Measurement of synchrophasors with GPS and IEEE 1588

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Abstract-Monitoring, control and management of modern electric power systems require more and more extensively the use of distributed measurement systems capable of providing accurate data from remote measurement stations located in the network nodes. Synchronization between the acquisition devices is one of the most critical tasks in designing such systems, since in many cases the practical usability of the measured data strictly depends on how accurate the time reference used in the remote stations is. When highly accurate time synchronization is needed, satellite systems, like GPS, can be used to provide the required time reference. Given that equipping every measurement station with appropriate GPS receivers can result in excessive costs, in this paper the possibility of using Precision Time Protocol (defined in the Standard IEEE 1588) to disseminate the time reference provided by the GPS in an electric subsystem is investigated. Experimental results will be provided to evaluate the performance achievable with this solution in one of the most challenging measurement problems, that is represented by the measurement of synchrophasors.

I. Introduction

Modern electric power systems can be considered as the consequence of the continuous technological evolution throughout the ages. Such evolution takes into account economical, political and social requirements. The impact of these changes involves significant transformations and innovations in both the transmission and distribution systems.

In particular, in modern substations, monitoring, control and protection tasks are usually performed by Intelligent Electronic Devices (IEDs), which can be by their nature connected to each other by suitable communication links. A well known example of this approach is represented by the Standards of the series IEC 61850 "Communication networks and systems in substations". IEDs can be sensors, actuators, controllers or any other networked electronic device.

As for the distribution systems, the main new aspects to be considered arise from the considerable presence of Distributed Generation (DG). This has significant implications on both energy management (since "active networks" are needed to take into account bidirectional energy flows by means of innovative devices for active and reactive power management [1]) and protection systems (since adaptive protections can be used to automatically reconfigure the network in the case of fault occurrence [2]). In this way, both energy management systems and protection schemes practically become algorithms, whose correct behavior is determined firstly by the quality of the input data, and therefore by the measurement of quantities simultaneously acquired in strategic points of the network.

Furthermore, the liberalized energy market makes more and more important to assess the responsibility of power quality disturbances among the different subjects. Therefore, opportune parameters, frequently based on distributed and simultaneous measurements [3], could be a possible metric to characterize the quality of the service provided by System Operators.

Considering the above issues, distributed measurement systems are necessary to provide a constant flow of up-to-date and reliable data on the system status. In many applications it is required that measurement, control and protection devices act in a strictly synchronized way. Typical synchronization specifications for protection and control systems range from milliseconds, for breaker operations and event reconstruction [4], to microseconds, for synchrophasor measurements [5-9], to a few hundreds of nanoseconds, for fault detection [4, 9]. These tighter synchronization requirements lead to the need of highly accurate clock settings.

In this work the main solutions for the synchronization in power systems are considered. In particular, a mixed structure able to combine the excellent accuracy of satellite-based systems with the capabilities of the modern synchronization systems designed for communication networks is studied. The considered application field is the measure of synchrophasors and harmonic synchrophasors [5-8].

The paper is structured as follows: in Section 2 the definition of synchrophasors is recalled; in Section 3 a short survey on the main synchronization sources for power system applications is presented; Section 4 presents the solution adopted here, based on a mixed GPS-1588 architecture, and discusses the accuracy achievable in the measurement of synchrophasors by considering data available in the scientific literature for 1588 performance; Section 5 shows and discusses experimental results obtained in a simple laboratory setup; Section 6 summarizes the main conclusions.

II. Measurement of synchrophasors

Phasor Measurement Units (PMUs) are among the most common instruments used in distributed measurement systems applied to power networks. They allow the measurement of the synchronized phasors (synchrophasors), defined in the IEEE Standard C37.118-2005 [5], which provides the measurement convention, a method of determining the precision of measurements and requirements for measurement performance under steady state conditions [6].

In particular the Standard considers the UTC (Universal Time Coordinated) as reference time and specifies that the synchronizing source shall have sufficient availability, reliability and accuracy to meet power system requirements.

