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Development and application of a smart grid test bench

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ABSTRACT

The current upward trend in large-scale integration of distributed energy resources (DER) in distribution networks has fueled interest in knowing their power quality issues (PQ), even in nearly real-time scale when possible. This trend involves researching new protection strategies that contribute to the reduction of supply interruptions times, which will ultimately result in greater energy efficiency. Based on this scenario, a research and development platform for testing the behavior of the electronic systems involved in supervision and control is presented. The proposed design is based on the experience acquired by our research group in the last ten years. The main objective is to reproduce on a laboratory scale the behavior of a 9 kVA power generation system associated with active loads. This setup allows reproducing all kind of perturbation that might happen in the actual grid and to verify the behavior of the system devoted to their detection. Therefore, the main interest of this system is to test the behavior of the physical devices, as well as the advanced algorithms for real-time detection. As one of its main characteristics, the setup makes use of a high-level synchronization system in order to guarantee the precise estimation of the response times. The most advanced objective is related to the global estimation of the response time considering the communication delays. Thus, the test platform contributes to the PQ, the protection, and the advanced communications, aspects which stand out as highly relevant in the imminent wide expansion of the Smart Grids. A case study, as well as the experimental results, are presented, which show and address the performance of the entire system.

1. Introduction

Smart power grids integrate various technologies such as electric vehicles (Amini et al., 2015a, 2017) or smart home appliances (Amini et al., 2015b) and incorporate methodologies such as demand response programs (Kamyab et al., 2016; Amini et al., 2013) or decentralized power management of renewable resources (Baghaee et al., 2017). Two aspects such as achieving a high degree of reliability or ensuring that power distribution facilities are easily adapted to the changing nature of electricity consumption (Cucchiella et al., 2016) are a clear examples of how to reduce CO2 emissions. It was initially proposed as an alternative to the depletion of fossil fuels, and currently, represents an optimal solution for the achievement of sustainable energy systems.

The upward trend in the integration of distributed energy resources (DER) in the electricity market, many of them renewable and non-dispatchable, involves a detriment of the network control capabilities since those resources are directly connected to any point of the medium voltage (MV) or low voltage (LV) grid. This is a major factor of disturbance that leads to the emergence of stability problems, the decrease of reliability or the presence of reverse flows. Therefore, it is necessary to effectively manage the real-time power flows involved in the entire electrical system.

The need for progressively providing more intelligence and autonomy to electricity distribution grid results in the enhancement of the protection and measurement equipment, so they can easily be adapted to the concept of Smart Grid as a disruptive technology (Shomali and Pinkse, 2016; Cardenas et al., 2014). This trend has driven the development of the intelligent electronic devices (IED), with a high level of integration and multifunctional features, which aim to control the DER interconnection with the electrical network (Moreno-Munoz et al., 2010; Real-Calvo et al., 2012). Moreover, these systems have been modularized by means of different standardized interfaces such as the IEEE 1159 (IEEE

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Nomenclature

AC	Alternating Current
BOOL	Boolean
CPU	Central Processing Unit
CRIO	CompactRIO
DAQ	Data Acquisition
DC	Direct Current
DB	Database
DER	Distributed Energy Resources
DSC	Datalogging and Supervisory Control
ENET	Ethernet
ES	Embedded System
FPGA	Field-Programmable Gate Array
GCPV	Grid-Connected Photovoltaic Plant
GOOSE	Generic Object Oriented Substation Event
GPIB	General Purpose Interface Bus standard
GPS	Global Position System
I/O	Input/Output
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
INV	Inverter
LABVIEW	Laboratory Virtual Instrument Engineering Workbench
LV	Low Voltage
MMS	Manufacturing Message Specification
MV	Medium Voltage
NI	National Instruments
PLT	Percentile Long Term Flicker
PMU	Phasor Measurements Units
PQ	Power Quality
PST	Percentile Short Term Flicker
PTP	Precision Time Protocol
PV	Photovoltaic
R&D	Research and Development
RMS	Root Mean Square
RTOS	Real-Time Operative System
SCADA	Supervisory Control And Data Acquisition
SCPI	Standard Commands for Programmable Instruments
SGTB	Smart Grid Test Bench
THD	Total Harmonic Distortion
THDG	Group Total Harmonic Distortion
THDS	Subgroup Total Harmonic Distortion
TTL	Transistor-Transistor Logic
V&I	Voltage and Current
VI	Virtual Instrument
WSN	Wireless Sensor Network

