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Time Synchronized Power Meters for Advanced Smart Distribution of Energy in Smart Grids

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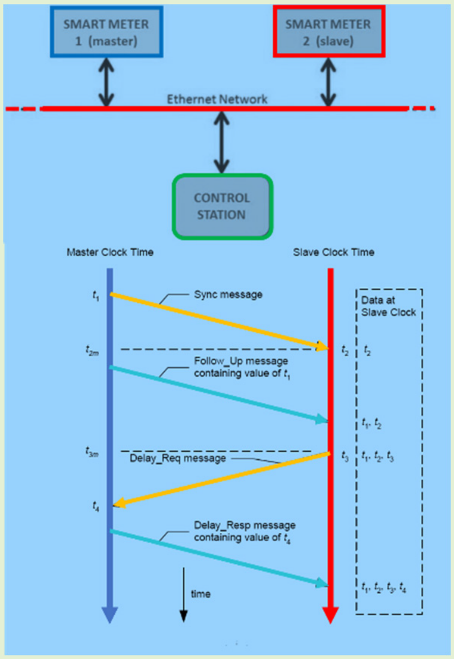
***Abstract*—With the spread of alternative energy sources, many aspects are changing in the electric grid. New electric energy generation plants are distributed in the network. As a consequence, the flow of electric energy becomes bidirectional in the grid. Energy flow changes direction based on needs, consequently, there is a need for new sensing systems and management tools of the grid such as smart meters. These sensing devices must be synchronized with each other based on the same clock to guarantee the correct management of the energy flows in the smart grid. This article presents a comparison between satellite and informatics-based protocols and then proposes the use of the precision time protocol (PTP) for synchronization. The developed smart meters have been synchronized by the PTP protocol and have been distributed in the nodes of a local microgrid. The development of an automatic control station for smart grid management is here described. The control station is able to localize the smart sensing devices distributed and connected to the grid. Experimental results have been carried out on two time-synchronized smart meters. The synchronization protocol has been validated and verified by performing different communication tests.**

***Index Terms*—Distributed sensing system, energy management, IEEE 1588, precision time protocol (PTP), smart grid, smart power meter, synchronization protocol.**



I. Introduction

LOOKING at the current scenario of the electric grid, many aspects are changing, from the sources of energy generation up to the users and passing through the transmission and distribution network. With the spread of alternative energy sources, the structure of the electric grid requires new features. With the geographical diffusion of energy production, the way to exchange energy in the network has changed. Now the flow of electric energy must be able to change its direction based on network needs. As a consequence, to better manage these energy flows, the network must become intelligent and capable of monitoring bidirectional flows. In addition, the grid has to check the power quantity and quality in each node. In other words, the grid must become smart. "This strict interconnection between the power grid and the communication technology is known as smart grid," [1]. Consequently, sensing devices and distributed systems become essential to increase network features and their management tasks. Sensors

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can allow the grid to check and monitor voltage and current waveforms in specific nodes, thus making decisions in real time about the most efficient energy distribution management according to energy demand, energy quality, and grid conditions.

Power systems are evolving toward the Smart Grid that is, a sustainable, safe, and accessible system for all users (people). This is the model fully representative of future energy systems, able to preserve our planet and its inhabitants. The combination of nonprogrammable a priori renewable sources, or not centrally coordinated by the distribution network operator, and the "Smart Grid" is, in this model, the key element of the energy transaction that we are experiencing [2], [3]. In the modern concept of the smart grid, there are an increased number of monitoring, communication, and management systems and sensing devices, which must manage in real-time such power flows. These systems must guarantee many functionalities: voltage and frequency control and regulation, system diagnostic, fault location and isolation, service restoration, and power quality monitoring [4]. With respect to the conventional power grid, the smart grid of the future has to regulate the energy exchange among nodes by using communication signals and sensor information among several nodes. The smart grid must be able to act in response to the changes occurring in any part of the grid, in accordance with the definition of the IEA "Smart grids are electricity networks that use digital technologies, sensors, and software to better match the supply and demand of electricity in real time while minimizing costs and maintaining the stability and reliability of the grid" [5].

Agreeing with this definition, smart grids have the following functions:

1) Optimizing the use of resources and their operation;
2) Minimizing costs and environmental impacts;
3) Maximizing network stability, flexibility, and resilience.

Sensors, control devices, and communication systems allow efficient exchange of information according to an advanced management logic for the management of energy flows in real time [6], [7].

The substations and each energy conversion point (transformers, converters, inverters, and generators) have to be constantly monitored. This may become possible by means of the use of advanced and innovative sensing systems and sensor networks distributed in the grid [8], [9], [10].

The nonprogrammable renewable generation plants are now numerous and therefore located in a capillary way throughout the energy distribution network. In order to manage the production of electricity from the many generating nodes, and to ensure the adequacy of the electricity system, the network electrical systems must operate as two-way systems, [11].

The management of the power flows in the grid requires specific criteria and energy routing algorithms in order to isolate specific microgrids or in order to directly connect two nodes according to the availability and demand of power. Therefore, information on energy consumption and power supply quality is indispensable to regulate suitably the electricity routing in the grid. In this scenario, a challenge for researchers and scientists is the design and development of new energy monitoring systems to manage the grid. Smart meters are sensing systems that provide interesting solutions to monitor the quantity and quality of electric energy, [12], [13], [14], [15], [16], [17], [18]. Such data can be consequently used to manage energy flows among nodes based on power availability and needs. In this way, the smart meter is no longer a simple metering system used to evaluate utility consumption. The revised concept of the smart meter considers its use in the distribution grid and in the nodes, so it has a key role in the integrated energy system [19], [20], [21].