According to [5], the synchrophasor representation of a sinusoidal signal $a(t) = \sqrt{2}A\cos(2\pi ft + \varphi)$, where A is the root mean square (rms), f the frequency and φ the phase angle relative to a reference time instant $t=0$, is $A = A \cdot e^{j\varphi} = A \cdot (cos\varphi + j\, sin\varphi)$. By observing the sinusoid at intervals which are integer multiples of an arbitrary basic interval T_0 the corresponding phasor representations can be obtained by taking the beginning of each interval as time reference for that observation.

The Standard does not specify the method of measurement, or other factors such as the sampling rate, algorithms or synchronization method. This allows manufacturers to use different measurement methods while assuring conformance with the result under a range of basic performance [6].

Even though [5] only refers to synchrophasors at fundamental frequency, the definition of the harmonic content of the synchronized electrical quantities can be obtained by extending to nonsinusoidal conditions the above definition of synchronized phasor, as stated in [8]. In particular a periodic signal $a(t)$ composed by H harmonic components can be expressed as:

$$a(t) = \sum_{h=0}^{H} a_h(t) = A_0 + \sum_{h=1}^{H} \sqrt{2}A_h \cos(2\pi hft + \varphi_h) \tag{1}$$

where A_0 is the possible dc component, while A_h and φ_h are the rms and phase, respectively, of the h-th harmonic component. As a consequence, the signal $a(t)$ can be decomposed into H synchronized phasors, each of which has the form:

$$A_h = A_h \cdot e^{j\varphi_h} = A_h \cdot (\cos\varphi_h + j\sin\varphi_h) \tag{2}$$

As for the accuracy, the old standard IEEE 1344.1995 ("IEEE Standard for synchrophasors for power systems") required synchronism to be maintained within 1 µs of UTC. The new version [5] defines a total vector error (TVE) as a vectorial difference between the measured and expected value of the phasor, expressed as a fraction of the magnitude of the theoretical phasor. This term aggregates magnitude, angle and timing deviations. The limit required for TVE is 1%, which would lead to about 31.8 µs at 50 Hz and 26.5 µs at 60 Hz if all the deviation was caused by synchronization inaccuracies. More realistically, if, as an example, a 20% of the maximum TVE is assigned to inaccuracy in the time synchronization, this would lead to maximum allowed deviations of 5 to 6 µs with respect to UTC [4].

The PMUs are placed on several points of the electrical network on which voltage, current and frequency values have to be measured. The collected data are sent to a Phasor Data Concentrator (PDC) and then to a control center.

The use of systems based on the synchrophasors measurements entails benefits on the following applications: state estimation, harmonic state estimation, real-time monitoring and control, post-disturbance analysis, power system restoration, adaptive protection, line parameter calculation, real-time congestion management, etc..

III. Synchronization sources and dissemination

Synchronization is a key factor in distributed measurement systems, such as the ones based on PMUs. Indeed, in order to properly correlate the events detected by the remote stations, the network nodes

have to share a common time reference with an established accuracy. Several synchronization systems exist, differing from each other in terms of functional features, complexity, performance and costs:

- *Satellite based synchronization systems*
  The operation principle of satellite systems is based on the time measurement of the synchronizing signal between satellites and terrestrial receivers, equipped with an internal clock. By opportunely processing signals coming from several satellites, an absolute time reference can be achieved.
  The most widespread of these systems is the *Global Positioning System* (GPS), which provides a global continuous coverage and is actually suitable for both military and civil applications. The accuracy achievable by using commercial receivers varies depending on the stability of the clock oscillator, easily allowing tolerances within ±100 ns.

- *Terrestrial Time-Synchronization Sources*
  Terrestrial time-synchronization sources include radio broadcast through the atmosphere or a broadcast over a controlled medium.
  Radio broadcasts are the least expensive but are the most susceptible to interference and usually have the lowest accuracy. The achievable tolerance varies from a few milliseconds (WWV and WWVH), to hundreds of microseconds (WWVB), up to a few microseconds (LORAN-C). The main drawback of these systems is due to limited transmitter sites, which reduce signal coverage to the only regions equipped with necessary stations.
  Higher accuracy can be achieved with microwaves and fiber-optics, but with higher installation costs.

