How to Guarantee that Devices are Properly Time Synchronized?

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Abstract

The use of time synchronization is essential in different applications. Time synchronization accuracy depends on the method being used, the structure of the time network and the implementation of time servers and IEDs. This paper discusses these topics and presents methods to help users to be able to check the quality of their devices.

1. Introduction

The use of time synchronism in substations and power plants has been increasingly expanded and is essential in applications such as synchrophasor measurement and traveling wave-based fault location because of the need of accurate data synchronization of several units. However, time synchronization is also related to protection systems monitoring, not only for the digital fault recorders, but also for remote terminal units and protective relays.

Normally, the internal clocks of different devices use high drift oscillators and crystals. Such devices require external references to control their internal clocks to provide timestamp accuracy. Some devices have to measure angle quantities with high precision, such as Phasor Measurement Units (PMU). To provide this required precision, the internal clock and the acquisition system need to be time synchronized with good accuracy.

The use of time synchronization also provides a precise timestamp of events in the power system, in order to compare the behavior of such events in different parts of the system.

In the absence of time synchronization systems, the fault and disturbance analysis using oscillography records requires manual adjustment, increasing the time and the effort for the analysis.

The timing networks are being used in new ventures not only because of technical requirements but also because of the requirement of regulatory agencies.

Therefore, it is important to know about different time synchronization methods, considering the characteristics of each method and how to ensure that all devices, time servers or time clients, are operating properly.

Regarding time synchronization, it is also important to understand the concept of accuracy and precision as it is possible to have an IED synchronized precisely but not accurately, as is shown in this paper. Figure 1 shows the difference.

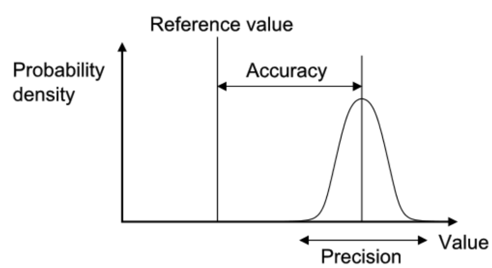

Figure 1 – Difference between accuracy and precision

In this paper, Section 2 presents some information related to the structure of the time synchronization networks. Section 3 describes the characteristics of the different methods of time synchronization. Methods to evaluate GPS clocks in laboratories and in substations are discussed in Section 4. Section 5 presents a methodology to check IED time synchronization, and finally, Section 6 presents the conclusions.

2. Structure of the Time Synchronization Networks

Time servers generally provide the time reference to several devices in a system. These time servers are typically installed in racks and are connected to IEDs creating a time synchronization network. Considering that different IEDs support different methods of time synchronization, it is important to evaluate which method is more appropriate for the whole system.

The connection between IEDs and time servers depends on the cable installation services and requires design and implementation by skilled professionals.

Before establishing the structure of the time synchronization network, it is important to consider some different aspects that impact on the costs of the system:

- Project: requires skilled professional to design and document the network structure considering the characteristics of each device to be installed. The technological level of each device can impact on the network topology and can bring project difficulties.
- Implementation: requires specific professionals to build the network structure, to purchase materials such as cables and conduits, and to manage civil works.
- Expansion: requires specific professionals to analyze the network structure and the devices that are already installed and those that would be installed, as well as to adapt the project and the documentation. Additional costs related to further implementations must be considered.
- Maintenance: the whole system must be maintained in service and some maintenance may be necessary.

Normally time synchronization infrastructure costs are higher than the time servers costs.

3. Methods to Provide Time Synchronization

Technically there are several methods to provide time synchronization, each one related to a certain topology. Therefore, all of them are basically associated with the use of GPS-based clocks.

The GPS (Global Positioning System) is based on a satellite constellation orbiting the Earth. These satellites transmit signals that are decoded by the GPS receivers. With the information received by at least four satellites, the longitude, latitude, altitude and time can be obtained. The precision of the GPS system follows a stochastic model and normally GPS receivers provide a precision of ±100 ns for 1 sigma (~70%). Figure 2 shows the curve of precision distribution.