To optimize energy consumption and production, the smart meter has to communicate in real-time with the grid control station by exchanging data on energy quality and analyzing information coming from sensors, loads, and energy storage systems. In this view, real-time decisions can be taken on the grid configuration so choosing the best routing path to reduce power dissipation and environmental impact [22]. The new task of smart meters is to coordinate energy flows between nodes where there is energy demand and nodes where there is energy surplus. Since the production of energy from renewable sources is intermittent, energy must change dynamically its direction. Consequently, the architecture of a modern and active grid, i.e., a smart grid becomes more complex. Even the used measurement systems require frequent checks and calibrations to verify their correct operability reducing the risks of incorrect decisions. Therefore, measurement data must be reliable, updated, and continuously synchronized [23], [24]. In order to ensure that all components of the network operate accurately, the clock synchronization process must be carried out safely and then standardized. In this regard, that process must achieve frequency (clock skew) and time synchronizations (offset or phase).

There are three protocols of clock synchronization on the network: global positioning system (GPS), network time protocol (NTP), and precision time protocol (PTP), which will be briefly introduced in Section II [25].

The article is structured as follows. Section II describes the main satellite and informatics synchronization systems by highlighting problems and advantages and analyses the state of the art regarding the synchronization of smart meters in the network. Section III describes the automatic control station developed for smart grid management. Section IV reports the validation and experimental results, and then conclusions complete the article.

II. ANALYSIS OF SYNCHRONIZATION SYSTEMS

The choice of the most suitable synchronization protocol is a basic issue for any distributed sensing system. By considering the specific application case, concerning the use of smart meters geographically distributed in the power grid, it is indispensable to guarantee a synchronization accuracy in the millisecond range or less, [26].

Sensing and measurement data must be continuously synchronized as accurately as possible. However, this is a complex task due to the complexity of the network. Technological advances have changed in the last years the accuracy of the synchronization protocols, which has been reduced from minutes to seconds, milliseconds, and now microseconds [23]. The

TABLE I
TIME SYNCHRONIZATION CLASSES FOR THE SMART GRID

Class	*Accuracy*	*Applications*
A	1 μs	*PMU, Distributed Measurements*
B	100 μs	*Automated Fault Recording*
C	1 *ms*	*Time tagging of events with an accuracy of* 1 *ms*
D	10 *s*	*Power Quality, Voltage Dips*
E	100 *ms*	*SCADA Logging and Monitoring*
F	> 1*s*	*Low time synchronization accuracy*

installation of a distributed sensing system for the measure of power quality requires the time synchronization of instruments and sensors to be able to correlate the measurements taken at different points of the smart grid. The time synchronization requirements depend on the applications. For example, the monitoring of the quality of the energy in different parts of a distribution grid requires time synchronization accuracy on the order of milliseconds, and the logging of fault events for monitoring purposes over the distribution grid requires synchronization on the order of hundreds of microseconds [27], [28]. Considering the above-mentioned applications, in the IEC 61850-5 [20], a classification of time synchronization is provided. The document introduces six-time synchronization classes, for smart grid and applications that require synchronization, which are described in Table I.

Currently, the most sophisticated time-synchronized tool for wide-area applications is the phasor measurement units (PMUs) protocol based on the GPS.

It has excellent accuracy and is used in those applications where there is a need for precision synchronization of the time. However, the use of the GPS has high costs and its maintenance is even a critical issue. For these reasons, the development of informatics-based synchronization protocols is taken here into consideration [26], [29], [30].

More and more applications and devices today use satellite-based solutions. Positioning and navigation systems or synchronization devices are the most common examples. Such systems use signals emitted by the satellite network in order to determine, with a good degree of accuracy, information on geographical location, and relative altitude or to synchronize time to coordinated universal time (UTC).

Currently, several global navigation satellite systems are operative and others are in development. The most important system is the Navigation System Time and Ranging Global Position System (NAVSTAR GPS), commonly called GPS [31]. Although the GPS system has better accuracy, its maintenance and implementation costs are more expensive than other solutions. Operating the satellite system requires outdoor antenna installations with a direct view of the sky, which has a cost of installation and maintenance. It has a low reception in indoor environments or in urban contests, where the satellite coverage is poor. However, a large part of the secondary substations located within cities are underground, increasing the installation costs of the GPS antenna, when the installation is possible. The GPS has a high precision of about 1 μs and an absence of errors. However, with the development of intelligent substations, the GPS clock has exposed its limitations, because installation costs of GPS solutions are expensive and, in addition, the clock signal is easy to interfere with, thus affecting timing accuracy [32], [33]. Therefore, the use of alternative systems, such as packet-based network synchronization solutions, is considered in the following. By considering the specific application case, the use of serial communication lines devoted to sharing information among nodes is suggested. In the power grid context, informatics synchronization systems can be used to ensure the suitable synchronization of sensing devices, thus minimizing the implementation costs. The main current synchronization protocols based on informatics networks are NTP and PTP. The first is the most widespread protocol developed by D.L. Mills in the eighties of the twentieth century for the synchronization of computer networks. The second was developed in 2002 for systems which required greater precision.

With the GPS synchronization systems, it is possible to synchronize the distributed devices and sensors, with an uncertainty of the order of hundreds of nanoseconds, more than enough to satisfy also synchronization requirements of more demanding applications, like PMU. While performances are completely different when the informatics-based protocol is adopted in a smart grid to distribute the information from the time server to the distributed measurement instruments. In a dedicated LAN, the NTP time synchronization could be on the order of hundreds of microseconds, while in a hybrid network, where different technologies are typically adopted for the connection of nodes over a distribution grid, the synchronization uncertainty can also reach tens of milliseconds. With the use of PTP for precise time synchronization, it is possible to achieve synchronization on the order of microseconds [28].