1159, 2009), the IEEE 929 (IEEE 929, 2000), the UL 1741 (UL 1741, 2010), the IEC 62116 (IEC 62116, 2014), the IEC 61727 (IEC 61727, 2004), or the V 0126 -1-1 (V 0126-1-1, 2013). This fact is leading to an increasing development of monitoring and control equipment for the power grid whereas reducing costs at the same time, which provides continuous improvement of the flexibility and the sophistication of these systems. In this context, and thanks to the advances in information technology and communication, the development of high specific level embedded systems (ES) applied to the electricity infrastructure is currently possible. These devices are able to simultaneously perform several tasks that have traditionally been carried out by individual devices, being, therefore capable of reducing losses and detecting any grid problems in order to ultimately avoid the occurrence of a critical scenario such as a lack of supply. An intelligent control system such as the one described can make a decisive contribution to the management of renewable generation. A strategy such as those proposed by the Rochester Institute of Technology, Industrial and Systems Engineering Department (Abikarram and McConky, 2017) is a clear example. This research sought for new alternatives to alleviate some of the burden imposed by renewable energy sources on the grid by coordinating a fleet of industrial machines. The application of instantaneous load smoothing strategies provides a new solution to mitigate the impact of renewable energy sources intermittency on the grid and could provide improved PQ to facilities with integrated renewables (Abikarram and McConky, 2017).

This paper presents the development of a laboratory scale test bench for Smart Grid research. The core of this Smart Grid test bench (SGTB) is an ES with a high computational capacity that has been developed for both real-time data acquisition and multifunctional processing. The system integrates measurement, protection, stability, analysis and PQ control features of the distribution system, as well as event logging, advanced remote applications, and energy balance, all of them in the basic level of signal acquisition. The real-time operation and analysis capabilities provide a platform for researching on many challenging aspects of a real smart power system. This features are in line with the Laboratory-based Smart power system described in Salehi Pour Mehr et al. (2013).

The use of this SGTB in the laboratory of the University of Córdoba allows emulating various real-time scenarios that might be found in the actual power distribution grid, as well as the usage of advanced modeling techniques for the rapid and reliable detection of problems and anomalies in distribution lines or components (Real-Calvo et al., 2016; Moreno-Garcia et al., 2015). Hence, the proposed SGTB is useful for assessing the technologies that enable the progress towards the new model of Smart Grid presented by Gudzius et al. 2011; Ilic 2014, which requires fast event detection and characterization, control of active power injection, smart relays protection, and asymmetric power injection, to name a few.

The generation of amplitude and phase difference unbalances, as well as unbalanced harmonic disturbance eases the testing of three-phase inverters with asymmetric power injection or capabilities of rerouting the energy flow to the grid so the voltage unbalance decrease (Neukirchner et al., 2017). This is also important from the environmental point of view since the achieved power losses reduction can easily be translated to both CO2 emissions and carbon footprint reduction. In brief, the laboratory of the University of Córdoba can be regarded as a useful tool for the development of renewable energy resources as part of the CO2 reduction strategies (Lund et al., 2015) or the evaluation of intelligent metering systems (Zhou and Brown, 2017).

Its main feature over other systems, developed to operate in Smart Grid (Meng et al., 2015; Celeita et al., 2016; Dufour and Belanger, 2014; Guo et al., 2013), is that it integrates a protocol for precisely synchronizing the data collection, and therefore, establishing a high degree of positive correlation over the total surface of a DER. For this aim, as a method of synchronism, the IEEE 1588 standard precision time protocol (PTP) is used (Pallares-Lopez et al., 2011). In the proposed system, DER, i.e. a wind park, a solar inverter or a data concentrator system, can be emulated by simulating an energy resource unit in the IEDs integrated into the SGTB. These IEDs are the real-time programmable controllers

CompactRIO of National Instruments (NI cRIO). Thanks to this built-in SGTB technology, it has been possible to verify in the laboratory of the University of Córdoba a real-time monitoring system for large-scale photovoltaic parks (Moreno-Garcia et al., 2016). An ES with PTP synchronization technology means a disruptive impact on the photovoltaic sector as occurs in other scientific and industrial sectors due to the accurate synchronization and the high degree of determinism that can be reached. Moreover, the SGTB enables the evaluation of IEC 61850 standard model. This model is dedicated to improving the communication between systems integrated into the Smart Grid. Subsequently, the SGTB developed here provides a detailed and comprehensive supervision of the communication devices, analyzing the performance of the IEC 61850 communications through quantifying the data processing and modeling times of this standard (Gonzalez-Redondo et al., 2016).

The organization of the article is as follows. Section 2 describes the ES developed, where the hierarchical structure of SGTB is addressed from both the hardware and the information communication levels. Subsequently, Section 3 describes a case study of the application of SGTB in a grid-connected photovoltaic plant (GCPV). Specifically, some key techniques employed to implement the integrated development environment are presented. Section 4 presents the trials to verify the SGTB's performance as real-time monitoring system installed in a photovoltaic plant connected to the grid. Moreover, in this section, the results of a communication test carried out to analyze the integration of the IEC 61850 standard in the SGTB are presented. Finally, Section 5 contains the conclusions.