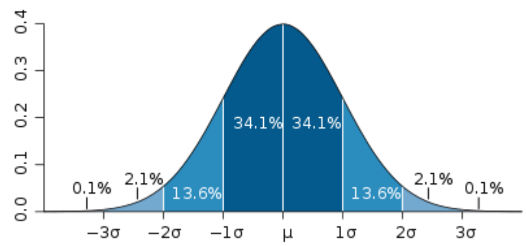

Figure 2 – Curve of precision distribution

Based on this precision the GPS clocks generate different types of time signals.

There are other systems similar to the GPS controlled by the U.S. such as the European Galileo and the Chinese Beidou. However they are not popular among non-military, and do not provide the same precision and global coverage.

The methods of time synchronization commonly used are the pulsed electrical signals such as PPS (pulse per second) and IRIG-B, specific serial datagrams such as NMEA, and sophisticated protocols such as NTP and PTP (IEEE 1588), which allow time synchronism using Ethernet networks. The evolution of these methods occurred with the technological evolution of the devices. However, with the fast paced changes in technology, there are also questions from users about the best method of time synchronization and what the benefits and limitations of each one are.

It is also important to note that although an IED is capable to be synchronized by IRIG-B, NTP, or other protocol, it does not mean that it will necessarily have its internal clock very accurate. It is very common to find implementations in IEDs, such as protective relays, that give high priority to protection functions and do not achieve a good precision.

3.1 Pulsed Electrical Signals

The use of pulsed signals is the simplest method for time synchronization. The time server generates pulses synchronized to the second rollover (PPS) or other pre-defined frequency. The equipment to be synchronized adjusts its internal clock with this signal.

The precision obtained with the pulsed signals is higher, especially when used for frequency control. However, the main disadvantage is that the timestamp information is not transmitted and clock changes are not considered.

Time synchronization networks demands cabling installation and maintenance, as well as skilled people.

The status of the time servers cannot be monitored. This method is rarely used in power systems, although the PPS signal was considered to provide time synchronization to Merging Units in the edition 1 of IEC 61850.

3.2 Serial Datagrams

Serial datagrams are data frames transmitted to serial ports (usually RS232 or RS485) and provide the timestamp and sometimes time servers status. Such information is typically transmitted once a second, either in the beginning of the second (first character starts in the second rollover) or immediately before the second rollover (last character ends in the second rollover).

Despite timestamps information being transmitted, serial datagrams precision is low due to serial communication limitation. Sometimes PPS signal is used in conjunction with serial datagrams to increase the precision.

The time synchronization network requires an end-to-end connection. The expansion and maintenance are not simple and requires skilled professionals.

Time server status may be monitored if the serial datagrams support status information. Time synchronization by using serial datagrams is common for meters and remote terminal units.

3.3 IRIG-B

IRIG-B is the widely used time format developed by the Inter-Range Instrumentation Group (IRIG), the group in charge of creating the standard for the Range Commanders Council (RCC) of the U.S. army. The first edition was launched in 1960 and the most recent version, IRIG Standard 200, was published in 2004.

IRIG-B signal is a 100-bit frame, containing information related to the date, time and optionally, control functions (CF) and straight binary seconds of day (SBS). This signal is typically transmitted in a PWM format by a DC level shift signal (no carrier signal) or by an amplitude-modulated signal (sine wave carrier). Figure 3 shows these signals.