Table II shows the characteristics of the two informatics-based protocols; these are put in comparison with the performances related to GPS synchronization [34]. The table highlights that GPS-based systems have better performances. However, in a smart grid context, all nodes should be equipped with external antennas increasing the development costs. In addition, the application case considered here does not require high performances (under millisecond precision), as a consequence, it is possible to use solutions with synchronization based on informatics transmission networks.

Because of these assumptions, the PTP protocol and IEEE 1588 Standard are considered in this work to optimize the project and development of the proposed smart meters.

Numerous studies are addressing the importance of synchronization in distributed sensing systems. The synchronization of time reference among nodes of a distributed system is a well-known problem in scientific and research communities. There have been numerous research papers discussing different methods to do this and several approaches have been proposed. Dingyong et al. [35] used NTP to synchronize the acquisition start signals of computers in different nodes. The computers receive the commands and trigger the acquisition in the devices at the specified time, but with this method, an accuracy of

TABLE II
SYNCHRONIZATION PROTOCOLS CHARACTERISTICS

	NTP	*PTP*	*GPS*
Extension	geographical	Subnets	*geographical*
Communication	Internet	Lan	*satellite*
Accuracy	ms	µs	*µs*
Communication typology	peer 2 peer	master/slave	*client/server*
Security	yes	no	*no*
Administration	configured	auto organized	*n/a*
Hardware	no	yes (max accuracy)	*receiver RF*

about 1.72 ms has been achieved. Also, in [27], the NTP synchronized smart grid measurements, but in the tests carried out, excellent synchronization values were not obtained. In another work [36], where there is a need for higher accuracy, GPS is used for managing the sampling clock. In this application, a dedicated microprocessor has been used to detect the start of the UTC second and send a high-priority command to the device to start the acquisition. The weakness is the cost of hardware, that is dedicated and cannot be used for different applications.

There are also numerous works in which an attempt has been made to implement the PTP protocol to synchronize sensing data in the smart grid and demonstrate good synchronization times achieved [33], [37], [38], [39], [40], [41]. Pallares-Lopez et al. [37], [38] and Li et al. [33] propose the PTP as a synchronized technique for smart grids. The study [39] presents a control/tracking algorithm for PTP that can achieve a time synchronization accuracy below one μs in a simulated Smart Grid environment. In this work, a slave clock model is built with an innovative approach using proportional–integral–derivative controller in cooperation with the wolf colony algorithm which is proposed to eliminate the offset of the slave clock with respect to the master clock. In the article [40], the authors do not present a synchronization solution for a specific application, but they show a solution with a PTP-driven software trigger that could potentially be used for multiple applications. The solution proposed can be used in almost any application, by simply changing the computer program according to the application but using a Windows computer to provide a software trigger for the acquisition modules. The use of the PTP is also recommended by the authors of the work [31], but only a theoretical analysis is exposed and does not carry out tests in real cases of use on the network.

There are scientific works that use LabVIEW for data acquisition for a PMU; Krishnan et al. [42] propose a simple application for didactic purposes and to show the calculations made by a PMU. There was no synchronization policy. The work in [43] explains a low-cost alternative to commercial products for specific research applications requiring fast estimation of synchrophasors for real-time control.

From the analysis of the state of the art, no works emerge in which innovative smart meters have been created and installed, synchronized with each other with the PTP protocol. Furthermore, there are no graphic platforms that allow you to control several smart meters of a microgrid simultaneously and that allow you to test the synchronization times of smart meters installed in a microgrid.

In detail, in this work, the PTP has been proposed and used to synchronize the developed smart meters. This protocol is based on the IEEE 1588 Standard, whose features will be discussed in more detail in Section III. Furthermore, an automatic control station has been developed, and from it, the user can communicate with all smart meters and read data in real time.

III. PRECISION TIME PROTOCOL

The IEEE 1588 Standard provides guidelines about the use and implementation of the Precise Time Protocol for networked sensing systems. It allows clocks distributed across an Ethernet network to be accurately synchronized using a process where distributed nodes exchange time-stamped messages [44]. The PTP protocol provides synchronization accuracy better than other informatics-based methods by providing a precise timestamp for each device connected to the network using standard Ethernet connectivity [45]. Therefore, the IEEE 1588 Standard offers the possibility to synchronize sensing systems distributed in the smart grid avoiding the use of GPS devices. The advantages include higher bandwidth, stronger anti-jamming capability, lower cost, lower bit error rate, and better security. "All of these outstanding features make IEEE 1588 suitable for time synchronizing system of distribution grid" [46].

The IEEE 1588 "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" was released in 2002 and was later adopted by the IEC with the IEC 61588 Standard in 2004 [47]. The first version of IEEE 1588 was successively revised in 2008, and newly in 2019 so this is the most recent release currently available [48]. This protocol can be implemented by means of a hardware or software approach. The hardware implementation allows to get precision in the nanosecond range, the software implementation provides microsecond precision. The proposed smart meters use a software approach. In addition, for the synchronization of distributed systems, it is used in automatic applications, robotics, printers, and in all systems made up of devices that must always be synchronized to work together, in a coordinated and precise manner, following a clock that must be trusted. For this reason, synchronization according to the IEEE 1588 Standard has become part of all real-time systems.

