This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIM.2020.3036691, IEEE Transactions on Instrumentation and Measurement

Methodology for power quality measurement synchronization based on GPS pulse-per-second algorithm.

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***Abstract*— Power quality disturbances (PQD) are generated by non-linear loads and they propagate through the electrical grid to other sensitive devices causing malfunction. To study the propagation of PQD, it is important to perform synchronized and simultaneous measurements at multiple locations in the electrical network. This paper proposes a methodology to synchronize measurements of electrical variables at multiple locations in the electrical grid based on the synchronization of the internal time reference of several data loggers with the pulse per second (PPS) reference provided by a global positioning system (GPS) receiver module. As the PPS signal is synchronized to the atomic clocks of the satellites in the GPS, a precise time reference in multiple sites can be obtained simultaneously. The proposed methodology has been tested in two stages. The first stage is a validation experiment that compares the number of samples obtained between three GPS synchronized data loggers and two data loggers with internal synchronization only. The PPS signal has been interrupted in one GPS synchronized data logger to simulate a signal loss and test the resynchronization capability of the methodology. A very low synchronization error has been obtained for the GPS synchronized data loggers whereas the data loggers with the internal synchronization show greater synchronization errors. The second stage consists in experimental case of study that measuring electrical variables in multiple locations of a real electrical grid where the propagation of multiple disturbances are tracked with the GPS synchronized data loggers.**

***Index Terms*—Power quality, global positioning system, electric variables measurement, smart grids, power system measurements.**

This work was supported in part by CONACYT under scholarship 486847.

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I. Introduction

POWER quality disturbance (PQD) events have increased in recent years; these events typically result in malfunctions of sensitive devices connected to the grid and energy losses in residential, commercial and industrial facilities. Typically, these events are caused by non-linear loads, motors, and switching devices. PQD that are generated at one section in the grid can be static or can propagate to other sections affecting the attached equipment [1][2][3]. For these reasons it is necessary to develop equipment that allows monitoring in different parts of an installation simultaneously to trace the propagation of PQD in the grid and to be able to detect their generating source.

A survey on the published literature shows that there are several techniques to perform synchronized measurements: real time clock (RTC), precise time protocol (PTP), network time protocol (NTP), Inter-range instrumentation group timecodes (IRIG-B) and global position system (GPS). As an example, in [4] an architecture of custom application-specific integrated circuit (ASIC) has been developed for power quality measurement using an RTC that enables system synchronization. Authors in [5] have developed a smart sensor network based on field-programmable gate array (FPGA) for measurement of standard power quality parameters and detect PQD. In order to synchronize data, the system uses an RTC with a resolution of 1 millisecond. These developments synchronize the initial time of the measurement but use different internal clock sources and this cause a time shift in long time measurements. To improve RTC problems, PTP and NTP were developed. These techniques synchronize the time reference every second, and have been used in [6] were authors present a low-cost, re-configurable Modular Intelligent Node for Distribution systems (MIND) for monitoring a power distribution system. MIND is synchronized to the universal

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time coordinated (UTC) using IEEE 1588 PTP. In [7], authors use the data from a phasor measure unit (PMU) and NTP-synchronized data from two different MV (medium voltage) networks to study the voltage unbalance and how it is affected by high penetration of photovoltaics and wind power. In [8] authors made a review of time synchronization techniques for smart grids and mention that PTP and NTP techniques have the inconvenience that their performance depends on the network infrastructure and the network interface to synchronize the time on the measurement system. In [9] authors discuss the uses of IRIG-B applied in PMU for its needs in power systems, which is a time code that can transmit PPS pulse and time information together, but has the disadvantage that it is necessary to have a source that provides the UTC time information and the time stamp, it is also necessary to use a modulator and demodulator of the IRIG-B time code.

