniczne, System Elektroenergetyczny, IEEE C37.118™.

Introduction

Time synchronization is supposed to co-ordinate at least two processes at the same time, pursued in parallel, independently of their course [3]. This makes it possible to determine which process occurred first in spacetime and it helps to establish the chronology of events. Time-stamped synchronized measurements offer a tremendous benefit to the system control and monitoring applications [17-20]. They are real-time measurements which represent current system conditions at any given time and can be also used in power system protection and the other applications. The synchrophasor technology requires high-accuracy time-stamping of all the measurements in the power system area [1-6], [17-18], [20]. There are two main ways to fulfill the above-mentioned requirement. Direct synchronization captures the reference time from the accurate time source for each of the synchronized devices. Indirect synchronization differs from the previous one in that only some parent devices (masters) are synchronized by the accurate time source (e.g. the GPS time). The other ones are synchronized (as slaves) with the master devices. In both cases it is necessary to use an appropriate telecommunications network structure and to transfer protocols for accurate flow of time-information between devices [14-15]. The advantage of direct synchronization is the lack of an intermediate stage in the process of synchronization. The big drawback in this case is the need for additional GPS receivers for each of the devices and possible time synchronization errors in the whole analysed area. On the other hand, in indirect synchronization a good knowledge of the transmission network topology can predict the time delay of the signal transmission between devices and it makes it possible to calculate pre-defined time shifts for the synchronizing signal. The application of one of these synchronization methods is dependent on the individual characteristics of the network [1-6], such as future teletransmission network extension, the number of synchronized devices, visibility of satellites in the area, etc. [12].

The influence of time synchronization error on the synchronous measurements accuracy

The IEEE Std 1344™-1995 was the original synchrophasor standard. It was replaced in 2005 by the the IEEE Std C37.118-2005 [7]. The newest standard has been split into two standards: the IEEE Std 37.118.1-2011 [8], covering measurement provisions, and the IEEE Std 37.118.2™-2011 [9], covering data communication. Both standards contain the previous material with updates and additional provisions. In the 2011 IEEE standard, there was a significant change of the requirements for synchronous measurements and the standard included additional clarification for the phasor and synchronized phasor definitions. The concepts of Total Vector Error (TVE) and compliance tests are retained and expanded [7-11]. In addition, limits and characteristics of frequency measurement and rate of change of frequency (ROCOF) measurement have been developed. Phasor representation of sinusoidal signals is commonly used in the AC power system analysis. The theoretical values of the synchrophasor representation of a sinusoid and the values obtained from a PMU (Phasor Measurement Unit) may include differences in both amplitude and phase. While they could be separately specified, the amplitude and phase differences are considered together in the Standard in the quantity called a total vector error (TVE). TVE is an expression of the difference between a "perfect" sample of a theoretical synchrophasor and an estimate given by the unit under test at the same instant. The value is normalized and expressed as per unit of the theoretical phasor. TVE is defined in following equation:

$$TVE(n)=\sqrt{\frac{\left(X_{\mathrm{r}}(n)-\hat{X}_{\mathrm{r}}\right)^2+\left(X_{\mathrm{i}}(n)-\hat{X}_{\mathrm{i}}\right)^2}{\hat{X}_{\mathrm{r}}^2+\hat{X}_{\mathrm{i}}^2}} \tag{1}$$

where $\hat{X}_{\mathrm{r}}$ and $\hat{X}_{\mathrm{i}}$ are the sequences of estimates given by the unit under test, and $X_{\mathrm{r}}(n)$ and $X_{\mathrm{i}}(n)$ are the sequences of theoretical values of the input signal at the times (n) assigned by the unit to those values. Synchrophasor measurements shall be evaluated using the TVE criterion of Equation (1).