The PTP protocol works according to a master/slave architecture. It is based on the exchange of a series of packets between a master clock and different slave clocks, this method allows to synchronization of mixed systems having different clocks with a precision in the microsecond range. According to the IEEE 1588 Standard, it is necessary to determine which device must provide the master clock and correct the differences between the slave clocks due to the initial offset

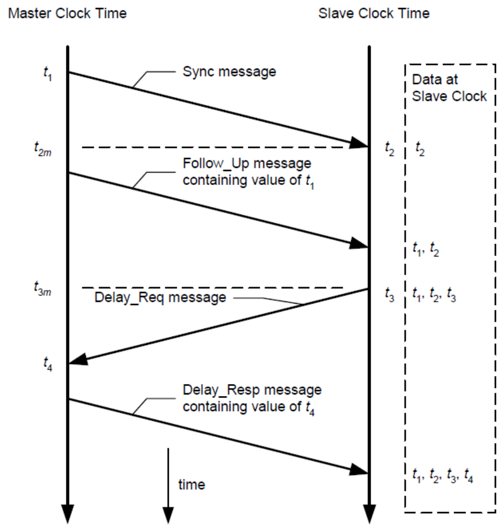


Fig. 1. Master and Slave messages.

and network delay. After the initialization process, the protocol uses the "Best Master Clock Algorithm" in order to determine the most accurate clock. This takes the role of the master clock and synchronizes all others (slaves) with it [32], [33]. The synchronization process is based on the exchange of four messages, as shown in Fig. 1: synchronization information message (Sync), following information message (Follow_up), delay request information message (Delay_Req), and delay response information message (Delay_Resp).

The master starts at instant t_1, by sending the synchronization message (Sync message) to the slave, which is received at instant t_2. If the master cannot insert the information on the exact instant of dispatch (shipment timestamp) in the Sync message, because the master can only know the timestamp after sending, then the master sends a second message (Follow_Up) containing the timestamp. The Sync messages are sent at regular intervals, while the slave sporadically sends a message (Delay_Req) at the instant t_3 that the master receives at instant t_4. The master responds to the slave with a Delay_Resp message containing the time t_4.

Let us assume that the phase shift between the master and slave time references is T_{offset} and the transmission delay is *Delay*, the following relationships can be assessed:

$$t_2 = t_1 + T_{\text{offset}} + \text{Delay}_{m-s} \tag{1}$$

$$t_4 = t_3 + T_{\text{offset}} + \text{Delay}_{s-m}. \tag{2}$$

If the transmission delay can be considered symmetrical, i.e., $\text{Delay}_{m-s} = \text{Delay}_{s-m}$, by the above equations, it is possible to obtain the expressions of the phase shift and transmission delay

$$T_{\text{offset}} = (t_2 - t_1) - \text{Delay} \tag{3}$$

$$\text{Delay} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}. \tag{4}$$

The phase shift T_{offset} is a parameter that is continuously updated by the master by sending a synchronization message followed in some cases by the Follow_Up message. Instead, the Delay can be considered a static value in the absence of particular traffic conditions. The transmission delay can be influenced by the number and type of switches that operate between master and slave. To bypass this problem, the IEEE 1588 Standard requires that the switches have their own clock [48], [49].

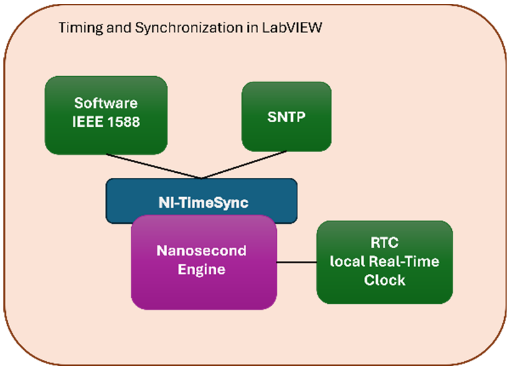


Fig. 2. LabVIEW timing scheme.

IV. AUTOMATIC CONTROL STATION FOR SMART GRID MANAGEMENT

In the present Section, the development of an automatic control station to manage energy flows in a smart grid is described. The project is based on the time-synchronization of the smart meters previously developed in [50], [51], [52], and [53]. The software implementation of the PTP is here proposed. The National Instruments LabVIEW software environment and the Synchronization tool have been used for the time-synchronization. The LabVIEW synchronization tool is described in the Section IV-A, whereas the developed real-time code is shown in the Section IV-B. Section IV-C describes the control station proposed for smart grid management.

A. LabVIEW Synchronization Tool

In the NI LabVIEW environment, the synchronization tool provides two specific functions, named Time Sync and Time Loop, for time synchronization based on the IEEE 1588 Standard. The tool offers even the possibility to test the synchronized devices. It uses the nanosecond engine software component to manage the timing. The nanosecond engine can use a local real-time clock (RTC) or it can be driven by an external reference clock integrated through the NI Time Sync Framework (NI-TimeSync). Fig. 2 shows the scheme that summarizes the different features and possible uses of the tool.

This tool allows to synchronization of multiple sensors connected on the same network using the same reference clock. The dedicated timing structure named Timed Loop can be used to synchronize the sensing devices at precise intervals of time. The internal timing source solution has been chosen in compliance with the IEEE 1588 Standard. The Timed Loop can be configured to use a 1 kHz clock or a 1 MHz clock mounted on board of a real-time target device. The used devices have been set up to use a clock source of 1 MHz, so to allow a synchronization resolution in the microsecond range.

B. LabVIEW Real-Time Code

The LabVIEW Real-Time Tool has been used to develop the source code implemented in the smart meters. The developed code is an improved and optimized version of the code used in [51]. In detail, the computing algorithms used to measure the current and voltage parameters are compliant with the previous version. The metrics suggested in the IEEE Standard 1459–2010 have been used. A fast Fourier transform (FFT) algorithm allows to evaluation of the harmonic content of the signals acquired utilizing the voltage and current sensors. The sensing parameters acquired and processed by the smart meters are shown in Table III.