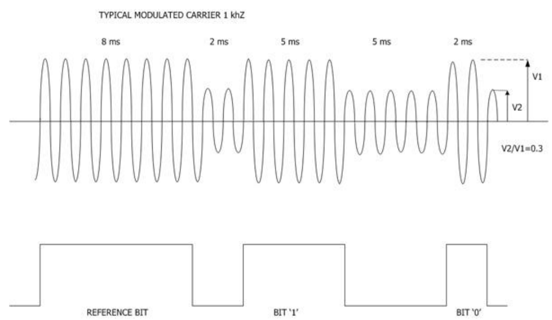

Figure 3 – PWM format for the IRIG-B signal

The use of IRIG-B time protocol can provide the precision in the order of nanoseconds, but it requires a lot of care in the project to meet this precision. Additionally, the architecture of the time synchronization network must consider the way that the IEDs are connected to the time server, the use of time repeaters and transceivers, the level of electrical insulation, etc. In addition to the cost of design, the cost of implement a dedicated network for time synchronization should also be considered even if a data communication network is in use.

IRIG-B time protocol is widely used by electric utilities to provide time synchronization of power system devices such as protection relays and Digital Fault Recorders (DFR), although it is being gradually changed by methods of time synchronization based on Ethernet networks.

3.4 Network Time Protocol (NTP) and Simple Network Time Protocol (SNTP)

The NTP (Network Time Protocol), was developed by professor David L. Mills of Delaware University in 1980, and has been used to provide time synchronization of devices connected in a Ethernet network. The NTP protocol has the following characteristics:

- Since time information is transmitted by using the Ethernet network, the protocol considers the measurement of time to send and receive the messages, allowing the delay compensation caused by cables, switches, signal adapters and other devices.
- Uses an algorithm that adjusts the time clock of the IED monotonically, i.e., without "jumps" in time to avoid discontinuities. Thus, it does not simply copy the timestamp received in the NTP message to the internal clock, but it adjusts the frequency controller to decrease the timestamp error. The disadvantage is the delay to converge.
- Uses the time clock drift estimation to compensate time deviation and provide time stability in the absence of the time source.

It is important to note that most of IEDs with the capability of time synchronization with Ethernet protocols do not use the NTP protocol, but instead they use the SNTP, where the S means SIMPLE, i.e., a simplified implementation of the method that does not consider some algorithms and does not keep the internal clock stable over long periods of time. The SNTP protocol messages are equal to the NTP protocol.

The first edition of IEC 61850 considered the SNTP for the IED time synchronization, however, with this protocol it is not possible to achieve the required precision when synchronizing Merging Units.

The use of NTP/SNTP protocols for time synchronization of IEDs can lead to a precision better than 1 ms. Real world implementation in substations with many switches usually achieve accuracy between 2 and 10 ms. Laboratory tests show that higher level of precision can be achieved under the following conditions:

- When using a good quality GPS clock. There are GPS clocks that support NTP messages but the timestamp in the message does not have good precision.
- When the network traffic level is low, especially without GOOSE messages.
- When the NTP/SNTP client that is running in the IED is able to adjust the internal clock with good precision.

Time synchronization by using the Ethernet network provides a stronger reduction in the costs because the cost of design and implementation of a specific time network is not considered.

3.5 Precision Time Protocol (PTP)

When analyzing the characteristics of the NTP protocol and the IRIG-B time protocol, it is possible to realize that the NTP has the advantage of using the data communication network, however, the precision is lower. On the other hand, the IRIG-B signal provides good precision but needs a dedicated network for time synchronization.

The PTP protocol was developed to provide time synchronization with the same precision as that of the IRIG-B signals by using the Ethernet network.

The use of the PTP protocol achieves higher precision over Ethernet communication because of the support in hardware. The time information in the frame is established only when the message is being transmitted and being received in the Ethernet port. In this approach, the time processing delays (especially the nondeterministic) in GPS clocks, switches and IEDs are compensated.

Figure 4 shows the nondeterministic delays in a communication between a time server and a client without considering any kind of compensation (NTP and PTP without hardware support).

The delays Δt_1, Δt_2, Δt_3, Δt_4 and Δt_5 vary because of the protocol processing times, of queues in lower layers of the network communication process, and because of the delays in the switches considering that the GOOSE messages are prioritized.