Synchrophasor measurements shall be synchronized with the UTC time with accuracy sufficient to meet the accuracy requirements of the Standard C37.118. What merits attention is the fact that the time error of 1 μs corresponds to a phase error of 0.022° for a 60 Hz system and 0.018° for a 50 Hz system. A phase error of 0.01 radian or 0.57° will by itself cause a 1% TVE as defined in Equation (1).

This corresponds to a maximum time error of ± 26 μs for a 60 Hz system, and ± 31 μs for a 50 Hz system. The system must be capable of receiving time from a highly reliable source, such as the Global Positioning System (GPS), which can provide sufficient time accuracy to keep the TVE within the required limits and it is indicative of the loss of synchronization. A special flag in the data output is provided to indicate that a loss of time synchronization shall be asserted when a loss of synchronization could cause the TVE to exceed the limit [7-11].

Measuring system components

The GPS receiver EM-406A [28] has been taken as the source of the time signal. This is a twenty-channel GPS receiver made by Globalsat. Two pieces of the receiver were used during the tests (Figure 1). On the basis of the signals received from the GPS network, the receiver generates messages in the NMEA 0183 and SiRF binary protocol. The EM-406A sensitivity is -159 dBm, and the accuracy of time for this receiver is 1 μs with respect to the GPS time. The receiver is powered by a DC voltage of 4.5 to 6.5 V. The output signal from the receiver has an amplitude of 0 to 2.85 V [28]. The last component of the measuring system was the digital oscilloscope. LeCroy Wavesurfer 424 is a four-channel digital oscilloscope operating under control of the Embedded version of Windows XP [27]. Depending on the version of the software, it makes it possible to process the data displayed on the screen and record them in popular file formats (e.g. text files, spreadsheets or images). The version of the oscilloscope used in tests lacked the option to save the entire series of measurements to the external file or spreadsheet. It was only possible to save the screenshots. Wavesurfer 424 allows the calculation of statistics such as a series of extreme values, the mean value and standard deviations, which will be presented in the paper.

The first step was to examine the delay of the PPS signal (*Pulse Per Second*) between the two antennas (GPS receivers with build-in antennas), which were in the same place. The PPS signals of the GPS receivers were put on two channels of the oscilloscope (Fig. 1). The trigger on an oscilloscope was adjusted for the slope of one of the PPS GPS signals. Both antennas were in the same location with the visibility of four (series A, B, C) or five (series D, E, F) satellites. Three measurement series (A, B, C) of 100 measurements were taken in [12] (Fig. 2), then another three series (D, E, F) in a different location. As shown in Table 1, the maximum difference in time between the PPS signal from the slopes of the two receivers in the same location was 692 ns.

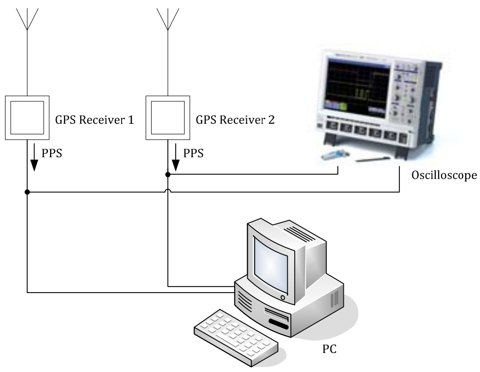

Fig. 1 The configuration I of the measuring system

The second measurement system is shown in Figure 3. The scheme of tests was the same as in the configuration I of the measurement system. The tests were carried out to check how the introduction of the twisted-pair cable into the transmission path would change the delay, and if so – what level and type it was. Figure 4 presents sample results of one series of 100 measurements. It is evident that the offset between the same signal, after passing through a UTP cable of the known length (305 m), is constant (1779 ns). Therefore, it can be used as the constant time-delay shift in future measurements.