There is commercial equipment that allows simultaneous measurement of several PQD indices, such as digital fault recorders (DFR) and PMU. The DFR is designed to trigger when it detects a fault event and measure current and voltage at the time when the fault occurs for analysis [10][11]; furthermore, DFR are not designed to perform continuous measurements of the entire current and voltage waveform or to perform other PQD indices. Another device that is used to measure some PQD indices is the PMU that can perform simultaneous measurements, but only measures voltage and current as phasors, which consists in calculating the magnitude and angle [7], so it does not allow obtaining the raw waveform of voltage and current or estimating other PQD indices. The use of the global positioning system (GPS) as a tool for simultaneous monitoring is suitable for PQD detection, where it is necessary a system that guarantees the complete measurement of the raw waveform of voltage and current signal for long periods of time in order to estimate different types of PQD indices, which is easy to install, does not require a network infrastructure and maintains a better cost-benefit ratio than other techniques. The use of the pulse-per-second (PPS) synchronization signal provided by a GPS receiver as time base allows maintaining synchronization in all the measurement systems since it is updated every second. This technique is also used in other fields, as physics, to synchronize their measurement systems as shown in [12] that uses a GPS for a global-time-synchronized data acquisition for a global network of optical magnetometers, which aims to search for signals heralding physics beyond the standard model. In [13], authors developed a novel virtual machine environment (VME) trigger unit for the extreme energy event (EEE) telescopes, by including an embedded GPS engine for timing application, because it requires a precise time synchronization to correlate the information collected from each detector and in [14] GPS is used on the development of a flexible measurement instrument for analyzing different types of signals that could be found in railway systems. To monitor power quality variables it is necessary to develop measurement instruments that comply with their characteristics and that are synchronized between them.

The aim of this work is to develop a three-phase voltage and current data logger for power quality measurement, which incorporates a methodology for synchronizing various instruments to track the propagation of PQD in a timely manner. This is achieved using the PPS signal of a GPS, and the proposed methodology has the ability to follow the measurement when the PPS is lost, and once the PPS is recovered it can be synchronized again. A set of three proprietary data loggers are developed to validate the proposed methodology under laboratory conditions, and afterwards, they are tested in an industrial installation where it is shown how they can accurately track the propagation of PQD on the network.

II. Theoretical Background

PQD tend to spread in the electrical network, for this it is necessary the simultaneous monitoring of several points at the network to track PQD and how they propagate in order to establish practices that minimize the PQD within the grid.

A. Propagation of PQD in the grid

Power quality (PQ) definition is how the voltage and current waveforms approximate to a pure sine wave; the ideal sine wave has constant amplitude and frequency, where any alteration is considered a PQD. From the different PQD that can be present on the grid, this paper presents the analysis of transients, harmonic contents, and flicker. A transient is a short-term PQD having high amplitude where most of them are dangerous to the devices connected to the grid [15]. Two types of transients that can appear on the grid are the impulsive transient and the oscillatory transient. The impulsive transient is a sudden change in the signal amplitude with a fast rise and fall time, which is shorter than a cycle of the fundamental frequency. The parameters that characterize the impulsive transient are the peak amplitude and the time duration of the disturbance. On the other hand, the oscillatory transient is a sudden change in the magnitude of the electric signal that oscillates with positive and negative extreme values with duration of several cycles of the fundamental frequency. The oscillatory transient is usually caused by the presence of switching loads on the grid [16]. The parameters that characterize the oscillatory transient are the peak amplitude and the number of cycles that is present the disturbance.

Another type of PQD is the harmonic contents of the electric signal. The harmonic contents are AC voltage and current integral multiples of the supply fundamental frequency [10]. Harmonics are generated by non-linear loads connected to the grid and produce overheating in electric equipment, appliances and the wiring; and also produce malfunctioning in variable speed drives [16]. The harmonic contents in a signal is characterized by the amplitude of each spectral component that is a multiple integer of the fundamental frequency that can be obtained by applying the discrete Fourier transform (DFT), and also by the relationship between the amplitude of the fundamental frequency component and the harmonics, known as the total harmonic distortion. The DFT allows converting a signal in the time domain to a signal represented in the frequency domain with signals acquired in discrete values [1].

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Eq. (1) represents the DFT X_k of a discrete sequence x_i of length N:

$$X_k = \sum_{i=0}^{N-1} x_i \mathrm{e}^{-\mathrm{j}2\pi ik/N} \tag{1}$$

For $k = 1,2, \dots, N-1$.

To calculate the total harmonic distortion using (2) it is required to obtain the signal spectrum using the DFT and thus obtain the power of the fundamental frequency represented by P_1 and the powers of the harmonics and interharmonics represented by P_h [5].

$$THD = \frac{\sqrt{\sum_{h\neq 1}^{\infty} P_h}}{P_1} \tag{2}$$

The voltage flicker is other kind of PQD, which is characterized by low-frequency cyclic variations in the magnitude of the voltage supply with amplitude below 10% of the nominal value. The main characteristics of the flicker are the amplitude of the oscillation, its period, and the time lapse [16]. Flicker is commonly produced by the operation of the connected load in the grid and the fluctuation in power consumption [17].