The code has been updated by adding the Timed Loop structure to synchronize the smart meters through the IEEE 1588 Standard. The Internal Timing Source has been set to 1 kHz.

A meter has to be chosen as the master of the grid. At any time, the smart meter network can be updated by adding new smart meters to the grid. In this case, it is necessary to program the meter by using the previous code.

C. Remote Control Station

A server-based control station has been developed to manage all smart meters distributed in the smart grid. The user interface of the control station has been made in the LabVIEW environment. The user can communicate with all smart meters of the grid and control them. The program is installed on a central server that coordinates the whole power grid.

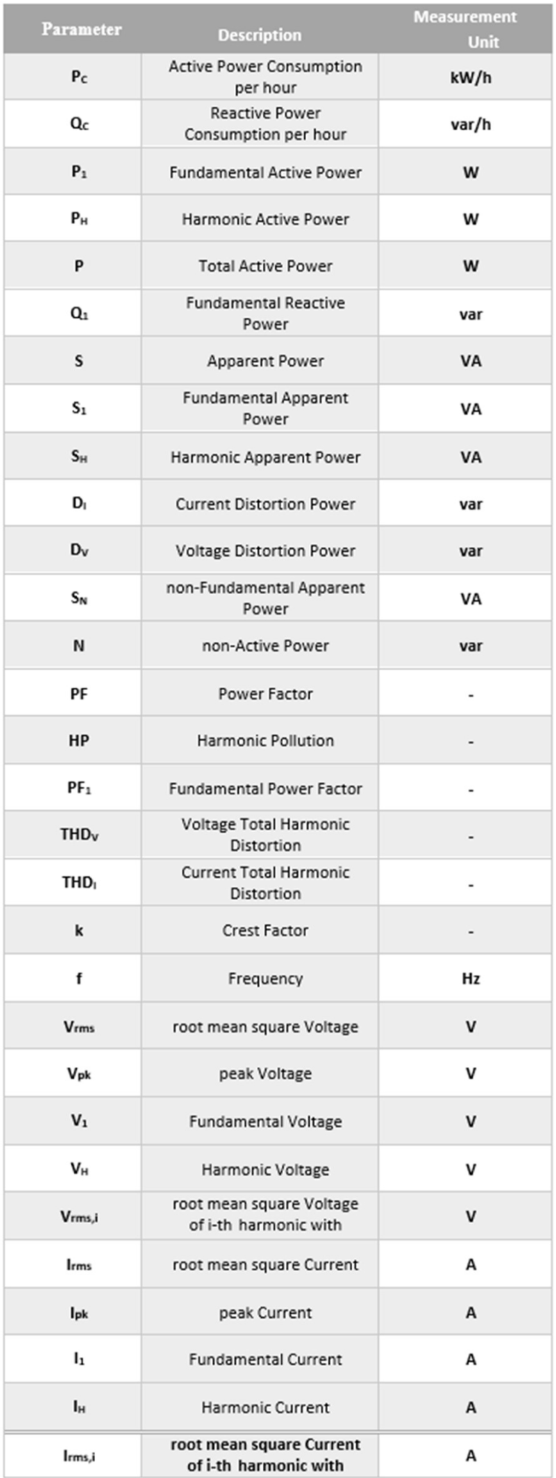
Each smart meter can be reached by its IP address. The control station can read data in real time from each smart meter.

By the user interface, it is possible to observe the status of each smart meter by entering its IP address. In this way, the remote-control station can get an overview of each node of the grid reading all sensing parameters: voltage and current waveforms, power trend, harmonic voltage, and harmonic current. Indicators show the working status of the selected smart meters, possible errors, and timestamp indicators to check the synchronization time. A tab control allows the user to choose the sensing data to be displayed, to save data, or to turn off a metering device if required. Furthermore, on the front panel, there is the "Localize" button, which permits the user to know the geographical coordinates of the specific smart grid node in which the smart meter has been installed.

V. VALIDATION AND EXPERIMENTAL RESULTS

In this section, the tests performed to validate the implemented synchronization protocol and the localization tool are described. In detail, in the following Section V-A, the used smart meters are presented, then the synchronization algorithm has been validated and data are reported in Section V-B. Last, the tests made to check the localization tool are shown in Section V-C.

TABLE III
SENSING AND COMPUTED PARAMETERS



Parameter	Description	Measurement Unit
P_C	Active Power Consumption per hour	kW/h
Q_C	Reactive Power Consumption per hour	var/h
P_1	Fundamental Active Power	W
P_H	Harmonic Active Power	W
P	Total Active Power	W
Q_1	Fundamental Reactive Power	var
S	Apparent Power	VA
S_1	Fundamental Apparent Power	VA
S_H	Harmonic Apparent Power	VA
D_I	Current Distortion Power	var
D_V	Voltage Distortion Power	var
S_N	non-Fundamental Apparent Power	VA
N	non-Active Power	var
PF	Power Factor	-
HP	Harmonic Pollution	-
PF_1	Fundamental Power Factor	-
THD_V	Voltage Total Harmonic Distortion	-
THD_I	Current Total Harmonic Distortion	-
k	Crest Factor	-
f	Frequency	Hz
V_{rms}	root mean square Voltage	V
V_{pk}	peak Voltage	V
V_1	Fundamental Voltage	V
V_H	Harmonic Voltage	V
$V_{rms,i}$	root mean square Voltage of i-th harmonic with	V
I_{rms}	root mean square Current	A
I_{pk}	peak Current	A
I_1	Fundamental Current	A
I_H	Harmonic Current	A
$I_{rms,i}$	**root mean square Current of i-th harmonic with**	A

A. Smart Meters

Small-scale field trials have been carried out in a local microgrid. Two smart meters have been used for the following experimentation. The developed automatic control station is based on these two sensing devices to simulate the management of a smart grid. The first smart meter, in Fig. 3, has been

Fig. 3. First Smart Meter (funded by PON Project “Laboratorio RENEW-MEL”).