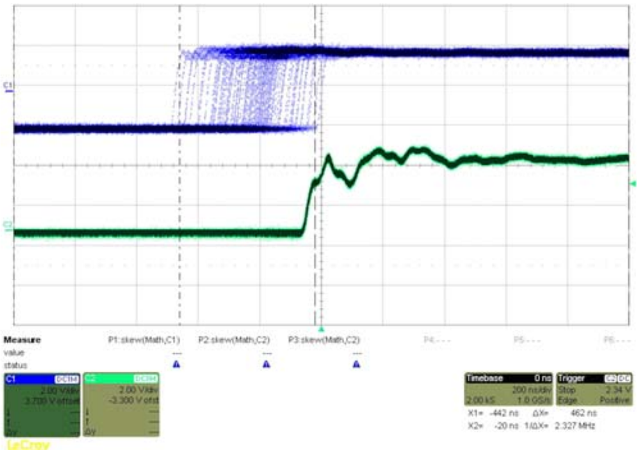

Fig. 2 Selected results of one sample series of tests obtained in the measuring system from Fig. 1

Table 1. Maximal and minimal time-delays recorded in a series of tests in the measuring system shown in Fig. 1

Test series	Minimal time-delay [ns]	Maximal time-delay [ns]
A	-140*)	401
B	85	368
C	-4*)	692
D	-23*)	462
E	-9*)	548
F	12	618

*) Negative value means that Signal 2 arrives faster than Signal 1

The following measurements were done when the antennas (GPS receivers) were located approximately 50 m from each other, in two different parts of the building. The antenna (GPS receiver), which was moved to the other side, was connected to the oscilloscope via a twisted-pair copper cable of 305-m length. The measuring system is shown in Figure 5. The methodology of the measurements was analogous to the methodology used in the measuring system in Figure 1. The results were presented in Figure 6. In the configuration III of the measuring system the GPS receivers were located in different locations and they determined their time on the basis of data obtained from potentially different satellites. What also merits attention is the fact that the signal from one GPS receiver was delayed by the constant value of 1779 ns with the presence of the twisted-pair cable of 305-m length. Therefore, in order to determine the “real delay” between signals, recorded values should be diminished by this constant as shown in Table 2.

The last test was performed in the configuration of the measurement system shown in Figure 7. It was similar to the configuration from Figure 5, but there was the switch T208 in the path of the PPS signal from the GPS Receiver 1.

To achieve real-time measurements using Ethernet communication between synchronized units it is important to use true deterministic Ethernet devices. Most common problems in Ethernet communication are the collisions and collision domains, which are alleged to be the non-deterministic features of Ethernet. However, industrial Ethernet switches using some unique qualities and specific features, provide the solution that can guarantee network data delivery which fulfills the rigorous requirements for synchronous measurements. Westermo T208 is one of the switches. It has a high-power switching core which ensures that the switch operates at full wire speed on all ports without any major loading. In addition, T208 contains two queues that have low and high priority [26]. A high-priority packet is placed into the high-priority queue with the switch alternating between the queues using strict prioritization. The switch also supports Layer 2 Priority (*Priority tagging*) and Layer 3 Priority (*QoS - Quality of Service*). The first one meets the requirements of the IEEE802.1p and the IEEE802.1q standards. They specify an extra field in the Ethernet MAC header. This additional 3-bit field enables the switch to determine the priority of the packet. The second one (Layer 3 Priority) uses the IPv4 header, which contains a ToS (*Type of Service*) field. Using this field, the switch can determine the priority of the packet. Setting of the field is implemented on the socket level of the IP (Internet Protocol) client and server. Another important feature is the Head of Line blocking prevention, supported on low priority packets. This guarantees that all low-priority packets will not be forwarded to ports that are congested. Therefore, data packets in the switch output buffer are kept to an absolute minimum.

