

# Time Synchronization for Smart Grids Applications: Requirements and Uncertainty Issues

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Smart grid implementation requires that multiple distributed systems are synchronized within and between substations. This is needed to coordinate the Intelligent Electronic Devices (IEDs) as well as to align in time the measurement data associated with the same event, but collected in different points of a broad geographical area. The time synchronization accuracy requirements in power systems are application-specific and are classified in the IEC Standard 61850-5:2013. Depending on such requirements, alternative solutions can be used. For instance, sub-microsecond time synchronization is essential for the implementation of Wide Area Monitoring, Protection, and Control (WAMPAC) systems. In fact, time synchronization directly and indirectly affects Phasor Measurement Units (PMUs) accuracy. The PMUs can measure the magnitude, the phase, the fundamental frequency and the Rate of Change of Frequency (ROCOF) of AC voltage and current waveforms at times synchronized to the Universal Coordinated Time (UTC). Among such quantities the phase data are those most strongly affected by time synchronization. If time synchronization accuracy is smaller than  $\pm 1 \mu\text{s}$ , its impact on synchrophasor phase measurement is in the order of a fraction of mrad, i.e., low enough to have a negligible impact on the state estimation uncertainty of most of transmission and distribution systems. However, the need to interpolate the missing phasor values when data from PMUs with a different reporting rate are collected and aligned in time may unexpectedly boost synchrophasor phase estimation uncertainty.

## 1. Time Synchronization requirements for power systems

In smart grids, transmission and distribution systems operators have to improve energy efficiency, prosumers' management flexibility, safety, security and more in general resilience. Services such as distributed generators scheduling, optimal energy dispatching (e.g., for electrical vehicles charging), volt/var optimization and advanced network protection schemes require

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widespread measurement and control devices as well as a ubiquitous information and communication infrastructure to improve situational awareness. A function that is very useful to support smart grid operation is *time synchronization*. Usually, the role of time synchronization is twofold. On the measurement side, time synchronization is needed to perform the time alignment of multiple and heterogeneous data sets collected by different instruments and sensors spread over the grid. Data alignment is particularly important if such data refer to a common event (e.g., a fault) and/or for system state estimation. From a control perspective instead, time synchronization is essential to coordinate the actions of different agents and Intelligent Electronic Devices (IEDs). Of course, the time synchronization accuracy requirements depend on the specific measurement and control application considered. The IEC Standard 61850-5:2013 provides a classification of time synchronization requirements for different kinds of applications and services [1]. This is shown in Table 1. The Standard specifies six levels of synchronization accuracy classes, ranging from *Class A* (accuracy in the order of  $\pm 1\mu\text{s}$ ) to *Class F* (greater than 1 s). It is important to emphasize that the IEC Standard 61850-5:2013 was purposely conceived to be technology independent in order to keep its scope as broad as possible. Nevertheless, different requirements can be mapped to different existing technologies. For instance, the traditional Supervisory Control and Data Acquisition (SCADA) systems are suitable to detect, record and handle “slow” events, i.e. with sampling periods ranging from a few seconds to a few minutes. In this case, a time synchronization accuracy in the order of hundreds of ms is sufficient to merge and to correctly process the data related to the same event (e.g. a severe fault or service interruption).

**Table 1 – Time synchronization accuracy classes for power systems applications specified in the IEC Standard 61850-5:2013.**

<b>Class</b>	<b>Synchronization accuracy requirements</b>	<b>Applications</b>
<b><i>Class A</i></b>	1 $\mu\text{s}$	Phasor and distributed measurements
<b><i>Class B</i></b>	100 $\mu\text{s}$	Automated fault recording
<b><i>Class C</i></b>	1 ms	Time tagging of fast/transient events
<b><i>Class D</i></b>	10 ms	Power quality monitoring
<b><i>Class E</i></b>	100 ms	Slow event monitoring and logging
<b><i>Class F</i></b>	>1s	Other no time-critical monitoring applications

For power quality measurements, higher time synchronization accuracy is needed because events such as voltage dips and sags may be so short as one power line cycle. So, higher temporal resolution and 10-ms synchronization accuracy are needed to investigate the correlation between multiple events detected in different points of the grid.

The coordination of protection devices installed in primary and secondary substations for the realization of logic selectivity systems is even more challenging. In fact, a time synchronization accuracy in the order of hundreds of  $\mu\text{s}$  is required to i) identify the source of the anomaly; ii) estimate its propagation through the grid and iii) perform a corrective action prior to service interruption.