According to the above considerations, and taking into account the accuracy required in the measurement of synchrophasors [5], the optimal solution for this application can be achieved by equipping each measurement instrument with GPS receivers.
On the other hand, in the presence of a large number of nodes, this solution could be unacceptable from the economic point of view.
Different choices can therefore be studied to accomplish the synchronization tasks in a cheaper way, by exploiting the possibility of distributing a time reference in communication networks. Usually, industrial buses do not autonomously guarantee the synchronization performance required for measurement and control in power systems. Therefore, specific network synchronization protocols, whose main capabilities are shortly recalled in the following, should be used (see [4] for more details).

- *Network Time Protocol (NTP)*
  NTP is a protocol designed to synchronize the clocks of a distributed system over the Internet network. NTP is used by a number of operating systems and network environments, assuring accuracy requirements from a few milliseconds up to a few hundred milliseconds, depending on the nature of the connection and the performance of the computers' operating systems.
  In simpler networks, not including Internet connections, the Simple Network Time Protocol (SNTP) can be implemented, which allows far better accuracy, also in the order of a few microseconds.

- *IEEE 1588*
  The idea behind the Precision Time Protocol (PTP) introduced by the Standard IEEE 1588 [10] was to provide hardware-level time accuracy using a standard Local Area Network (LAN) connection (e.g. Ethernet). IEEE 1588 provides for both software-only and hardware-aided implementations. The former ones have demonstrated timing deviations of 10 to 100 μs (similar to NTP in a small local area network). Hardware-assisted PTP implementations have demonstrated deviations of tens to hundreds of nanoseconds, depending on both the devices used and the traffic conditions [11, 12].

IV. GPS-PTP hybrid system for synchrophasor measurement

A. Structure of the system
An alternative solution to using one GPS receiver on each measurement instrument could be therefore obtained by disseminating the reference synchronization signal provided by a single GPS receiver to all the measurement instruments located in the same area, by employing the network synchronization protocols described in the previous Section [11]. This can be convenient especially in situations where the remote devices, such as IEDs, are already connected to each other by suitable communication links. Indeed, most IEDs contain a clock, which can be synchronized through some sort of timing bus. Instead of using special purpose and proprietary networks and protocols, greater efficiency, as well as less communication bandwidth, could be obtained with Ethernet based LANs [11].
Obviously, the quality of the synchronization depends on both the chosen protocol and the structure of

the communication network. In the case of synchrophasors, due to the high accuracy required by [5], the most promising solution, especially for future installations, is represented by the IEEE 1588.

A 1588 system consists of one or more sub-nets defined by the router. Each sub-net consists of several 1588 clocks, embedded in some devices communicating with its peers in the sub-net via a switch or repeater.

If, as in the case of synchrophasors, the application requires the reference to an "absolute" time, such as UTC, the grandmaster clock is synchronized to UTC through a GPS receiver.

Fig. 1 shows the scheme of a synchronization network which uses GPS to gauge the absolute time reference and PTP to allow the measurement of synchrophasors in all the nodes of an electric subsystem.
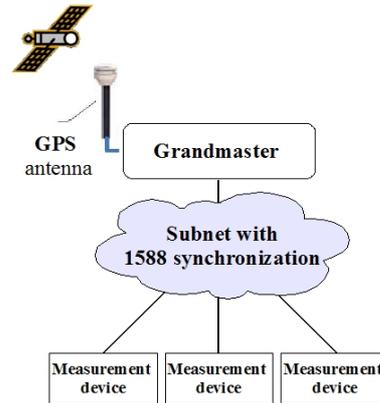

Fig. 1– Scheme of the synchronization network

B. Expected performance in synchrophasor measurement

Ethernet network components, such as repeaters, switches and routers, introduce considerable fluctuations in transmission latency that can degrade synchronization accuracy. Statistical techniques can reduce these fluctuations to acceptable levels for repeaters and, with proper care in network and traffic design, for switches. This is not possible with routers, where only the use of a IEEE 1588 boundary clock provides a mechanism to eliminate router fluctuations. The boundary clock mechanism may also be implemented in switches to eliminate the effects of latency fluctuations in these devices.

As a consequence, the performance achievable in the measurement of synchrophasors depends on both network structure, used devices and traffic conditions. In the literature several reports (e.g. [11] and [12]) show examples of synchronization performance with IEEE 1588, for example expressed in terms of deviations of the PPS provided by clocks linked via either repeaters, switches, etc..