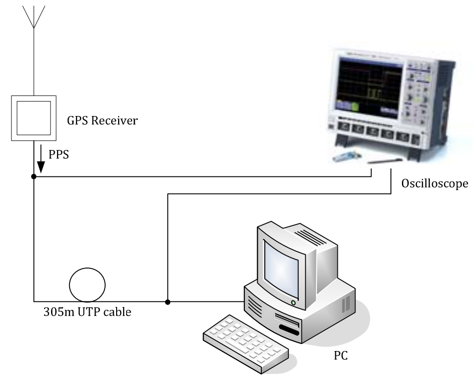

Fig. 3 The configuration II of the measuring system

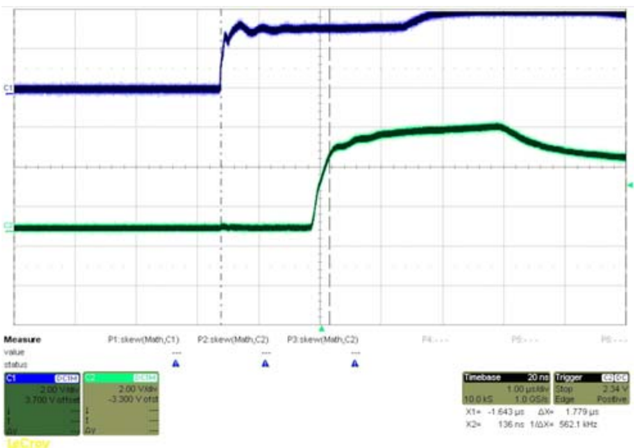

Fig. 4 Results of time-delay of PPS signal in UTP cable of 305 m length obtained in the measuring system from Fig. 3 [12]

The most important feature of the switches for the tests to be carried out is to ensure correct time stamping. The switch has an integrated time server that provides high-accuracy SoE (*Sequence of Events*) time stamping to all IP-enabled devices. The time server has an internal clock, and if absolute time is required, a GPS receiver can be connected to the switch.

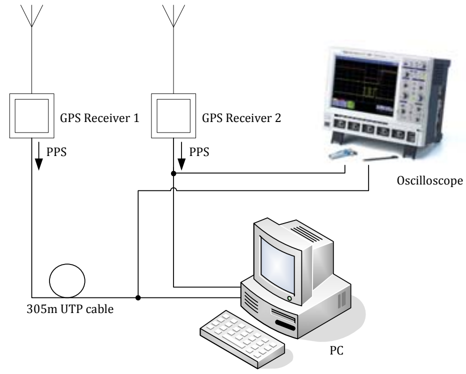

Fig. 5 The configuration III of the measuring system

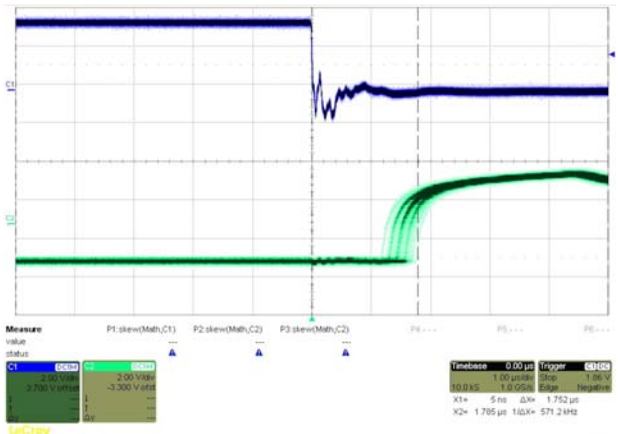

Fig. 6 Sample results of the measuring series D (Table 2)

Table 2. Time-delays recorded in a series of tests and the revised time-delays obtained in the measuring system configuration shown in Fig. 5

Test series	Recorded time-delays *)		Revised time-delays *)	
	Minimal time-delay	Maximal time-delay	Minimal time-delay	Maximal time-delay
	[ns]	[ns]	[ns]	[ns]
A	882	1665	-897 **)	-114 **)
B	1151	1780	-628 **)	1
C	1158	1761	-621 **)	-18 **)
D	998	1752	-781 **)	-27 **)
E	1012	1723	-767 **)	-56 **)
F	892	1692	-887 **)	-87 **)