Fig. 4. Second smart meter (funded by PON Project “DOMUS Energia”).

realized by using a Single-Board RIO 9626 with on board two additional modules: NI-9225 and NI 9246, more details are reported in [51].

For the second smart meter, an NI CompactRIO 9082 has been used with two modules mounted on board: NI-9225 and NI-9246 to acquire the voltage and current signals, respectively, see Fig. 4 for reference. The signals are acquired through the FPGA interface and then digitally converted by a real-time processor for data processing. In detail, the hardware includes a 1.33 GHz Dual-Core processor with 2 GB DRAM, 32 GB storage memory, and a Xilinx Spartan-6 LX150 FPGA. The two smart meters are compliant with the requirements of the International Standard Family IEC 61000-4, IEC 62052-11, and IEC 62053-21.

The code described in previous Section IV has been implemented on both smart meters. The two sensing systems can work stand-alone in real time and are able to operate independently in the grid. By considering the specifications and performances of the two meters, they belong to class A.

The structure system analyzed is composed of these two smart meters, positioned in the grid and connected to the Ethernet Network, and a PC (used as a server) on which runs the Control Station Application realized for monitoring the grid. Through the Ethernet Network, the smart meters are connected to the Control Station and receive continuously the synchronization signal of the master device. The master smart meter sends the clock signal on the network, which is received by the slave devices. Fig. 5 shows the layout of the analyzed structure.

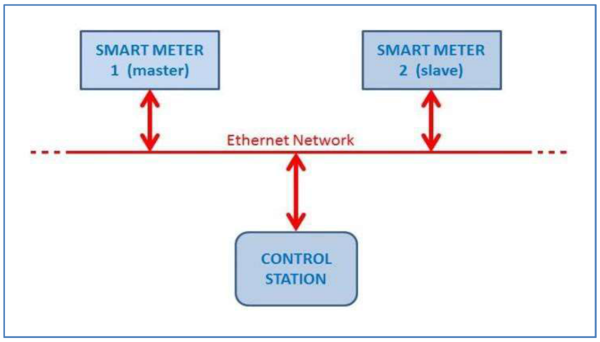
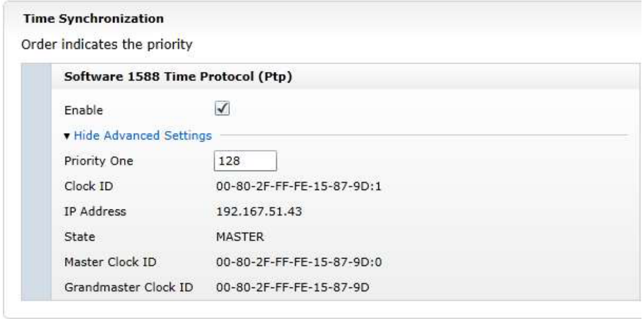


Fig. 5. Control and communication architecture.



Time Synchronization

Order indicates the priority

Software 1588 Time Protocol (Ptp)

Enable ☑

▾ Hide Advanced Settings

Priority One	128
Clock ID	00-80-2F-FF-FE-15-87-9D:1
IP Address	192.167.51.43
State	MASTER
Master Clock ID	00-80-2F-FF-FE-15-87-9D:0
Grandmaster Clock ID	00-80-2F-FF-FE-15-87-9D

Fig. 6. Software 1588 setting page.

B. Synchronization Test

To test the embedded time-synchronization protocol, the two smart meters have been located at two different points of the local electric grid of the University Mediterranea of Reggio Calabria, in Italy. The considered microgrid powers different buildings geographically dislocated in an area of about 1 km. Some energy-renewable plants, such as photovoltaic and wind generators, input power inside the microgrid.

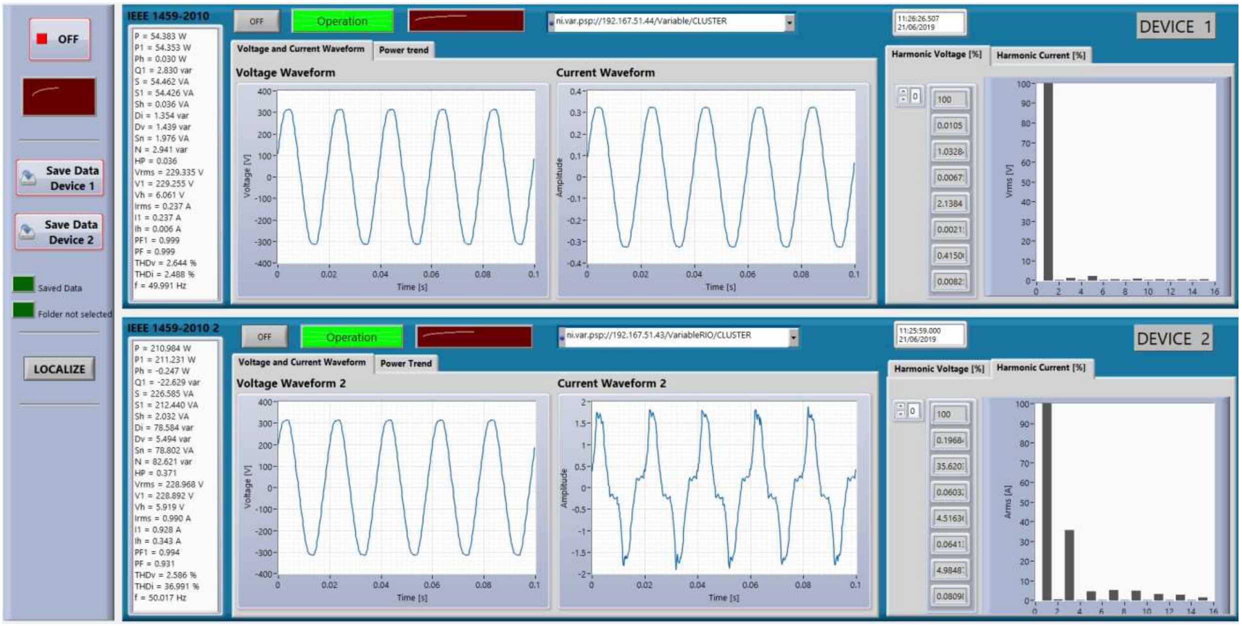
The first smart meter has been set as master. Fig. 6 shows the Software 1588 Time Protocol setting page.