Moreover, the increasing penetration of renewable-based and distributed energy resources is expected to cause not only sudden variations of power supply and demand, but also voltage amplitude and frequency oscillations that require the implementation of fast detection and stabilization techniques. To address these problems, the so-called Wide Area Monitoring, Protection, and Control (WAMPAC) systems are used. Such systems strongly rely on Phasor Measurement Units (PMUs), i.e., instruments able to measure amplitude, phase, frequency and rate of change of frequency (ROCOF) of AC voltage or current waveforms at times synchronized to the Universal Coordinated Time (UTC). In this case, sub-microsecond time synchronization accuracy as well as immunity to cyberattacks must be achieved. However, the security issues are generally not related to the technique employed to provide time synchronization as they depend instead on the communication protocol and on the technology used to transfer the temporal information.

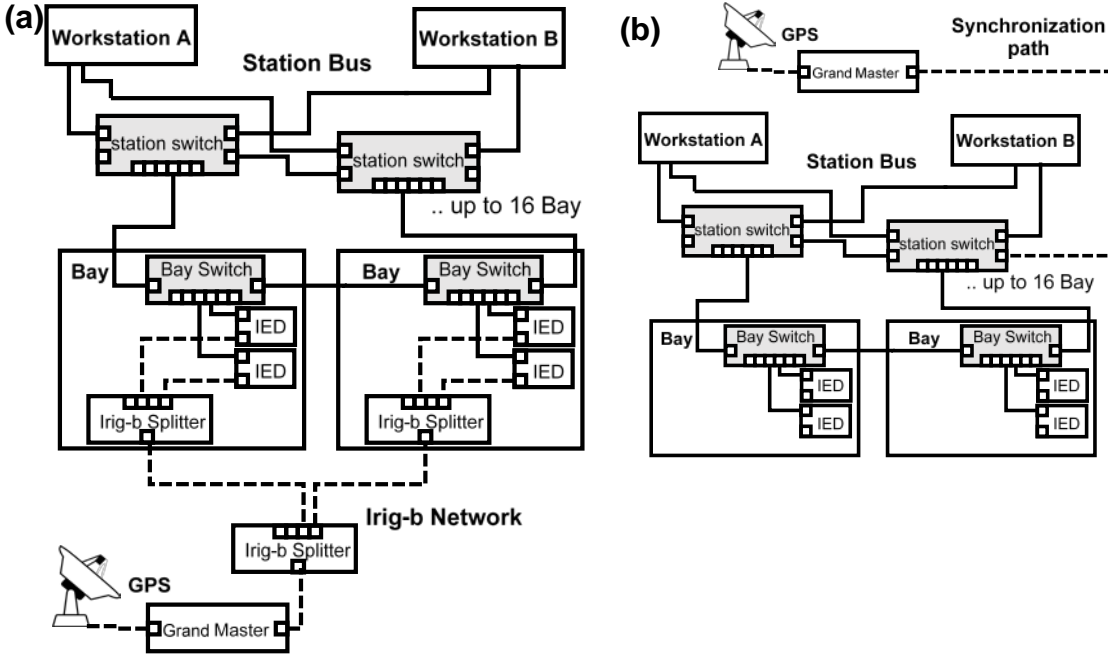
## **2. Overview of time synchronization techniques**

Electronic devices are typically equipped with a *clock* whose purpose is to provide a local time reference to the rest the system. Unfortunately, the time values measured by different clocks tend to drift away from one another due to oscillator tolerances and a variety of phase and frequency power-law noises. Thus, the time synchronization techniques are needed to keep the time values measured by different clocks aligned on the same time scale. In particular, “two clocks are synchronized to a specified uncertainty if they have the same epoch (i.e., the timescale origin is the same) and their measurements of the time of a single event at an arbitrary time differ by no more than that uncertainty” [2].

## **2.1    *Traditional time synchronization solutions***

The series of Standards IEC 61850 defines the architecture and the requirements that a Substation Automation Systems (SAS) must fulfill, including those related to time synchronization, as explained in Section 1. As shown in Figure 1(a)-(b), an SAS consists of multiple bays (called also process buses) whose goal is to control the field-level devices (e.g., circuit breakers, relays) of a portion of a line by using the data collected from various sensors and IEDs. A local network allows all the IEDs in a bay to communicate. The station bus connects the various bays of an SAS to the SCADA workstations.

A Global Positioning System (GPS) receiver is typically used to satisfy the most stringent synchronization requirements. Indeed, a GPS receiver can provide not only accurate estimates of the position of an object, but also an accurate time reference (i.e., in the order of  $\pm 100$  ns) as a result of the frequency stability of the Cesium clocks installed in the GPS satellites. In fact, the GPS receivers usually include a dedicated 1 Pulse Per Second (1-PPS) signal that can be used as a local time reference. The main disadvantage of GPS-based solutions is that they are not scalable, as they need an antenna for each receiver and, therefore, for each network node. However, the time obtained from a GPS receiver can be distributed, even indoors and over long distances, using the Inter-Range Instrumentation Group Time Code B (IRIG-B) over a dedicated copper or optical fiber cable. Figure 1.a shows how the time reference signal obtained from a GPS receiver is typically distributed to the bays of a primary substation. It is worth noting that the IRIG-B clock distribution network (dotted lines) relies on a physical infrastructure that is different from the main communication network (solid lines). This solution is widely used in the power industry. If the delays due to the signal propagation through the IRIG-B cables is compensated, a time synchronization accuracy better than 1  $\mu$ s can be easily achieved. Quite importantly, IRIG-B-based solutions do not support any redundancy mechanism different from physical network duplication.