Considering the use of the PTP protocol with hardware support in all devices of the network, the errors are minimized because the timestamp is assigned in the lowest layer of the communication process. Thus, all errors related to the processing time are irrelevant. Additionally, it is mandatory to use switches capable to compensate the delays related to prioritization of GOOSE messages. Figure 5 shows the behavior of timestamps when using devices with hardware support to compensate the delays.

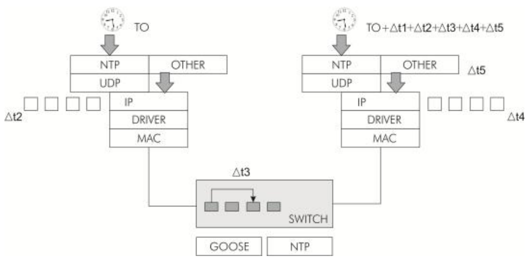

Figure 4 – Nondeterministic delays in a communication between a time server and a client.

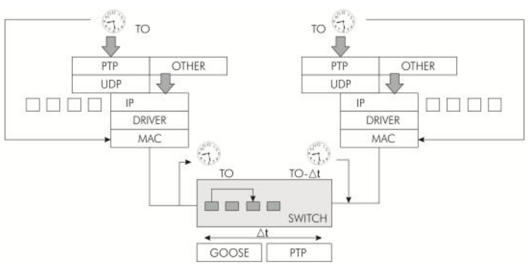

Figure 5 – Delay compensation using hardware support for PTP protocol

PTP protocol is commonly used in telecommunication systems. In power systems, considering technological aspects, by using the concepts of IEC 61850 in new ventures, the natural tendency is the use of PTP protocol as the alternative to the dedicated time synchronization network. In this scenario, to provide the time precision required for the system, it is imperative that the network structure be properly designed.

Because most of the devices on the market do not support the PTP protocol, an alternative is the use of small devices especially designed as PTP clients, which locally provide time synchronization protocols such as IRIG-B signal in outputs proper to be connected directly to the IED. Therefore, if the structure of the communication network is appropriated to the use of the PTP protocol, it is possible to install IEDs not compliant with this time protocol and take advantage of having the time synchronization network in conjunction with the data communication network.

4. Evaluation of GPS clocks

The choice of which GPS clock will be used depends on the technology and the architecture of the time synchronization network, the methods of synchronization, the auxiliary equipment, and the IEDs to be synchronized.

It is important that users be able to evaluate if the time reference equipment are providing suitable signals to the devices that need to be synchronized. And, how to guarantee that these time servers are operating correctly?

Basically, all GPS clocks have an indicator that signalizes if the internal clock is “locked” with the primary timing source. "Locked" means that the equipment was able to recognize the GPS satellites, decode the received signals and finally adjust its internal clock to provide time signals within the specified precision. If the equipment does not indicate this condition, there is the first evidence that there is some failure in the time system.

It is important to note that the time system does not depend sole on the GPS satellites. Both the antenna and the cable that connects the antenna to the equipment have to be adequate. It is common practice to install cables with characteristics of impedance and attenuation improper for the required length, as well as the antenna is installed in places with low visibility of the sky.

Once the GPS clock has indicated "locked", it is possible to consider that probably the precision of the equipment met the specification.

For the evaluation of GPS clocks two specific situations will be considered: laboratory testing and field monitoring.

4.1 Laboratory Testing

In this section the GPS clocks are analyzed based on the comparison of signals produced by the equipment under test and a reference equipment. In the test, the behavior of the GPS clock when generating frequency signals and network protocols such as NTP and PTP are evaluated in a controlled environment.

4.1.1 Frequency Signals

Initially the type of frequency signal to be monitored is established. Typically the PPS (Pulse Per Second) signal is used.

Considering the equipment under test and the reference in service for a previous period of time, the pulsed outputs of both pieces of equipment are simultaneously monitored by using an oscilloscope in trace mode and triggered by the reference equipment. After several hours, the time differences between pulsed signals generated by both units can be graphically displayed and the statistical errors for these signals can be evaluated.