In [18] and [19] PQD are discussed, the causes of deficient PQ can be single large sources of disturbance connected to the grid or aggregated smaller non-linear loads. These disturbances may decay with distance from their source but can also amplify depending on each specific network topology and impedance. For this reason, network operators need to understand the level of PQD in the networks and ensure PQD will not exceed safe levels [20]; this procedure is done with on-site measuring devices. These PQD produce several problems to sensitive devices and sometimes lead to permanent damage; also, in industry can cause high energy loses. To minimize PQD in the grid some agencies are in charge to establish norms that allow maintain PQD in safe levels [21].

B. *Synchronization technique*

To monitor electrical signals it must be possible to detect the presence of disturbances and their propagation in various points of a grid, so it is necessary to develop a system that is easy to install in different points of the grid, which is capable of maintaining synchronization during long-term measurements and that can maintain a cost effective so that the installation of several devices is viable. Based on different applications found in the state-of-the-art the development a GPS based methodology allows to comply with the requirements mentioned above.

The data loggers based on GPS use a PPS signal as reference; PPS is a 1 Hz pulse synchronized to the atomic clock carried by the satellites and is used to synchronize the internal time base of the data logger every second such as in [22]. For the initial configuration, the GPS receiver provides UTC time to the data logger and it is synchronized every second. The PPS pulse is received and used to synchronize the internal time base of the data logger and a flag is stored indicating whether the acquired samples have been taken with the internal time base synchronized to the PPS or not, allowing knowing if there is a PPS synchronization loss of the system such as in [23].

III. Methodology

Commercial equipment such as PMU and DFR allow simultaneous measurement of some PQD indices, but the PMU is used to measure voltage and current as a phasor (magnitude and phase angle only), and the DFR is designed for recording only the failures and disturbances in the system. Therefore, it is necessary to develop an instrument that allows synchronized measurements of the raw waveform of voltage and current signal during long periods of time for analysis, as well as to estimate PQD indices.

In order to synchronize the signals obtained by several data loggers in an electrical grid, it is proposed a methodology that uses a broadcast time stamp, provided by a GPS receiver module. To synchronize the internal time base of each data logger, this methodology is similar to a combination of the methodologies presented in [22] and [23]. This methodology consists of two stages: 1) internal time base synchronization with the PPS signal, and 2) a procedure to match the synchronized measured signals.

Fig. 1 shows the flow diagram of the first stage of the methodology to perform the internal time base synchronization with the PPS signal. The first step checks for whether the PPS signal has arrived or not. If the PPS signal has arrived, the internal time base of the data logger is disciplined by the received PPS pulse and a flag signal named SMP is set to logical 1. If the PPS signal has not arrived, the internal clock of the data logger is used as reference for the acquisition and SMP is set to logical 0. Then, the corresponding UTC is updated and stored. Finally, the voltage and current signals are sampled and stored during 1 second until the arrival of the next PPS where the cycle is repeated.

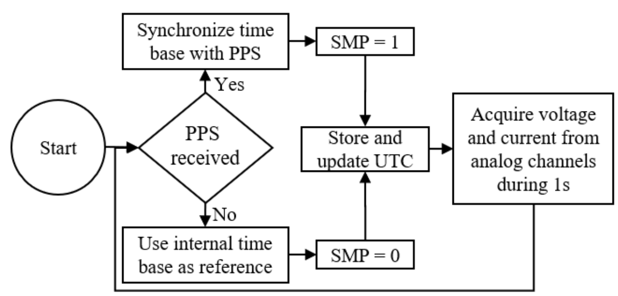

Fig 1. Block diagram of internal time base synchronization with PPS for each GPS synchronized data logger.

Fig. 2 shows the flow diagram of the second stage of the methodology; the procedure to match the synchronized signals of several data loggers listed as D1, D2, to DN, for a number of N data loggers. In the first step it is selected by the user the starting point UTCs for analysis. As all data loggers are synchronized with the PPS from the GPS receiver, this starting point UTCs can be located as a specific sample on each data logger D1, D2, …, DN and the algorithm matches all data to be synchronized to UTCs. Afterwards, the user selects the time lapse for analysis by setting UTCe as the end of the data to be analyzed. Finally, from UTCe the algorithm matches the acquired samples from all data loggers and prepares the data for further analysis. This procedure is done offline to perform the analysis of the event occurrence within the signal.

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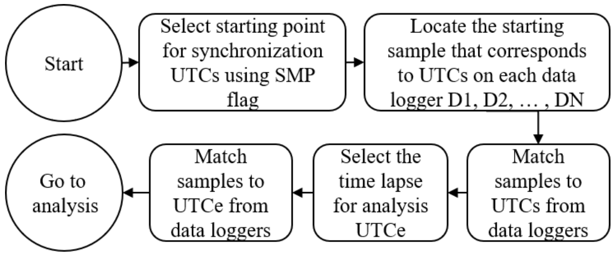

Fig. 2. Procedure to match synchronized signal measured.