*) “Recorded time-delays” are the original values recorded during the tests and the “Revised time-delays” are calculated by subtracting the constant value of 1779 ns of the time-delay induced by the twisted pair cable.
**) negative value means that Signal 2 arrives faster than Signal 1

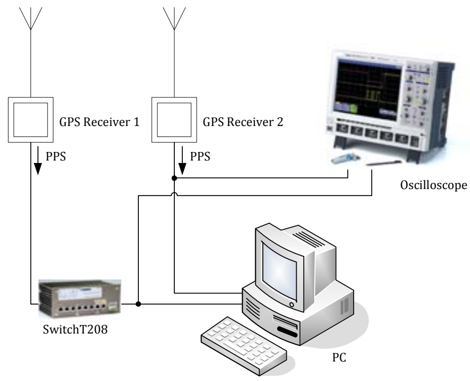

Fig. 7. Configuration of the measuring system with the Westermo T208 switch

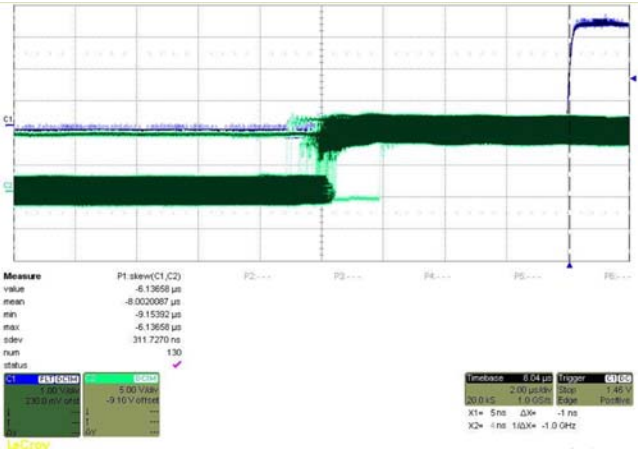

Fig. 8. Results of time-delay of the PPS signal passing through the T208 switch [12]

Figure 8 shows sample results of a series of tests (130 measurements). Signal "blue", generated by the switch, is the referencing signal. During the measurements there were some instances in which a slope (rising edge) of the PPS signal did not appear. This situation occurs when the GPS signal does not have an adequate quality. In all cases the signal coming directly from the GPS receiver arrives faster than the signal from the switch. The smallest difference in the time was -6.13658 μs. The biggest difference in the time was -9.15392 μs. Figure 8 additionally shows the mean and the standard deviation of the entire series.

Conclusions

Typical accuracy of time synchronization in computers and network devices is about 1÷10 ms. It results from low accuracy of their internal clocks and – in general – from an absence of mechanisms supporting high precision of time synchronization. Synchrophasor measurements should be synchronized to the UTC time with accuracy sufficient to meet the accuracy requirements of the C37.118 Standard. Time-stamp error should be of just a few (single) μs. To fulfill this requirement the accuracy of the time source should be about ten times higher than the level of the expected time-error. The basic problem in the tests of the accurate time-source parameters is the presence of a precise reference signal to which the results are linked. In this study it was assumed that the GPS receiver does not have any fluctuations of the PPS signal. Thus, the greatest potential difference in the accurate time in this study will be when one PPS signal is "accelerated" by the maximum time-error, and the second signal is delayed by the maximum time-error. Undeniably, a more accurate determination of the maximum time-delay between two PPS signals requires long-time measurements. However, the tests presented in this paper indicate that it does not exceed the permissible error assumed in the C37.118 Standard. Therefore, it can be concluded that the cable of specific technical parameters causes permanent offsets of the PPS signal that can be predicted e.g. by knowing the network topology. The cable does not introduce noticeable random time shift in the transmitted signal. The random time shift can occur e.g. in the wireless network, where it is not possible to achieve constant delays between successive nodes due to the "instability" of the transmission medium and its environment [14-16]. After subtracting the time-delay caused by the twisted-pair cable we may conclude that the PPS signal in most cases "overheads" the reference signal. The measuring system used in the study generates a situation in which the PMU devices are directly synchronized with the GPS signal via their own GPS receivers. As it can be seen, the scatter of time signals is quite significant. It can therefore be concluded that the direct synchronization is usually an inferior solution in most cases e.g. due to the synchronization of time based on the data obtained from a different number of visible satellites. A much better solution is an indirectly synchronized system with a specified network layout with one high-level synchronized device. In this configuration, knowing accurate information about the location of each device in the network makes it possible to synchronize all the devices with more accurate time-source parameters.