Figure 6 shows the comparison of the PPS signal generated by two GPS clocks from different manufacturers.

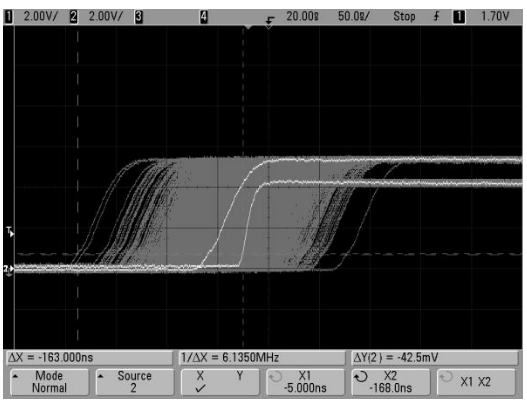

Figure 6 – Differences of PPS signals between the equipment under test and a reference

Statistically, it is expected that in 70 % of the pulses, the difference of the PPS signals must be lower than 200 ns (considering that the precision of each piece of equipment is ±100 ns for 1 sigma). Based on the test results, the differences of the PPS signals are in accordance with the statistical errors expected for the test.

4.1.2 NTP Protocol

The NTP protocol is based on a client-server architecture where the equipment to be synchronized sends request messages and the server responds indicating the timestamp of the moment when the request message was received and when the response message was sent.

To evaluate the behavior of the NTP servers, a typical NTP client is configured to be synchronized by different NTP servers simultaneously.

Two GPS clocks from different manufacturers were configured as time servers for a computer with an NTP client. The reference GPS clock was considered as the preferable server so that the computer's internal clock is directly synchronized to this source. The time differences between the reference server and the equipment under test are evidenced by the differences reported by the NTP client. The servers and the client were directly connected to a switch creating an isolated network to minimize the impacts of delays caused by network traffic. No GOOSE messages were transmitted during the test.

After some hours of monitoring, based on the statistical information provided by the NTP client, the time differences were evaluated and the results can be seen in Figure 7.

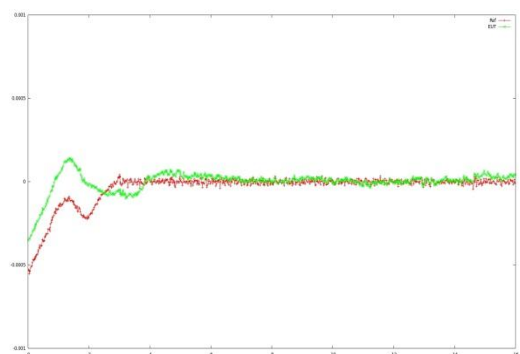

Figure 7 – Time differences between the reference NTP server and the equipment under test

At the beginning of the test, the errors are naturally higher because the NTP client is not time synchronized. After a period of time, the NTP client stabilized and became synchronized to the reference server. After that, the time differences evaluated were lower than 50 us.

Based on the results, the NTP server of the GPS clock under test had a good performance.

4.1.3 PTP Protocol

Usually, GPS clocks compliant with PTP protocol (IEEE 1588) are very precise clocks. The higher precision is provided by the hardware support to the protocol. A simple way to evaluate the precision of the timestamp provided by the PTP protocol is to use the event input commonly available in GPS clocks like that. The events generated in this input are reported with the precision of the PTP internal clock. In the test, events produced with high precision timestamps allow the comparison between the timestamps reported by the event input and the real timestamp of the event, and thus, evaluate the precision of the GPS clock.

For the test, the PTP client was configured to generate PPS signals from a TTL output. This signal was connected to the event input of the reference GPS clock and the events related to the PPS signals were reported in the event log for a period of 5 minutes.

Figure 8 shows the connection diagram.