IV. Experimental Setup

The experimental setup is organized in two sections: the hardware description of the GPS synchronized data logger, and the description of the validation tests.

Hardware description

Fig. 3 shows the block diagram of the proprietary GPS synchronized data logger, [5] composed of the modules: GPS receiver, Bluetooth module, 8-channel data acquisition system and a field programmable gate array (FPGA) based processor. The GPS receiver provides the PPS signal that is a high precision time stamp synchronized with the atomic clock of the satellites in the GPS constellation; in contrast to IRIG-B, it is not necessary to use a special modulator and demodulator, and also provides time, date and position data through the UART (universal asynchronous receiver-transmitter) communication port, using the NMEA-0183 [24] (national marine electronics association) protocol. The GPS receiver sends time and navigation data to the FPGA communication port and it is stored in memory; this way, the time data are associated with the samples and they are used as reference. The Bluetooth module establishes the communication between the FPGA processor and the user to configure the settings of the data logger via UART communication protocol. The proprietary data logger has 8 channels for acquiring analog data of electrical signals, connected to the FPGA-based processor via serial peripheral interface (SPI) protocol. The FPGA-based processor coordinates all modules and performs the synchronization using the PPS pulse provided by the GPS receiver. This processor performs the synchronization of the internal time base in the data logger with the PPS signal and generates the SMP flag. The data logger stores the information from the 8 analog channels, the GPS position, and the UTC.

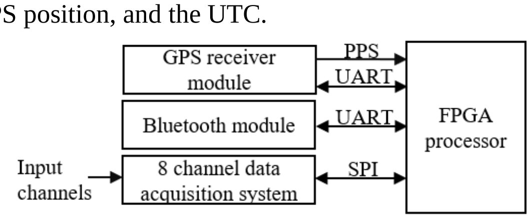

Fig. 3. Block diagram showing the main components of the proprietary GPS synchronized data logger.

Fig. 4 shows a photograph of the proprietary GPS synchronized data logger with a Xilinx Spartan 6 FPGA board. The data acquisition system has 8 analog channels with signal conditioning and a 12-bit 8-channel analog-to-digital converter (ADC), model ADS130E08 [25]. The proprietary GPS synchronized data logger acquires 8000 samples per second on each channel, which can be a voltage signal (up to 480 Vac) or a current signal (up to ±30 A) using a non-invasive split core current transformer SCT-013-030 [26], the measured signals are stored in a flash memory, which is interchangeable and by using a 120 GB memory capacity allows to measure for 11 days. The proprietary GPS synchronized data logger complies with IEEE-1159, UNE-EN-50160 and UNE-EN-61000 standards.

Validation

Table I shows a comparison of the main capabilities and disadvantages between DFR, PMU and the developed data logger for applications in estimating PQD indices, where the DFR and PMU do not completely satisfy the necessities for the application, since it is necessary to have the raw waveform voltage and current measurement to perform analysis of the propagated disturbances.

TABLE I
Capabilities and Disadvantages Between DFR, PMU and the GPS Synchronized Data Logger for Applications in Estimating PQD Indices.

System	Capabilities	Disadvantages
PMU	- PMU can directly measure frequency, voltage and current waveforms along with phase angle differences at high sampling rates and with great accuracy [27]. - PMU utilizes a Global Positioning System (GPS) reference source to provide the required synchronization across wide geographical areas [28].	- Does not capture the raw voltage and current waveform. - No PQD indices calculation. - High cost.
DFR	- DFR triggers on fault event and records current, voltage and their waveform at the time of the fault for analysis [10]. - DFR is defined as a device to graphically record all the voltages and currents as well as protective relays' operations during any fault condition and switching transients using a fast sampling rate [29].	- Only stores fault events, does not capture the raw voltage and current waveform. - The time base that DFR trigger is not perfectly synchronized [30]. - No PQD indices calculation. -High cost.
GPS synchronized data logger	-Continuous measurement of raw waveform of voltage and current. -GPS synchronization with PPS obtaining 1 error sample in 24 hours during a PPS interruption. -Calculation of PQD indices. -Under 2,500.00 USD per unit.	- Data need to be collected for further post-processing.

Once the methodology for synchronizing electrical signals from several GPS data loggers has been completed, a validation stage is developed. For the validation stage three proprietary GPS synchronized data loggers are used along two data loggers with internal time base without PPS synchronization capabilities. This validation process allows comparing the synchronization of the three proprietary GPS based data loggers using the PPS signal and the deviation accumulated in those data loggers with the internal time base without PPS synchronization.