2. Overall structure of the smart grid test bench

The details of the SGTB's equipment are introduced in this section. The SGTB proposed is a solution which integrates several measuring and protective devices for an efficient energy management. The conceptual scheme is shown in Fig. 1a, whereas Fig. 1b shows an overview of the facility. In the SGTB the devices can be grouped in four systems, whose features and operation represent different parts of the Smart Grid conceptual architecture. In this way, the simulation system emulates the actual electrical grid, but with the capabilities of disturbing voltages and currents as it would happen the Smart Grid with the presence of DER and distributed consumers with nonlinear loads. The energy flows, as well as the electrical variables are being acquired by the control system with a high temporal resolution and accuracy that guarantee a fast response to events. All this information is accessible and interchanged thanks to the communication system level which implements a bidirectional information flow in parallel which the power system. Finally, the collected measures can be visualized in real-time by means of a monitoring system. Each of these four levels is explained below.

2.1. Hardware emulation system

This test bench had been employed for testing protective algorithms, communication protocols, and control and management functionalities, as well for sensors of measurement test, within the Smart Grid paradigm. Over all by the integration in the system of any of the standards compiled by the IEC here in the "Smart Grid Architecture View" (IEC).

To achieve this, a simulation system to reproduce the behavior of the electrical power generation system, such as the operational state of the generators, lines, transformers, circuit breakers, inverters, loads, etc., is used. This system is composed of a controllable three-phase power supply and a controllable three-phase load. Moreover, both devices can be easily controlled and supervised by means of standard commands for programmable instruments (SCPI) from the general-purpose interface bus standard (GPIB). In this way, the power system joint to the communication and control systems can be used to test the behavior of devices typically used in distributed system for control and supervision, like IEDs or smart meters.

The power supply system that was used in the test is the 3009 ix AC/DC power source of California Instruments which has an integrated network analyzer, as well as a three-phase output rated up to 9 kVA. The power supply is connected to the low voltage network of the laboratory allowing maintaining a pure three-phase sinusoidal system fully balanced and symmetrical. Nevertheless, this ideal waveform can be altered and configured in order to generate any possible perturbation, including line distortion simulation and arbitrary waveform generation, with the aim of analyzing the response under certain load conditions. The power supply can be controlled by means of the front panel keypad or the remote control to configure several functions such as transients, harmonics and arbitrary waveforms generations. Furthermore, the reliability and accuracy of all the measures are guaranteed and confirmed by the integrated acquisition system of the power supply. Thus, the power supply selected is ideal for AC and DC power testing.

The 3091LD AC controllable three-phase load, from California Instruments, can simulate high crest factor and variable power factor load conditions. Measurements such as volt RMS, volt peak, current RMS, current peak, crest factor, true power, apparent power, power factor and frequency can be carried out. Moreover, the load is equipped with an integrated measurement system that provides a second source of values for assuring the correct interconnection between the power supply and the load.

Finally, a data logging and supervisory control (DSC) is used for the configuration and monitoring of the power system composed by the AC power supply and the AC load. This whole system enables to emulate a Smart Grid in the low voltage side, simulating a distributed generator, with the aim of generating not only voltage perturbance but also current deviations, through the AC power supply and the AC load respectively. Test for harmonics (IEC 61000-3-2, 1995), flickers (IEC 61000-3-3, 1994) or immunity (IEC 61000-4-1, 2006) standard can be run with this setup through the graphical programming software LabVIEW by means of an application being executed in the DSC.

2.2. Communication system

The communication system allows for the interconnection between the devices that integrate the SGTB. The communication system consists of a GPIB-ENET Gateway, two devices devoted to synchronization tasks through the IEEE 1588 v2 protocol - grandmaster XLI 1588 and switch IEEE 1588 - and a LINUX-based server for real-time database management.

The SGTB uses a global position system (GPS) module for the synchronization of the PTP master unit (IEEE 1588 v2), which guarantees similar levels of accuracy as those observed in a laboratory environment. As the GPS synchronization is not a high computational demanding task additional features can be integrated into the system, like the coordination of a wireless sensor network for collecting remote measures in a large installation.