Predictably, the introduction of the active switching device (T208) into the PPS signal path delays the PPS signal obtained from the GPS receiver. Thus, each additional device or the cable part of the transmission path will trigger a time-delay [12]. However, as it has been discussed, some of the delays are fixed. They can be predicted and corrected and therefore they do not affect the quality of time-synchronization. Measurements made in the last configuration of the measuring system show that the T208 switch accounts for an average time-delay of about 7.5 μs compared to the results obtained in the Configuration I of the measurement system, and it never exceeds 10 μs. A low standard deviation makes it possible to correct the time signal in the synchronized devices by a constant value to achieve a more precise synchronization. The GPS unit, constructed on the basis of the GPS EM-406A device, is used to synchronize PMU devices [17], [29]. Figure 9 shows sample course of the Time Quality Code [8-9] during the PMU initial synchronization of time. This unit will be also used in the future functional tests of algorithms allowing the implementation of the forecast PMUs measurements and their functional features.

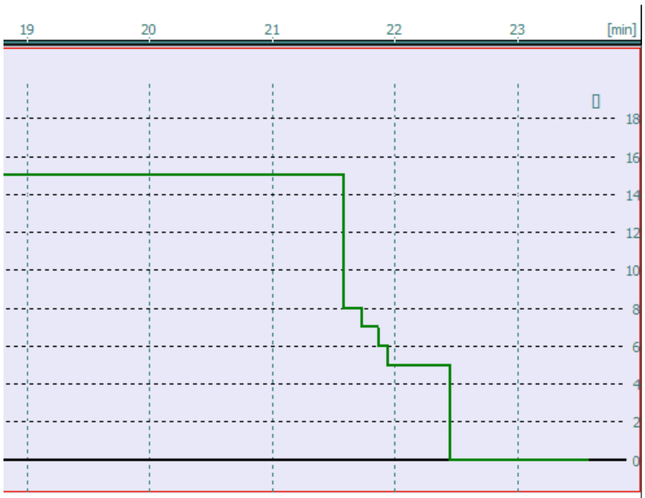

Fig. 9. Sample course of Time Quality Code during PMU initial synchronization of time

In a PMU network, the Global Positioning System (GPS) will be used to provide the precise clock signal. This enables PMUs to give their measurements a reliable time stamp. Nowadays attacks threatening PMU networks should be seriously considered. In the case of the transmission network most of these attacks may fall into the category of Denials of Service (DOS), Man-in-the-Middle (MITM), packet analysis, malicious code injection or data spoofing attacks. First and foremost, the loss or jamming of the GPS signal can be a serious problem for a reliable PMU operation [21-22].

The ongoing evolution of Electric Power Systems (EPS), especially distribution systems within the EPS structure, is driven by the proliferation of intermittent DG, PEVs, micrograds and power electronic components [24]. This requires new approaches and technologies to continue ensuring a reliable and secure supply to end users [23], [25]. Thus, the use of high-accuracy time-stamped measurements and reliable protective algorithms with adequately high accuracy and prompt decision-making [17-20] should guarantee an effective operation and protection of the EPS from the consequences of disturbances.

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