**Fig. 1. Traditional (wired) (a) and network-based (b) time synchronization in primary SAS.**

## 2.2 Network-based time synchronization

Although the synchronization solutions based on the distribution of a signal through a dedicated wiring infrastructure provide good accuracy, they lack flexibility and they suffer from high installation costs. However, the time information can be alternatively distributed via a communication network, as shown in Figure 1.b. In this case, the information on time, provided by a GPS receiver, is encapsulated in messages and broadcasted from one or more reference nodes (denoted as a Grand Master in Figure 1.b) to the rest of the networked devices. The network delay used to transfer the time information is measured and compensated by a synchronization protocol. Thus, any error in estimating this contribution may have a significant impact on the overall accuracy. Unfortunately, the network delay is a non-zero-mean random variable that depends on several contributions (e.g., the network load or possible cables and transceivers asymmetries).

The time reference node and each device to be synchronized exchange a sequence of timestamped messages to estimate the network delay and the time offset between them. One of the main sources of uncertainty in network-based synchronization is indeed timestamping. Timestamping accuracy depends indeed on the layer of the ISO/OSI stack of protocols at which the ingress times of incoming messages and the egress times of outgoing messages are actually measured. Low-level timestamping is usually more accurate.

The Network Time Protocol (NTP) was designed to distribute time over networks with variable propagation delays by using TCP/IP messages. The nodes of an NTP network, called clocks, are arranged into a hierarchical structure. A single NTP clock can recover time information from one or more redundant time servers: the “Clock Selection Algorithm” decides which time references should be selected based on their quality. The NTP synchronization accuracy is in the order of a few ms, i.e., sufficient for the power systems applications of Classes C, D, E, F (see Table 1).

The Precision Time Protocol (PTP), standardized as IEC/IEEE 61588-2021 or simply IEEE 1588 [2], is a time synchronization protocol similar to NTP, but it is optimized for Local Area Networks (LANs). The PTP protocol usually self-arranges the clocks of the devices connected to a LAN into a tree structure with a master-slave hierarchy: the clock with the highest stability is automatically selected by the Best Master Clock (BMC) algorithm as the local time reference, also called *Grandmaster clock*. The Grandmaster clock sends multicast synchronization messages to the rest of the nodes, which progressively estimate the message propagation delays and their time offset with respect to the nodes at a higher level of the hierarchy, so that all nodes are ultimately synchronized to the same Grandmaster clock. Local servo-clocks are used to discipline the tick rate of slave nodes. PTP software-only implementations timestamp all messages at the operating system level (i.e., as a part of the device drivers). This solution ensures full compatibility with existing and non-PTP network devices, but at the price of a lower accuracy (generally in the range 1-10  $\mu$ s). The PTP solutions in which instead all devices involved in a time transfer chain perform message timestamping at the physical or Media Access Control (MAC) layer can ensure sub-synchronization accuracy. In this case fully PTP-compliant switches are required. They can be classified as Boundary Clocks (BCs) or Transparent Clocks (TCs). The former ones are used in hierarchical networks and include servo-clocks as well, whereas the TCs are primarily conceived for networks consisting of many cascaded devices (as it frequently happens in power systems applications) because they just measure and compensate for the propagation delays of all the PTP messages crossing them.

The PTP profiles describe specific settings of the PTP protocol conceived to optimize synchronization performance in specific application domains. Among them, the Power Utility Profile (PUP), standardized as IEC/IEEE 61850-9-3 [3], is focused on the needs of the power industry. The key PTP settings specified by the PUP are: hardware-only PTP implementation; use of Layer-2 synchronization messages over Ethernet; support of priority mechanisms for

communication; fault tolerance through redundant synchronization messages over duplicated network paths; support of simultaneously active redundant master clocks; use of TCs only as network switches. As a result, a PTP implementation based on the PUP can achieve sub-microsecond accuracy even when up to 15 TCs are cascaded.

The High Accuracy (HA) PTP profile (also called White Rabbit) has instead the ambitious goal to reach sub-nanosecond accuracy through a variety of additional features such as [4]: the use of synchronous Ethernet for low-level reference frequency transfer, the estimation and correction of the delays due to optical fiber cables and transceiver asymmetry, and the compensation of possible phase errors at the physical layer. Thus, the HA profile requires a much more complex and costly implementation. Table 2 summarizes the main features of the various synchronization techniques described above.