Evaluating how these deviations affect the accuracy of synchrophasor measurement is straightforward, since there is a linear relationship between time deviations and phase shifts. Tab. 1 shows, in the case of the time deviations reported in [11], the contribution that these deviations would have on the accuracy of synchrophasor measurement for a fundamental frequency of 50 Hz.

Table 1. Expected contribution of time deviations reported in [11] to synchrophasor accuracy

Network device between clocks	PPS deviation (ns)		Phase shift of synchrophasor (rad)		TVE of synchrophasor (%)	
	Mean	*Standard deviation*	*Mean*	*Standard deviation*	*Mean*	*Standard deviation*
Repeater	22	99	6.9E-06	3.1E-05	6.9E-04	3.1E-03
Switch	49	233	1.5E-05	7.3E-05	1.5E-03	7.3E-03

Even if we add to the values shown in Tab. 1 the deviation introduced by the GPS receiver (e.g. a maximum of 100 ns), the contribution of the uncertainty in time synchronization to the TVE expected at fundamental frequency is far below the 1 % limit allowed by [5], thus meaning that practically the entire uncertainty budget is left to other uncertainty sources.

As for the harmonic synchrophasors, the corresponding phase shifts for the h-th harmonic can be obtained by simply multiplying by h the phase shifts at fundamental frequency.

V. Experimental tests

In order to experimentally evaluate the metrological performance of the synchronization system described in the previous Section, an ad hoc laboratory setup has been used. The test system consists of three PMUs designed by the authors and presented in previous works [7, 8], connected in a three-nodes IEEE 1588 network, with a master and two slave units.

The master unit is implemented in a PXI hardware platform, National Instrument PXI-1042Q, equipped with a PXI-8106 PC embedded dual-core processor. The two main hardware components of this PMU are a GPS synchronization module and a data acquisition module. Specifically, the PXI-6682 timing and synchronization module synchronizes the measurement system by using GPS and can be used as IEEE 1588 master. The acquisition data module is a PXI-6133, consisting of eight analog inputs, with a

resolution of 14 bits and a maximum sample rate of 2.5 MSample/s (simultaneous sampling).
The two slave units are PC-based systems, each with a multifunction data acquisition board and a 1588 plug-in board. In both cases the National Instruments PCI-1588 is used as PTP board. As for the acquisition system, a Data Translation DT 9832 (four-channel simultaneous sampling board connected to the PC by means of a USB 2.0 interface, with resolution of 16 bits and maximum sample rate of 1.25 MSample/s) is used in one station and a NI PCI-6132 (four analog inputs, resolution of 14 bits and maximum sample rate of 2.5 MSample/s, simultaneous sampling) in the other one.

A. Tests on synchrophasors

The three units, equipped with voltage transducer LEM CV 3-1000 (maximum peak voltage U_p = 1 kV; bandwidth 500 kHz at -1 dB; accuracy 0.2% U_p) and connected in a three-nodes IEEE 1588 network via a network switch (Linksys SRW248G4), have been used to measure the synchrophasors of the phase-to-phase voltages of the three-phase system that supplies the Measurement laboratory at the Department of Electrical and Electronic Engineering, University of Cagliari (Fig. 2).

The differences between the quantities measured by both the slaves and the master are evaluated and statistically analyzed. In all tests the monitoring time was 20 s, with ten evaluations per second, thus leading to the calculation of two hundreds synchrophasor values.