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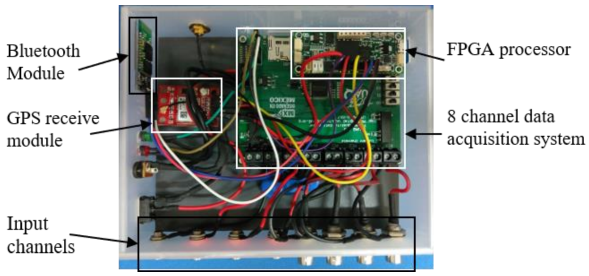

Fig. 4. Photograph showing the main components of the proprietary GPS synchronized data logger.

Perfectly synchronized systems require the same time base and consequently the same number of samples for the same time period; however, having different time bases can cause a drift between the different data acquisition systems. For GPS synchronized data loggers the drift is expected to be minimal because the time base resynchronizes every second while data loggers without PPS synchronization do not. To validate the accuracy of the GPS synchronized data loggers, three GPS synchronized data loggers called D1, D2 and D3 and two data loggers with internal time base without PPS synchronization called D4 and D5 are used. The GPS synchronized data logger D1 is set as the reference of the experiment to which, all other data loggers are matched. During the experimentation, it is guaranteed that the PPS signal is present for the whole time lapse. D2 is a mirror tester with exactly the same conditions than D1. On the other hand, D3 is a data logger where it is applied a PPS signal interruption for 5 minutes. During this interruption, the data logger uses the internal time base as reference. The interruption is used to verify that the drift is minimal, even if the data logger has a loss of the PPS signal for short periods of time. The data loggers without PPS synchronization, D4 and D5, are used to compare the drift that non-synchronized data loggers accumulate against the drift of the GPS synchronized data loggers. The 5 data loggers perform a continuous measurement of the same electrical signal, at the same point, during a proposed time lapse of 24 hours using 2 channels of the data logger; 1 for voltage and the other one for current in a single phase of a three-phase system.

To estimate the drift of the data loggers in the selected time lapse, D1 is set as reference, and the expected number of samples N1 for a time lapse of 24 hours is as stated in (3), considering that the sampling frequency is f_s=8000 samples per second and there are 86400s in 24 hours. Then the matching of the GPS synchronized data loggers is done with the procedure for matching measurements of synchronized signals described in Fig. 2, which uses the universal time references UTCs and UTCe to establish the same time period for the comparison. The matching procedure is done automatically for the GPA synchronized data loggers and manually for the data logger without PPS synchronization. The matching of the data logger without PPS synchronization is done by counting the cycles of the acquired signal by the reference D1, and then matching the samples of the non-synchronized data loggers to that reference. After the matching process is done, it is determined how many samples each data logger acquired N2, N3, N4, and N5. The drift error e_i at each data logger can be estimated using (4), which represents the difference between the number of samples that the i-th data logger acquired, and the number of samples acquired by the reference.

$$N_1 = N_{ref} = fs * 86400\,\mathrm{s} = 691200000\, samples \quad (3)$$

$$N_i = N_{ref} \pm e_i \quad (4)$$

To perform the validation stage, the experimental configuration of Fig. 5 is used, showing the GPS synchronized data loggers D1, D2 and D3, and the data logger with internal time base without PPS synchronization D4 and D5, which simultaneously measure the same electrical signal during 24 hours. Fig. 6 depicts the experimental setup for the validation stage, showing the three GPS synchronized data loggers D1, D2, and D3, and their respective GPS antennas; and the two data loggers without PPS synchronization, D4 and D5. Fig. 6 pinpoints where voltage is measured, as well as where the current sensors are placed at the same point inside the low voltage distribution cabinet.

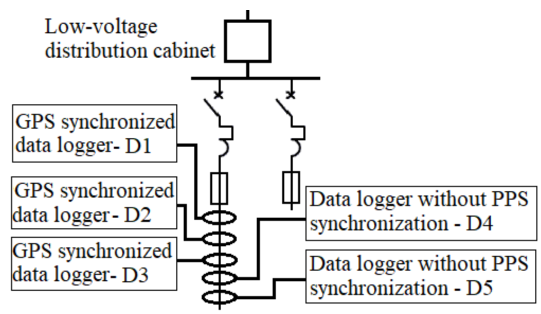

Fig. 5. Setup diagram of the three GPS synchronized data loggers (D1, D2 and D3) and two data loggers without PPS synchronization (D4 and D5) to perform the validation stage.