**Table 2 – Time synchronization solutions for smart grid applications.**

<b>Solutions</b>	<b>Pros</b>	<b>Cons</b>	<b>Time Sync. Accuracy</b>
NTP	Network-based, well-known	Limited accuracy	$\pm 1$ ms
PTPv2 (Soft. TS)	Network-based, good accuracy	Accuracy affected by the network traffic	$\pm 1$ $\mu$ s - $\pm 10$ $\mu$ s
IRIG-B	Indoor and outdoor	Dedicated synchronization line, cable calibration	$\pm 1$ $\mu$ s
PTPv2 (Hard. TS)	Network-based, good accuracy	Dedicated devices	$\pm 100$ ns
GPS	Available worldwide, No-cable required	Not for indoor applications	$\pm 100$ ns
PTPv2.1-HA	Network-based, extremely high accuracy	Dedicated hardware and wiring, expensive calibration	$< \pm 1$ ns

### **3. Time synchronization and synchrophasor measurements**

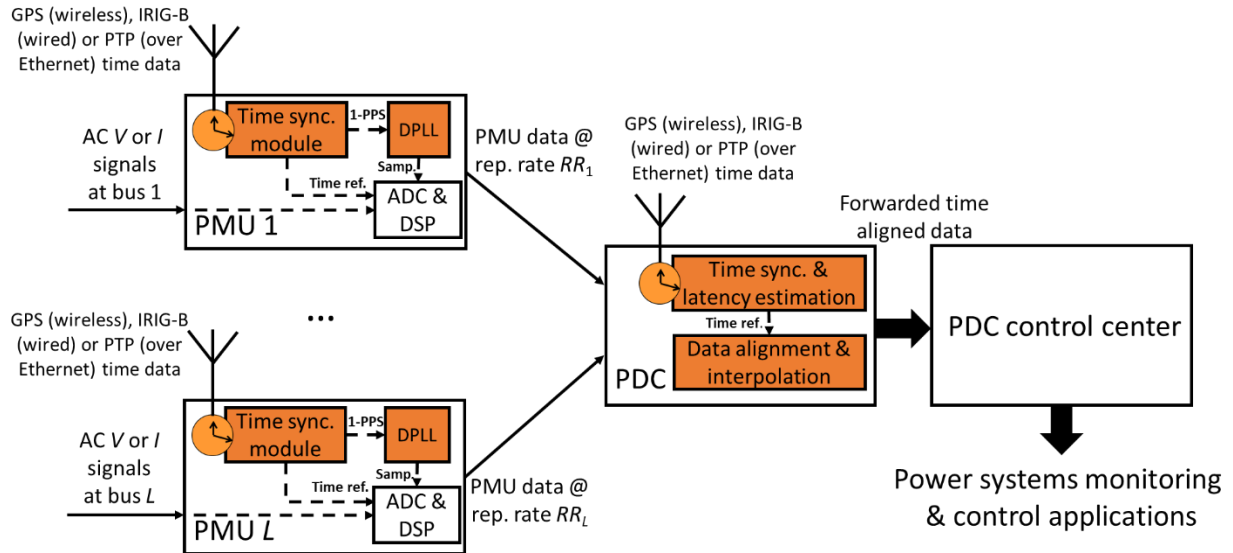
#### **3.1 *Synchrophasor angle accuracy requirements***

The state variables of power transmission or distribution systems (namely the quantities that should be measured to monitor the operation of a grid) are usually the bus nodal voltage phasors and/or the line current phasors [5]. To provide direct observability of such state variables, the PMUs can be used. The phasors of the AC voltage or current signals acquired by different PMUs, but referred

to the same UTC reference time, can provide a snapshot of the actual state of a grid [6]. The measurement results of multiple PMUs are usually decimated and transferred to a Phasor Data Concentrator (PDC) at rates ranging from 10 frame/s up to 100 frame/s or 120 frame/s depending on whether the power system nominal frequency  $f_0$  is 50 Hz or 60 Hz [7]. The role of a PDC is to aggregate and to align data with identical timestamps over time (if available) or even to reconstruct some missing samples if the reporting rates of the input PMUs streams of data are different or when some data are lost [6]. A qualitative overview of the role of time synchronization in PMUs and PDCs is sketched in the block diagram of Fig. 2. Focusing on the highlighted blocks only, time synchronization is essential:

1. To timestamp PMU values;
2. To discipline the frequency of the device used to sample the input AC voltage or current signals.
3. To aggregate and to reconstruct the missing data within the PDC.

The physical quantity that is most directly affected by time synchronization uncertainty is the synchrophasor angle, namely the angle of an input AC signal at each UTC reference timestamp. This problem is particularly critical, because the phasor angle differences between grid nodes at the same time are usually very small, at least in ordinary operating conditions.