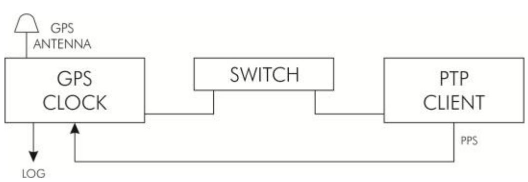

Figure 8 – PTP client testing

The difference between the timestamps of the events and the related PPS during the test is shown in Figure 9.

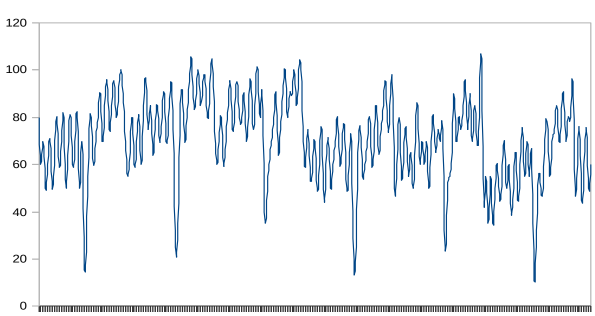

Figure 9 – Difference (in nanoseconds) between the timestamp of the PPS provided by the PTP client and the timestamp reported by the event input

Considering the results of the test, it is noted that the precision of the PTP internal clock of the equipment under test is in the order of nanoseconds.

PTP has a very important advantage in comparison to NTP and IRIG-B, namely the built in redundancy support. To have a time server redundancy simply install a second time server. The IEDs will synchronize to the most accurate server available in the network.

4.2 Field Monitoring

Monitoring the equipment in the field is essential to ensure that the whole synchronization system is operating properly. This monitoring can be done in the most basic form, by using a simple contact failure indicator associated with the SCADA, or by using sophisticated protocols for on-line monitoring.

In general, each manufacturer offers their own software for the equipment configuration and monitoring. By using the monitoring software it is possible to check the information provided by each device such as the synchronization status, number of satellites in use, etc.

Depending on the number of GPS clocks to be monitored in a whole utility, accessing each one individually becomes a hard task. The use of some network protocols such as SNMP (Simple Network Management Protocol) provides the automatic monitoring of all GPS clocks in the utility. Based on this protocol, it is possible to periodically request information from some equipment. By using special algorithms, it is possible to automatically evaluate its status, and thus, warn operators of a failure and consequently, have a specific problem solved more quickly.

Monitoring makes it possible to check the behavior of the equipment and the installation characteristics. Monitoring the number of visible satellites by each piece of equipment allows to evaluate the position of the GPS antenna and, with the level of signals from satellites gives an indication of the quality of the cable that connects the antenna to the GPS clock. Furthermore, it is possible to generate statistical data related to the equipment such as the number of operating hours, network communication access, etc.

The tendency for the future is that monitoring of GPS clocks will be accomplished using the approach of IEC 61850. The second edition of the standard provides the settings for the logical node related to time synchronization, leading to the use of monitoring methods like any other IED compliant with IEC 61850.

For the optimal operation of a GPS clock, it is necessary that at least four GPS satellites be visible. Some equipment have special features such as oscillators with low drift or drift compensation algorithms that keep the internal clock stable for a period of time even without the minimum number of visible satellites.

5. Methodology for Evaluation of the Quality of IEDs time synchronization

In this section a methodology for performance evaluation of IEDs when synchronized in different methods is presented. To perform this test, different events with known timestamps are produced and the IED event log is analyzed. The comparison between the timestamp reported in the event log and the real timestamp of the event produces the estimate synchronization error.

The best way to produce events with known timestamps is by using a GPS clock. Usually these devices have an open collector output that can be configured to generate signals in frequency. In the test, the PPS (Pulse Per Second) is generated by a reference GPS clock. The open collector output drives the digital input of the equipment under test. The performance test considered three IEDs from different manufacturers. Figure 10 shows the connection diagram for the test.