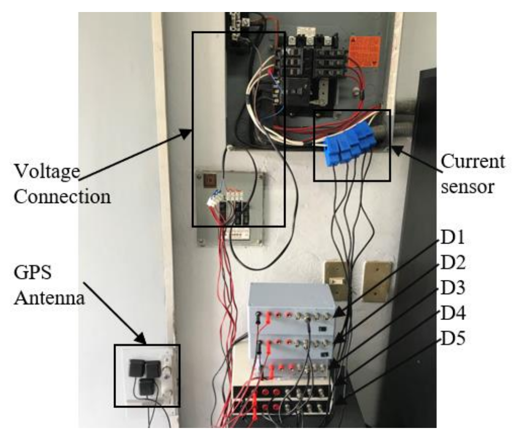

Fig. 6. Hardware connection used to perform the validation stage.

Experimental case of study

For the experimental case of study, three proprietary GPS synchronized data loggers D1, D2 and D3 are used to monitor the propagation of PQD within an electrical grid at different locations of a real industrial facility. The experiment setup diagram is depicted in Fig. 7, showing the GPS synchronized data logger distribution. All the data loggers acquire three-phase voltage and current at the electrical grid using 6 analog channels for acquisition.

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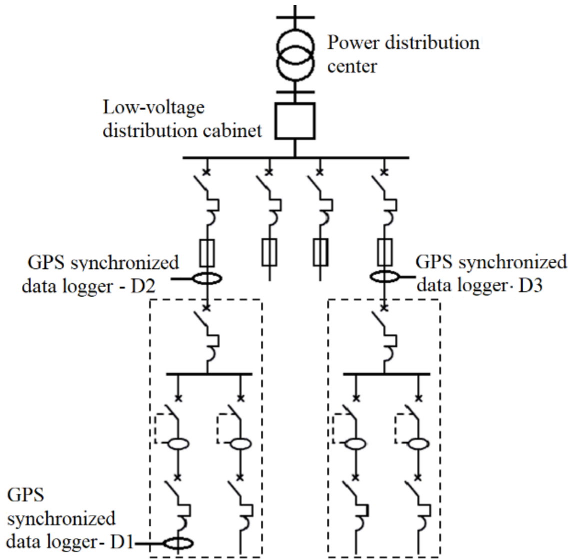

Fig. 7. Setup diagram of the experimental case of study for the monitoring of PQD propagation in an electrical grid.

The analysis of the experimental case of study consists in matching the signals of the three GPS synchronized data loggers using the procedure described in Fig. 2, and then tracks PQD and follow their propagation to other parts of the grid.

V. Results and Discussion

This section presents the results and discussion of the validation stage and the experimental case of study.

Validation

According to the validation stage for 24-hour continuous acquisition from five data loggers, the number of samples N_i obtained from each data logger is shown in Table 1, which also contains the drift error e_i in samples, the corresponding drift in seconds, and the percentage of each data logger drift in comparison to the reference D1.

TABLE II
Results of first validation stage showing the drift error of the PPS synchronized data loggers compared to the non PPS synchronized data loggers.

Device	Samples during 24 hours - N_i	Drift error - e_i (samples)	Drift (s)	Drift (%)
Data logger without PPS interruption – D2	691200000	0	0	0.0
Data logger with PPS interrupted during 5 minutes – D3	691199999	1	1.25 $x10^{-4}$	144.7 $x10^{-9}$
Non PPS synchronized data logger 1 – D4	691041642	158358	19.79	22.91 $x10^{-4}$
Non PPS synchronized data logger 2 – D5	690973955	226045	28.25	32.7 $x10^{-3}$

Table II summarizes the drifts of the data loggers. From this table, it can be seen that the mirror data logger using the PPS synchronization D2 has 0 drift compared to the reference. For the PPS synchronized data logger D3, which has a disconnection of 5 minutes from the PPS signal, the obtained drift is only 1 sample, corresponding to a drift of 0.125ms or 0.00000014%. These results show that the proposed methodology is able to precisely track time of several independent data loggers and match the acquired data for analysis, even if some interruptions of the PPS signal are produced during the acquisition. In comparison, the non-PPS synchronized data loggers have a significant drift error of several orders of magnitude, making difficult the matching of the acquired data. For this experimentation, D4 gives a drift of almost 20s, whereas the drift at D5 is around 28s, corresponding to 0.0229% and 0.0327% relative deviation, respectively. According to the drift errors, a precision of almost 100% is obtained for the PPS synchronized data loggers during a 24-hours continuous acquisition, and for the data loggers without PPS synchronization the average precision is around 99.97%.

Experimental case of study

The aim of the experimental case of study is to highlight the capabilities of GPS synchronized data loggers to track the propagation of PQD disturbance through the grid.