**Fig. 2. Role of time synchronization functions for PMU signal processing and PDC data aggregation.**



For instance, Table 3 shows the range of variability of the voltage phasor angles at the buses of four different power transmission and four power distribution systems of growing size. The bus voltage phasor angle values result from a power flow analysis performed using the MATPOWER toolbox under nominal load conditions [8]. The angle values are computed with respect to the phase angle of the slack bus, which is usually taken as a reference (i.e., the voltage phasor angle at the slack bus is assumed conventionally to be 0). Therefore, the obtained angle values refer to an ideal scenario and they are not affected by any measurement uncertainty. The results of Table 3 show that in the case of transmission systems, the phasor angles generally differ by hundreds of mrad. Therefore, if PMUs with a resolution of a few mrad and accuracy within  $\pm 10$  mrad are used, a transmission system can be adequately monitored. This result is consistent with the PMU maximum Total Vector Error (TVE) values specified in the IEC/IEEE Standard 60255-118-1:2018 (e.g., 1% in most of testing conditions) [7], although no limits on phase errors are explicitly reported.

**Table 3 – Range of variability of the bus voltage phasor angles in various power transmission and distribution system of increasing size under nominal load conditions.**

	<b>Grid size</b>	<b>Phasor angles [mrad]</b>
<b>Transmission systems</b>	30 buses	$-39.5 \pm 47.5$
	89 buses (Pegase)	$-27 \pm 366$
	145 buses (IEEE)	$-203 \pm 901$
	1354 bus (Pegase)	$-273 \pm 508$
<b>Distribution systems</b>	37 buses (IEEE)	$-2.8 \pm 1.6$
	69 buses	$4.8 \pm 11.9$
	85 buses	$22.0 \pm 18.3$
	141 buses	$-4.2 \pm 2.6$

Observe that the phasor angle accuracy requirements become stricter at the distribution level since the angle differences between pairs of bus voltage phasors are from one to two orders of magnitude

smaller than in transmission systems. This is due to shorter lines, a smaller reactance/resistance ratio and the lower amount of power to be transferred over the lines. As a consequence, in distribution grids, the synchrophasor angle measurement resolution and accuracy must be better than 1 mrad, and possibly in the order of 0.1 mrad.

### 3.1 Impact of time synchronization uncertainty

In general, the uncertainty affecting synchrophasor magnitude and phase measurement is dominated by the contributions of the PMU acquisition circuitry, the signal processing estimation algorithm embedded in the PMU and the instrument transformers. However, since the focus of this paper is just on the impact of time synchronization uncertainty, for the sake of simplicity in the following all the phase uncertainty contributions different from those directly or indirectly related to time synchronization will be assumed to be negligible. In such conditions, the synchrophasor angle error at a generic UTC reference time  $t_r$  can be expressed as

$$\gamma_\varphi(t_r) \approx \varphi_d + \varphi_s(t_r) + \varphi_j + \varphi_c = 2\pi \left[ f_0 (\tau_d + \tau_s(t_r)) \right] + \varphi_j + \varphi_c. \quad (1)$$

where:

- $\varphi_d = 2\pi f_0 \tau_d$  is a possible systematic phase shift caused by the overall signal propagation delays  $\tau_d$  (e.g., from the GPS antenna);
- $\varphi_s(t_r) = 2\pi f_0 \tau_s(t_r)$  is the zero-mean, random phase noise due to the time fluctuations  $\tau_s(t_r)$  affecting the reference timestamp  $t_r$  as a result of time synchronization uncertainty;
- $\varphi_j$  is the intrinsic phase noise of the sampling clock signal;
- finally,  $\varphi_c$  is a random variable modeling the random uncertainty contribution due to the finite temporal resolution with which each period of the AC waveform acquired by the PMU is discretized through sampling. Therefore,  $\varphi_c$  can be assumed to be uniformly distributed in the interval  $[0, 2\pi f_0 T_s]$ , since it depends on the sampling period  $T_s$ .

Usually,  $\varphi_d$  can be omitted in (1), because the systematic delays affecting signal acquisition that are not corrected by the synchronization protocol have to be properly estimated and compensated through calibration. Even though residual delays (i.e., in the order of some ns) persist, their impact on synchrophasor uncertainty is quite negligible. For instance, if  $\tau_d = 10$  ns, then

$\varphi_d \approx 3.1 \text{ } \mu\text{rad}$  at 50 Hz or  $\varphi_d \approx 3.8 \text{ } \mu\text{rad}$  at 60 Hz, i.e. two order of magnitude smaller than the strictest accuracy requirements explained in Section 3.1.

The phase noise term  $\varphi_s(\cdot)$  in (1) is due to the chosen time synchronization technique. Excluding NTP, whose time accuracy in the order of a few ms is excessive for phasor measurement applications (i.e., in the order of hundreds of mrad), the typical solutions adopted in PMUs are based on:

- GPS receivers;
- PTP-based solutions with either hardware or software timestamping;
- The IRIG-B protocol.