The second smart meter has been connected to another node of the microgrid and has been set as a slave. Both devices have been referenced at the same time to synchronize measurements by using the same clock. New smart meters can be added to the measurement network by adding them to the control station. In addition, the code checks continuously the synchronization clock and automatically adjusts it in the presence of possible delays or errors.

To verify the functionality of the control station, different connectivity and synchronization tests have been carried out.

The panel in Fig. 7 shows the acquired data of the two smart meters, whereas the “Operation” led shows if the meters are properly working and if the synchronization timestamp is compliant with the system specifications.

Several tests in different operating conditions have been carried out to verify if the synchronization works properly.


IEEE 1459-2010

P = 54.383 W
P1 = 54.353 W
Ph = 0.030 W
Q1 = 2.830 var
S = 54.462 VA
S1 = 54.426 VA
Sh = 0.036 VA
Di = 1.354 var
Dv = 1.439 var
Sn = 1.976 VA
N = 2.941 var
HP = 0.036
Vrms = 229.335 V
V1 = 229.255 V
Vh = 6.061 V
Irms = 0.237 A
I1 = 0.237 A
Ih = 0.006 A
PF1 = 0.999
PF = 0.999
THDv = 2.644 %
THDi = 2.488 %
f = 49.991 Hz

IEEE 1459-2010 2

P = 210.984 W
P1 = 211.231 W
Ph = -0.247 W
Q1 = -22.629 var
S = 226.585 VA
S1 = 212.440 VA
Sh = 2.032 VA
Di = 78.584 var
Dv = 5.494 var
Sn = 78.802 VA
N = 82.621 var
HP = 0.371
Vrms = 228.968 V
V1 = 228.892 V
Vh = 5.919 V
Irms = 0.990 A
I1 = 0.928 A
Ih = 0.343 A
PF1 = 0.994
PF = 0.931
THDv = 2.586 %
THDi = 36.991 %
f = 50.017 Hz

Fig. 7. A screenshot of the control station panel.

To execute the test in synchronization, a tool for data acquisition has been developed using LabVIEW. The tool can collect and store the time references (timestamp) of the operations of the two smart meters under test, and then process them to calculate the synchronization delay of the Slave with respect to the Master.

The parameters monitored by the tool are as follows:

1) *Expected Start:* Expected start time of the current operation;
2) *Actual Start Master:* Actual start time of the Master current operation;
3) *Actual Start Slave:* Actual start time of the Slave current operation;
4) *Iteration Duration Master:* Time stamp of the execution length of the Master iteration;
5) *Iteration Duration Slave:* Time stamp of the execution length of the Slave iteration.

To execute the tests, the tool has been programmed to memorize the time references of synchronization with intervals of one second, for a time period of 1 h [1], [30]. Therefore, 3600 samples were stored and analyzed for each test. The data are automatically stored in an Excel file, so it can be used for further analysis. The tool, in automatic mode and for all 3600 measurements, calculates the synchronization delay of the slave with respect to the master, starting from the measured parameters. Then is calculated the average value of the delay during the test, was calculated as the arithmetic mean of the 3600 samples stored in an hour.

The first tests have been performed with the two smart meters connected to the network. They have been synchronized with each other assuring no interruption of their operation. The tests were performed in different time slots and on different days, to verify the accuracy of synchronization under changing conditions of data traffic in the used network. The aim is to understand how the delay changes with the network bandwidth usage in different day moments.

TABLE IV
DELAY VALUE

Test numbers	*Start Time*	*Delay*
1	9:00	***88 μs***
2	10:15	***105 μs***
3	11:20	***104 μs***
4	13:00	***92 μs***
5	17:35	***107 μs***
6	19:00	***88 μs***

In the tests performed, different average values of the synchronization delay were detected, the Table IV shows the most significant, relating to different time slots of execution.

For each test performed, the delay has been measured during a 1-h interval with a sampling rate of 1 s.

The following is an example graph showing the time dispersion of the synchronization delay concerning one of the various tests performed (fifth test in Table IV), see Fig. 8. Moreover, Fig. 9 reports the histogram of data distribution representing the time dispersion of the delay. The estimated Measure of Central Tendency is $\bar{x} = 107$ μs, and the estimated standard deviation is $\sigma = 5.42$ μs. The results show that the synchronization time belongs to the range of microseconds.