Transient analysis

Fig. 8 shows three current signals corresponding to the GPS synchronized data loggers of the experimental setup from Fig. 7 at a given time window where there are two PQD recorded by D1 as depicted in Fig. 8a, and they propagate to the point where D2 is located because they are connected to the same section of the electrical grid, as it can be seen in Fig. 8b. It can also be seen that these PQD do not propagate to the point D3 because it is located in another section of the electrical grid. It can also be seen that there is a delay on the PQD propagation from D1 to D2, which can be measured precisely, thanks to the synchronization capabilities of the GPS synchronized data loggers. The disturbance of the transients observed is caused by the starting of a high-power milling machine, which consumes a large amount of current during the start-up and it propagates only in D1 and D2 because they are in the same branch, whereas D3 is in a different branch as shown in Fig. 7. The current signals in Fig. 8 show the presence of two transient PQD, one oscillatory and the other one impulsive. The transient parameters of the signals from D1 in Fig. 8a and D2 in Fig. 8b have been extracted, where δa1 is the amplitude of the oscillatory transient and δa2 is the amplitude of the impulsive transient. Also, it has been obtained the start time ti1 of the oscillatory transient and start time ti2 of the impulsive transient, thus obtaining the duration of the transient represented by δt1 for oscillatory transient and δt2 for impulsive transient. From the obtained data, it is observed that the propagated oscillatory transient from D2 in Fig. 8b is of similar amplitude and duration in comparison to the oscillatory transient from D1 in Fig. 8a, as well as the impulsive transients are similar in amplitude and duration.

Harmonic analysis and THD

Fig. 9 shows a time window where a PQD having high harmonic contents propagates to all measurement points. No delay is observed at the different points for this case. For this PQD, a harmonic analysis has been performed where the normalized THD is calculated obtaining THD=4.64% for D1 in Fig. 9a, THD=4.56% for D2 in Fig. 9b, and THD=1.36% for

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D3 in Fig. 9c. These values indicate that THD from the signal in D3 is lower than the THD present in signals from D1 and D2. This is because D1 and D2 are connected in the same section of the grid that has non-linear loads which produce the distortion. On the other hand, D3 is connected to a different section of the grid and is also affected by the non-linear loads, but in less proportion. Fig. 10 shows the frequency spectra of the signals from Fig. 9, respectively.

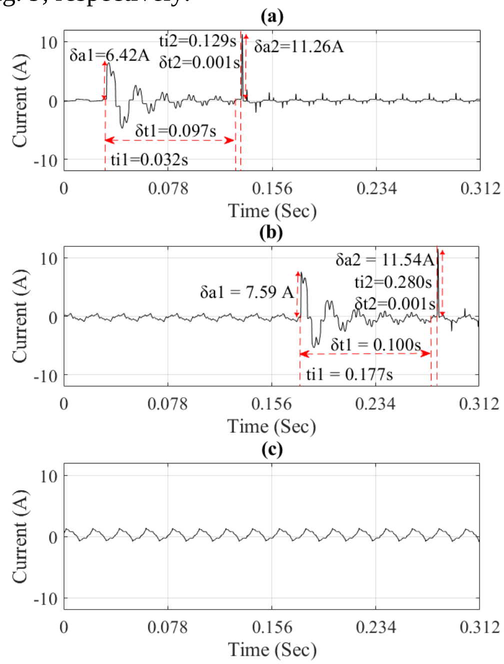

Fig. 8. Current signals from GPS synchronized data loggers with PQD propagation. (a) Data logger D1, (b) data logger D2, (c) data logger D3.

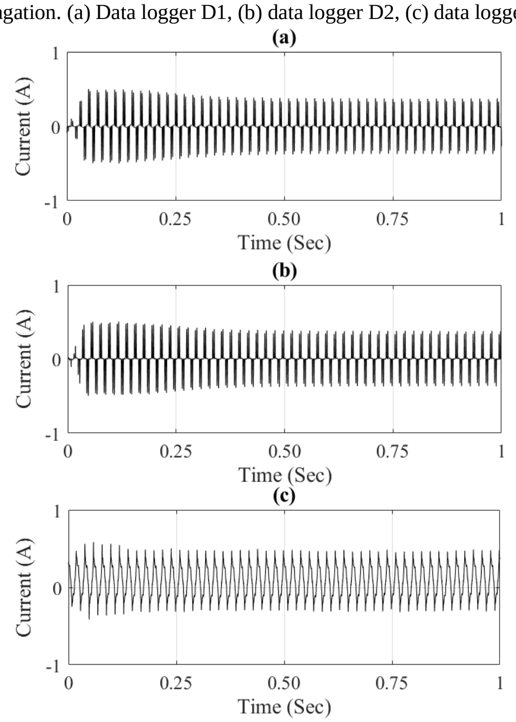

Fig 9. Current signals from GPS synchronized data loggers with PQD propagation. (a) Data logger D1, (b) data logger D2, (c) data logger D3.