Currently, the use of GPS receivers is by far the most used approach, but it is not scalable for the reasons already explained in Section 2.1. Therefore, PTP solutions along with the PUP are definitely preferable for next-generation substation automation. Since, as summarized in Table 2, GPS and PTP solutions with hardware timestamping can keep  $\tau_s(\cdot)$  bounded within  $\pm 100 \text{ ns}$  over very short chains of devices, then it follows that  $|\varphi_s(\cdot)| \leq 31 \text{ } \mu\text{rad}$  at 50 Hz or  $|\varphi_s(\cdot)| \leq 38 \text{ } \mu\text{rad}$  at 60 Hz. These values are small enough even for accurate distribution systems monitoring. The use of the PTP protocol with standard software timestamping (whose accuracy is within  $\pm 10 \text{ } \mu\text{s}$ ) may cause phase errors up to  $\pm 3 \text{ mrad}$  at 50 Hz and  $\pm 4 \text{ mrad}$  at 60 Hz. These values are borderline for transmission systems state monitoring and they are definitely too large for distribution-level state estimation. However, such uncertainty contributions can be roughly decreased by a factor 10 if just a few cascaded PTP-compliant switches are used for substation automation. Indeed, in such conditions it is possible to constrain  $|\tau_s(\cdot)| \leq 1 \text{ } \mu\text{s}$ , and, consequently,  $|\varphi_s(\cdot)| \leq 314 \text{ } \mu\text{rad}$  at 50 Hz or  $|\varphi_s(\cdot)| \leq 380 \text{ } \mu\text{rad}$  at 60 Hz. Such values are also consistent with the results achievable with the traditional solutions based on the IRIG-B protocol. Some researchers also explored the possibility to use the PTP HA profile to make  $|\varphi_s(\cdot)| \leq 1 \text{ } \mu\text{rad}$  [9]. However, in this case a dedicated communication infrastructure and a local disciplined servo-clock with superior frequency stability in the PMU signal acquisition stage have to be used.

In general, terms  $\varphi_j$  and  $\varphi_c$  in (1) depend on jitter and frequency of the sampling signal. Recalling that the PMU sampling frequency usually ranges from some kHz to a few tens of kHz,

the value of random variable  $\varphi_c$  can potentially be so large as to prevail over all the other contributions, i.e., from tens to hundreds  $\mu\text{rad}$ , which would be unacceptable. To make  $\varphi_c \approx 0$ , it is essential that the sampling frequency is an integer multiple of power system frequency. To this purpose, the 1-PPS reference signal produced by the GPS or the PTP-compliant modules has to be used to discipline the sampling clock signal. This can be done through a Phase-Locked Loop (PLL), a frequency synthesizer or the same servo-clock used for time synchronization. Nowadays, digital PLLs are often used since a Direct-Digital Synthesizer (DDS) driven by a Temperature-Controlled Crystal Oscillator (TCXO) or, even better, by an Oven-Controlled Crystal Oscillator (OCXO) provides a much higher frequency stability than any classic analog Voltage-Controlled Crystal Oscillator (VCXO).

Quite importantly, if the PMU sampling frequency is in the order of several kHz, then the phase comparator of the PLL (namely the component that measures the phase difference between the synthesized sampling signal and the 1-PPS input reference signal) can feed the PLL loop filter with just one phase comparison every several thousands of cycles of the DDS clock signal. As a consequence,  $\varphi_j$  is dominated by the local stability of the local TCXO/OCXO and it depends instead just weakly on the frequency stability of the reference 1-PPS signal, which is nonetheless essential to avoid long-term drift phenomena.

Thus, assuming for instance that the digital PPL generates a 12-kHz sampling clock signal [10], if the DDS is driven by a TCXO with frequency stability within  $\pm 1$  ppm, then the sampling period fluctuations are in the order of  $\pm 83$  ps, i.e., with a standard deviation of about 28 ps. If such fluctuations are normally distributed and white (i.e. uncorrelated in time, which is reasonable over short time intervals), the  $\pm 3\sigma$  Time Interval Errors (TIE) limits over 1-s intervals can be conservatively assumed to be about  $\pm 10$  ns because of the Central Limit Theorem (CLT). Thus, the values of  $\varphi_j$  can be so large as  $\pm 3.1$   $\mu\text{rad}$ , i.e., negligible. Considering that this scenario is quite pessimistic, since in practice TCXO or OCXO with a stability of tens of ppb can be used, we may conclude that the contribution of  $\varphi_j$  in (1) is significant only if PTP with the HA profile is used.

Table 4 summarizes the results of the analysis reported above and confirms that, if coherent sampling is performed and all systematic delays are reasonably compensated, sub-microsecond synchronization accuracy (and preferably within  $\pm 100$  ns) is usually sufficient for both transmission and distribution system monitoring and state estimation, in accordance with the *Class*

A requirements of the IEC Standard 61850-5:2013 [1]. The values separated by symbol “/” in Table 4 refer to  $f_0=50$  Hz and  $f_0=60$  Hz, respectively. The maximum  $\gamma_\phi(t_r)$  values reported in the rightmost column of Table 4 are the  $\pm 3\sigma$  limits of (1) computed from the sum in quadrature of the RMS values of  $\phi_s(\cdot)$  and  $\phi_j$  assuming to a first approximation that they are uncorrelated and that the impact of  $\phi_d$  and  $\phi_c$  is made negligible.