Then another type of test was performed. The slave sensing device was disconnected from the network, and reconnected after a few seconds, in order to simulate a communication/connection problem and analyze the behavior of the connected devices. After reconnecting the Slave device to the network, it synchronizes again with the master clock, with an increased delay but always in the range of 100 μs. Analyzing the data, it was observed a synchronization delay value equal to 88 μs before the detachment and equal to 112 μs after the new reconnection to the network. The measured time value to reestablish synchronization after reconnection to the network

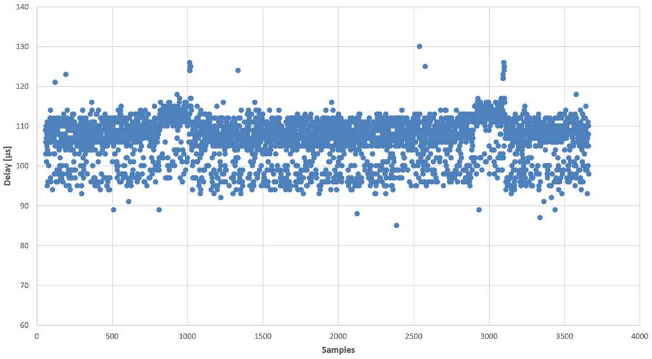


Fig. 8. Time dispersion of the delay.

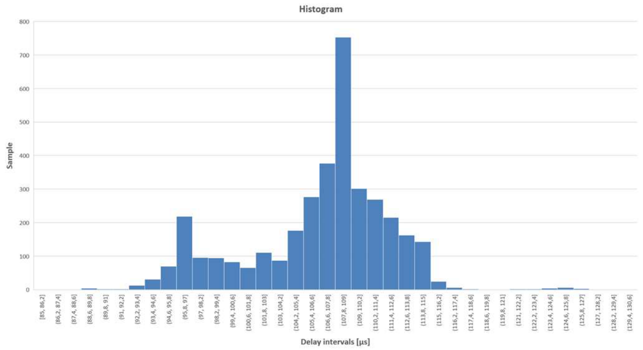


Fig. 9. Sample delays histogram.

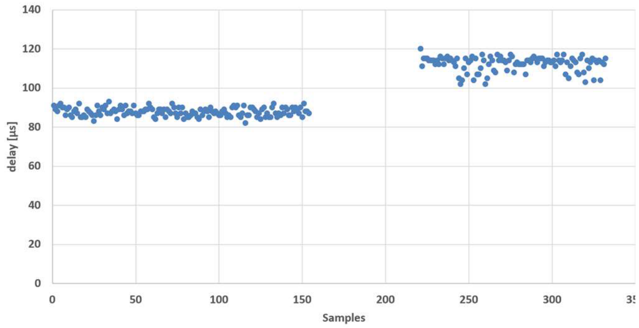


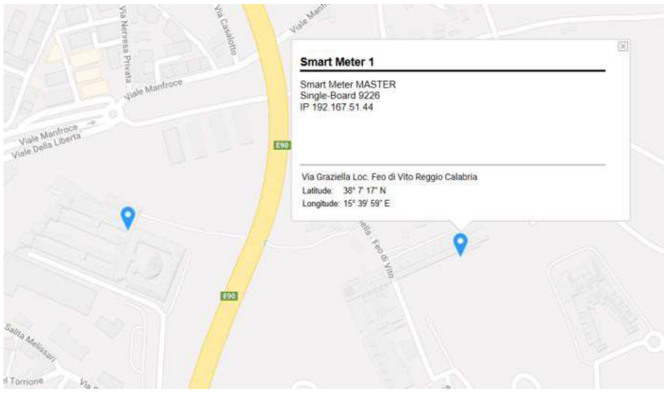
Fig. 10. Time dispersion of the delay.

was equal to 20 μs. The delay increase is compatible with the delay range obtained in Table IV because it has still an amplitude order belonging to the microsecond range.

The values stored during this test have been reported on the following graph, excluding the data detected in the absence of synchronization, see Fig. 10.

C. Localization Test

In the panel of the control station, there is an application named "Localize" that allows to localization of the sensing devices connected to the smart grid. By pressing the button, a popup window shows a map with the smart meter locations. By clicking on each indicator, it is possible to know the features of the selected smart meter, including geographical coordinates and address. In Fig. 11, it is visible the map with the geographical position of the smart meters dislocated in the microgrid.



Smart Meter 1

Smart Meter MASTER
Single-Board 9226
IP 192.167.51.44

Via Graziella Loc. Feo di Vito Reggio Calabria
Latitude: 38° 7' 17" N
Longitude: 15° 39' 59" E

Fig. 11. Smart meters localization.

VI. CONCLUSION AND FUTURE WORK

The article has proposed a preliminary comparison between informatics-based synchronization protocols and satellite-based synchronization systems. The aim was to show the weaknesses and strengths of both protocols with reference to the proposed application case. Accuracy, communication type, the need for hardware, and implementation costs have been compared. The PTP has been chosen to synchronize the measurements of the developed sensing network connected to a local microgrid. This protocol was able to assure a suitable accuracy for the time- synchronization and lower realization costs, in addition, it does not need dedicated hardware.

The development of an automatic control station for power grid management has been successively presented in the article. The NI LabVIEW Synchronization Tool has been used to configure the smart meters by implementing the PTP protocol. The whole sensing network can be managed and checked by the panel of the control station. Additional smart meters can be added to the network according to needs at any time. The control panel allows to control of each meter, verifying real-time synchronization, reading and saving sensing data, and checking possible faults. In addition, the control station is able to localize the devices connected to the network and show their dislocation on a map. Tests have been carried out to check the network functioning and the synchronization accuracy.

Future work focuses on the development of optimal algorithms for energy rooting in order to manage energy flows in the grid. Algorithms will be based on information concerning the presence of energy amount and demand in the several nodes of the grid. All meters will be synchronized and will provide information on power quality to optimize the energy rooting algorithms avoiding interruptions or possible failures due to energy supply having low quality.

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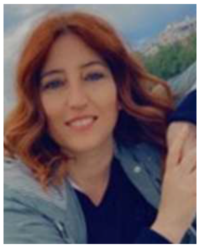

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