The results related to synchrophasors at fundamental

Fig. 2 – Measurement setup with IEEE 1588 synchronization

frequency are expressed, according to [5], in terms of TVE (see Section II). Actually, in the performed tests the TVE has been measured by considering as reference quantities the values provided by the master unit. Fig. 3 shows the histograms of the TVE evaluated between master and slave no. 1. The results for slave unit no. 2 show a very similar behavior.
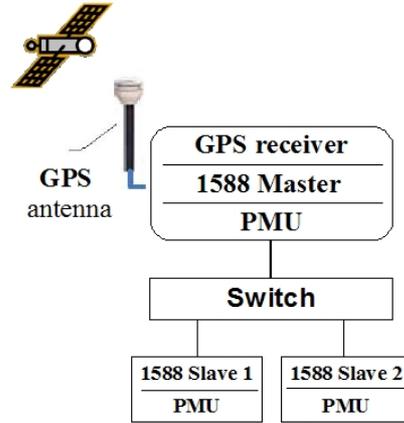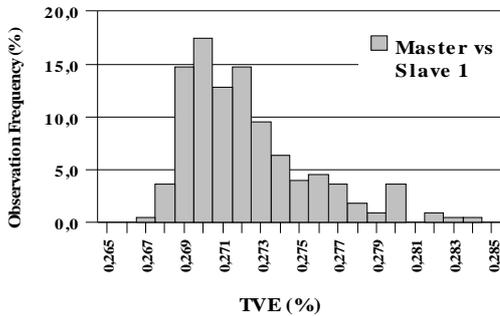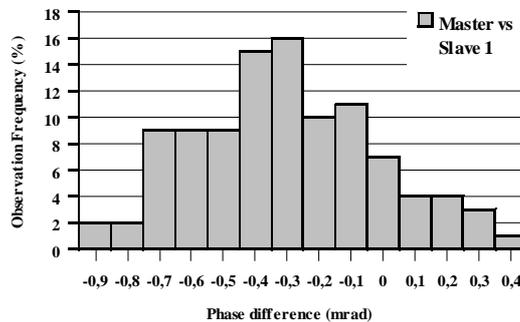
Fig. 3 – Histogram of TVE

Fig. 4 – Histogram of phase differences

In order to highlight the role of time synchronization in the differences between the values obtained with the measurement units, Fig. 4 shows the histograms of the difference between the phase quantities. Both mean value and standard deviations are in this case equal to 0.3 mrad.

The results obtained with PTP synchronization can be compared to the ones achievable with a direct GPS synchronization. For this reason, in a second series of tests the two slave unites have been equipped with external GPS receivers (Symmetricom XL-750, with timing accuracy of ±100 ns). Nearly the same values as before have been obtained for both the TVE (≈ 0.27 %) and the phase differences (as shown in Tab. 2). This puts in clear evidence that the impact of synchronization provided by 1588 is a minor problem, since the overall accuracy of the measurement mainly depends on the other uncertainty sources, such as the input transducers, as shown in [7] and [8].

Table 2 - Phases differences at fundamental frequency by using direct GPS synchronization

Phase differences between PXI and Device 1	
Mean (mrad)	*Standard deviation (mrad)*
0.5	0.3

B. Tests on harmonic synchrophasors

The analysis can be further extended by evaluating the harmonic synchrophasors of the same input voltages. Since the harmonic voltages featured a small value the analysis has been limited to the first nine harmonics. Tabs. 3 and 4 show the mean values and the standard deviations of the harmonic phase

Table 3 - Harmonic phase differences in the tests with IEEE 1588 synchronization

Harmonic order	Phase differences between PXI and Slave 1	
	Mean value (mrad)	Standard deviation (mrad)
3	-2.9	3.3
5	-0.6	1.4
7	-0.6	4.1
9	1.0	13.1

Table 4 - Harmonic phase differences in the tests with GPS synchronization

Harmonic order	Phase differences between PXI and Device 1	
	Mean value (mrad)	Standard deviation (mrad)
3	-8.1	3.8
5	-0.4	1.3
7	0.2	4.7
9	-2.0	15.7

differences obtained, for each harmonic component, by synchronizing the measurement stations with 1588 and GPS, respectively. Once again it can be noticed that the differences resulted quite low and definitely acceptable for most applications in electric power systems.

VI. Conclusions

Between the different approaches that can be used to synchronize measurement devices in power system applications, a solution based on a mixed GPS-1588 architecture has been analyzed in this paper. It allows the accurate time reference of a single GPS receiver to be disseminated to all the measurement instruments located in the same sub-area.

The performance achievable by the considered solution in the measurement of synchrophasors and harmonic synchrophasors has been evaluated by means of both a priori analysis and experimental tests on a low voltage distribution network. The results show that such synchronization system is able to satisfy the accuracy required in power system monitoring, protection and control.

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