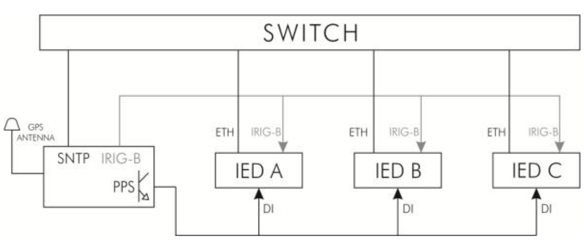

Figure 10 – Connection diagram

For the SNTP performance test, all IEDs under test were connected to a dedicated Ethernet network by using a standard switch and, being a lower traffic level environment.

5.1 Test Results

All IEDs were synchronized by the reference GPS clock. For all IEDs under test, the results with IRIG-B and SNTP were equivalent. Since the events were related to the PPS (one pulse per second) signal, the timestamp of the event reported by the IED was compared to the second rollover and shown in milliseconds.

A total of 60 pulses were used for each IED. The results in Figures 11, 12 and 13, show that IED A has poor accuracy and precision. IED B has expected accuracy and precision and IED C has an accuracy error of 3 milliseconds but a good precision because all pulses were with the same error.

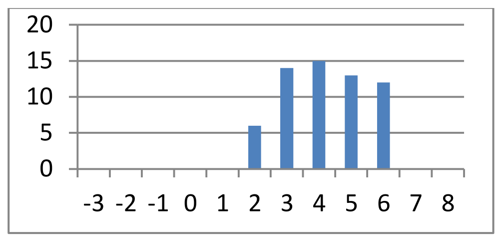

Figure 11 – Test results for the IED A

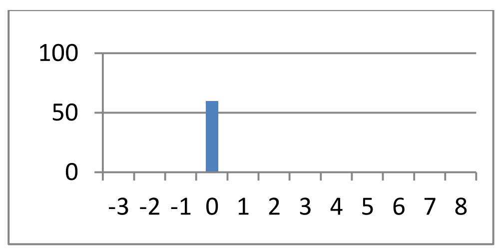

Figure 12 – Test results for the IED B

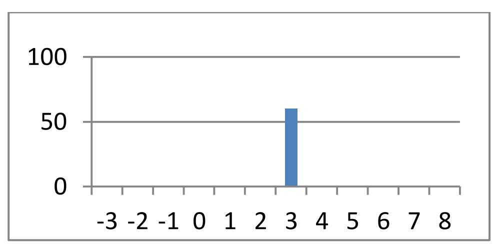

Figure 13 – Test results for the IED C

The events were applied to all the IEDs simultaneously. The IEDs were configured by qualified personnel. All the IEDs were maintained in service for at least two hours before testing.

6. Conclusions

The most common methods of time synchronization, as well as its main features and general applications, are shown in this present work.

Based on the evaluation of different time signals and protocols in a laboratory environment, it was shown that it is possible to guarantee that GPS clocks are providing precise time information, as well as the means to analyze the behavior of time servers when they are in service.

Management of GPS clocks in a single substation, or in a whole utility, can be accomplished by using SNMP services. Thus, the status of GPS clocks can be monitored by a central station, reporting any malfunctioning of the equipment as well as problems in the installation such as weak satellite coverage.

A methodology that makes is possible to evaluate the quality of time synchronization of IEDs was presented. This methodology was based on the comparison of time differences between timestamps of events produced by a reference GPS clock and timestamps of these events reported by the IED. Different IEDs synchronized by IRIG-B signals and by SNTP protocol were analyzed by using this methodology.

The performance tests showed that the timestamps reported by some IEDs may not be precise. The methodology described in this paper enable the users to check the IEDs performance by themselves, leading them to know the limitations of each one.

7. References

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Biography

Carlos Alberto Dutra received his degree in Control and Automation Engineering from the Federal University of Santa Catarina, Brazil, in 1999. He has been working in Reason Tecnologia since 2003. In the Reason Research and Development Department, he worked in the development of different devices such as the traveling wave-based fault locator, digital fault recorders, and GPS clocks. He is currently the Development Manager, and is in charge of the management of the development and the lifecycle of Reason products.

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