**Table 4 – Examples of 50/60-Hz maximum synchrophasor angle estimation errors due to both time limited synchronization accuracy and sampling jitter assuming that all the systematic phase delays are compensated and the random fluctuations due to finite clock resolution are made negligible through coherent sampling.**

	<b>Sync. Accuracy</b>	<b>Max. <math>\phi_s</math> range [<math>\mu</math>rad]</b>	<b>Max. <math>\phi_j</math> range [<math>\mu</math>rad]</b>	<b>Max. <math>\gamma_\phi</math> range [<math>\mu</math>rad]</b>
<b>PTP with SW timestamping (typical case)</b>	10 $\mu$ s	$\approx \pm 3142/3770$	$\approx \pm 3^a$	$\approx \pm 3140/3770$
<b>PTP with SW timestamping (best case) or IRIG-B</b>	1 $\mu$ s	$\approx \pm 314/377.0$	$\approx \pm 3^a$	$\approx \pm 315/378$
<b>GPS or PTP with HW timestamping over short lines</b>	100 ns	$\approx \pm 31/38$	$\approx \pm 3^a$	$\approx \pm 32/39$
<b>PTPv2.1-HA</b>	1 ns	$\approx \pm 0.3/0.4$	$\approx \pm 0.1^b$	$\approx \pm 0.4/0.5^c$

<sup>a</sup>Jitter computed over 1 s, assuming a TCXO with  $\pm 1$  ppm frequency stability.

<sup>b</sup>Jitter computed over 1 s, assuming an OCXO with  $\pm 10$  ppb frequency stability.

<sup>c</sup>Possible residual uncompensated delays may be comparable with the reported values.

### 3.3 Further uncertainty contributions affecting synchrophasor pangle estimation

When the PMU measurement data are collected and forwarded to a PDC, a variety of further latencies and uncertainty contributions may affect the data records aggregated by the PDC. The latencies are due to possible waiting times of the incoming PMU streams of data at the PDC input channels (e.g., because of heterogeneous networking delays) as well as to message propagation and processing times through the PDC. However, since the PDCs are also usually synchronized to the UTC, such latencies are not critical. In fact, they do not affect the PMU measurement data directly

and, in any case, they can be estimated and corrected by measuring the differences between the ingress and egress timestamps of input and output messages.

A subtler and more crucial accuracy problem may instead arise when the reporting rates of the PMU data collected by the PDC are different. In fact, the IEEE/IEC Standard 60255-118-1-2018 specifies that the PMU reporting rate can range from 10 frame/s up to 100 or 120 frame/s depending on whether the system frequency is 50 Hz or 60 Hz. If the PMU data rates are different, those collected at a lower rate should be interpolated to be aligned with those collected at a higher rate. Thus, the missing phasor angles at generic time  $t_r + \Delta t$  have to be reconstructed. For instance, by applying the Taylor's series of the phasor angle function truncated to the second order, the phasor angle at time  $t_r + \Delta t$  can be estimated from:

$$\hat{\phi}(t_r + \Delta t) \approx \hat{\phi}(t_r) + 2\pi \left( \hat{f}_0(t_r) \Delta t + \frac{\Delta t^2}{2} \widehat{ROCOF}(t_r) \right). \quad (2)$$

where  $\hat{f}_0(t_r)$  and  $\widehat{ROCOF}(t_r)$  are the frequency and ROCOF values measured by the PMU at the reference time  $t_r$ . Since both  $\hat{f}_0(t_r)$  and  $\widehat{ROCOF}(t_r)$  are affected by some measurement uncertainty, the synchrophasor angle reconstructed at time  $t_r + \Delta t$  is affected by the additional phase uncertainty contribution

$$\varphi_a(t_r + \Delta t) = 2\pi \left( FE(t_r) \cdot \Delta t + \frac{\Delta t^2}{2} \cdot RFE(t_r) \right). \quad (3)$$

where  $FE(t_r)$  and  $RFE(t_r)$  are the frequency and ROCOF errors at time  $t_r$ . Expression (3) shows that the phase reconstruction error grows with  $\Delta t$ . For instance, assuming to interpolate the PMU data by a factor 5 (i.e. from 10 frame/s to 50 frame/s) and keeping into considerations the FE and RFE limits specified in [7], it follows that if  $\Delta t = 80$  ms:

- For *P Class* PMUs  $|\varphi_a(\cdot)| \leq 10.6$  mrad in steady-state conditions (i.e., if  $|FE(\cdot)| \leq 5$  mHz and  $|RFE(\cdot)| \leq 0.4$  Hz/s) and  $|\varphi_a(\cdot)| \leq 27.1$  mrad under the effect of amplitude or phase modulations (i.e., for  $|FE(\cdot)| \leq 30$  mHz and  $|RFE(\cdot)| \leq 0.6$  Hz/s);
- For *M Class* PMUs  $|\varphi_a(\cdot)| \leq 4.5$  mrad in steady-state conditions (i.e., if  $|FE(\cdot)| \leq 5$  mHz and  $|RFE(\cdot)| \leq 0.1$  Hz/s) and  $|\varphi_a(\cdot)| \leq 106.6$  mrad under the effect of amplitude or phase modulations (i.e., for  $|FE(\cdot)| \leq 120$  mHz and  $|RFE(\cdot)| \leq 2.3$  Hz/s).

The analysis above shows that the uncertainty of synchrophasor phase angle reconstruction over intervals consisting of a few power line cycles can be dominated by the indirect effect of frequency and ROCOF measurement uncertainty contributions. As a result, the overall phase measurement uncertainty may become unacceptably large for *Class A* applications especially under dynamic operating conditions, since it is likely to exceed the accuracy requirements described in Section 3.1.

## 4. Conclusions

This paper presents an overview of the time synchronization accuracy requirements for power systems monitoring applications as well as the related crucial uncertainty issues in the context of synchrophasor measurement. Special attention is devoted to the effect of time synchronization uncertainty in PMUs and its potential impact on smart grid state estimation. In particular, the paper explains why sub-microsecond time synchronization accuracy is needed. The direct and indirect effect of time synchronization uncertainty on synchrophasor phase measurements is analyzed. If the signal propagation delays affecting PMU signal acquisition and preprocessing are properly estimated and compensated, the accuracy of the time reference used to timestamp individual synchrophasor values (and particular the phase angle ones) prevails over other time-related uncertainty contributions such as the sampling jitter and the sampling time resolution errors, provided that the same time synchronization module adopted for timestamping is also used to discipline the sampling clock signal and that a coherent sampling of the input waveforms is achieved. Under standard operating conditions, sub-microsecond accuracy is adequate not only for transmission systems, but also for distribution systems real-time monitoring and state estimation. However, when the data collected by a PDC from multiple PMUs at different rates are aggregated and aligned in time, the uncertainty of the frequency and ROCOF measurement values used to reconstruct the missing synchrophasor data may unexpectedly boost the phase measurement uncertainty regardless of how accurate the adopted time synchronization technique is.

## References

- [1] IEC 61850-5:2013, “IEC Communication networks and systems for power utility automation – Part 5: Communication requirements for functions and device models”, Jan. 2013.
- [2] IEC/IEEE 61588-2021, “IEC/IEEE International Standard - Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,” Jun. 2021, pp.1-504.

- [3] IEC/IEEE 61850-9-3:2016, “IEC/IEEE International Standard - Communication networks and systems for power utility automation – Part 9-3: Precision time protocol profile for power utility automation,” May 2016, pp.1-18.
- [4] Rizzi, M., Lipinski, M., Ferrari, P., Rinaldi, S., Flammini, A., “White Rabbit Clock Synchronization: Ultimate Limits on Close-In Phase Noise and Short-Term Stability Due to FPGA Implementation”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, art. no. 8400550, pp. 1726-1737, Sep. 2018.
- [5] D. Della Giustina, M. Pau, P. A. Pegoraro, F. Ponci and S. Sulis, “Electrical distribution system state estimation: measurement issues and challenges,” in *IEEE Instrumentation & Measurement Magazine*, vol. 17, no. 6, pp. 36-42, Dec. 2014, DOI: 10.1109/MIM.2014.6968929.
- [6] A. G. Phadke, J. S. Thorp, *Synchronized Phasor Measurements and Their Applications*, Springer, E-ISBN: 978-3-319-50584-8, New York, NY, USA, 2010.
- [7] IEEE/IEC 60255-118-1-2018 - Measuring relays and protection equipment - Part 118-1: Synchrophasor for power systems – Measurements, Dec. 2018.
- [8] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, “MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, Feb. 2011, DOI: 10.1109/TPWRS.2010.2051168.
- [9] A. Derviskadić, R. Razzaghi, Q. Walger and M. Paolone, "The White Rabbit Time Synchronization Protocol for Synchrophasor Networks," in *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 726-738, Jan. 2020, doi: 10.1109/TSG.2019.2931655.
- [10] X. Zhao, D. M. Lavery, A. McKernan, D. J. Morrow, K. McLaughlin and S. Sezer, "GPS-Disciplined Analog-to-Digital Converter for Phasor Measurement Applications," in *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 9, pp. 2349-2357, Sep. 2017, doi: 10.1109/TIM.2017.2700158.



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