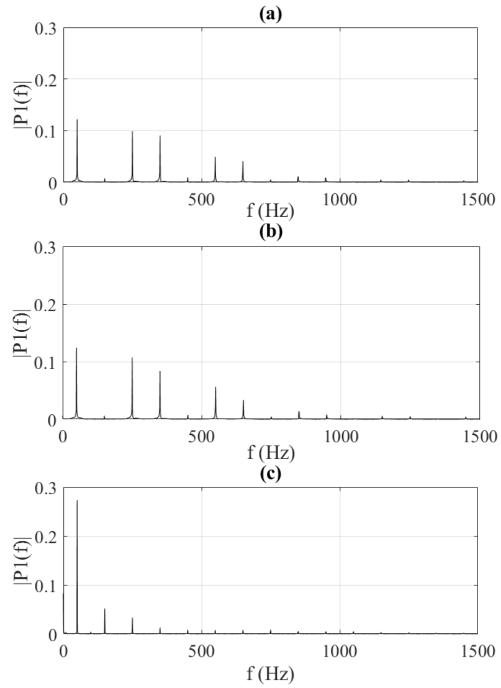

Fig. 10. Frequency spectra of the current signals from GPS synchronized data loggers with PQD propagation. (a) Data logger D1, (b) data logger D2, (c) data logger D3.

Flicker analysis

Fig. 11 shows the zoomed voltage signals of the GPS synchronized data loggers D1, D2 and D3, where flicker PQD is present. It can be seen that the low-frequency period of the flicker is 112.7s or 0.008 hertz in the three signals. The amplitude of the flicker variation is similar in the three points of measurement and it is around 1V, representing a voltage variation of 0.625%. This PQD is produced by the presence of switching loads which induce this phenomenon in the voltage signal and it is propagated to the whole grid.

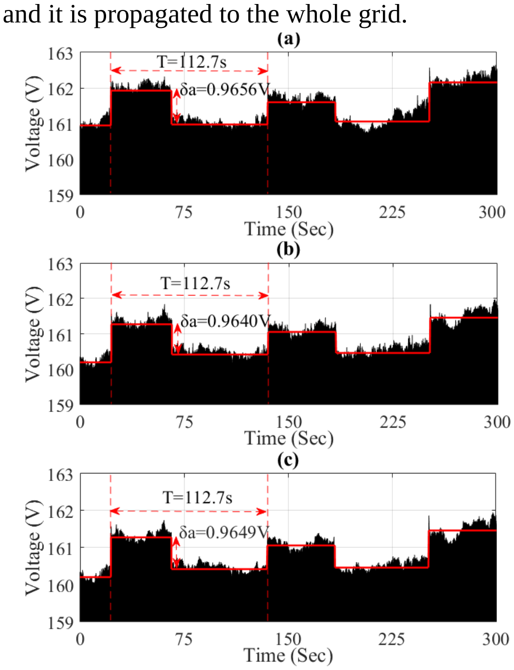

Fig. 11. Zoom at the voltage signals from GPS synchronized data loggers with flicker. (a) Data logger D1, (b) data logger D2, (c) data logger D3.

VI. CONCLUSION

In this paper it has been developed, implemented, and validated a methodology that allows synchronizing measurements of electrical signals at several data loggers using the PPS signal from the coordinated universal time (UTC) provided by the GPS. The accuracy of the proposed methodology is validated by comparing the error in the number of samples acquired by each data logger during a 24-hour time lapse, synchronized by the UTC. The precision of proposed methodology is close to 100% for the GPS synchronized data loggers, whereas the precision of the data loggers without PPS synchronization is around 99.97%. An experimental case of study is developed to show the efficiency of the proposed methodology to track the propagation of PQD to other locations at the grid, such as transients, harmonics, THD, and flicker; having great precision to determine the propagation delay of the PQD. It can be concluded that the use of a PPS signal to synchronize the internal time bases of several GPS synchronized data loggers allows performing simultaneous and synchronized measurements to track PQD and observe their propagation in the electrical grid. In case of occasional GPS signal loss, the methodology allows synchronization once the GPS signal is received again. The uses of a precise time reference transmitted through the satellites and GPS receivers allows synchronize measurements in sites that are located at long distances.

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