To establish determinism conditions in data transferring tasks, the communication system uses the IEC 61850 standard. This is the standard for communication networks and systems for power utility automation. The use of this technology provides smart distributed energy, allowing the integration of intelligent devices that communicate in real time (Moreno-Garcia et al., 2013; Cucinotta et al., 2009) and with a high degree of stability, coordination, and synchronization (Gonzalez-Redondo et al., 2016;

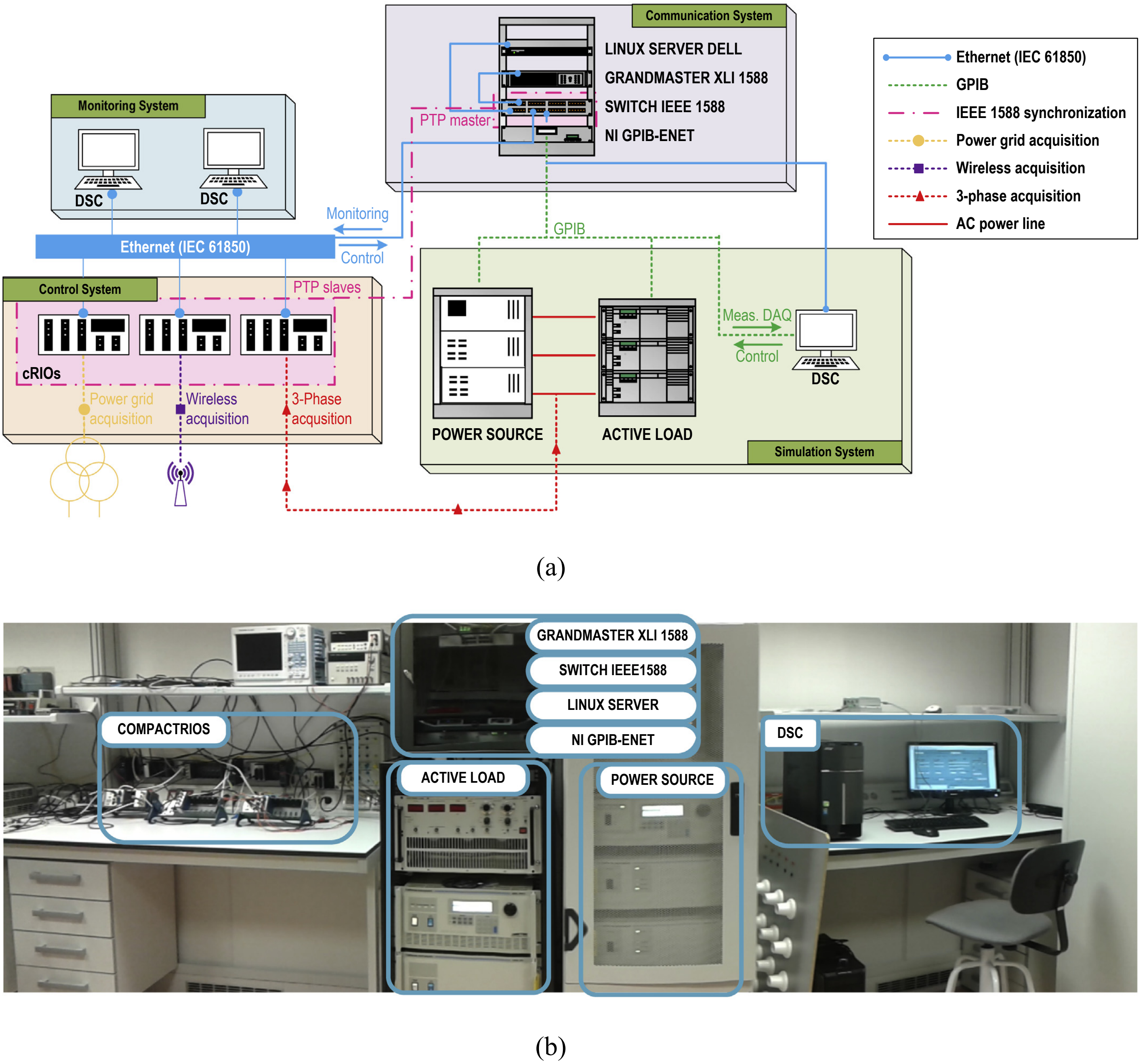


Fig. 1. Overview of the laboratory test bench: (a) Block diagram; (b) Photograph.

Moreno-Munoz et al., 2013).

2.3. Control system

The control system is dedicated to managing the acquisition of signals from the power grid, the three-phase system, as well as sensors of different nature. This system is based on a set of programmable controllers supported by the cRIO platform by National Instruments.

The cRIOs can operate according to international standards such as the IEEE C37.118 (C37.118.1a, 2014) for phasor measurements units (PMU), the IEC 61000-4-30 (IEC 61000-4-30, 2003) for PQ equipment, the IEEE Std. 1588 (Eidson, 2002) for synchronism task of distributed systems or the IEC 61850 (IEC 61850-7-2, 2010) for real-time communications. This platform can be customized as well as upgraded in the field, without changing the hardware, to behave as the different applications above mentioned, so this technology is the ideal approach for smart grid applications that demands evolving functionality and requirements (IEEE Std 1588, 2011; IEEE Std, 2030, 2011).

In the SGTB, the cRIO platforms were configured as computing nodes in a Smart Grid system. Its instrumentation enabled to develop the following applications (National Instruments):

- Programming applications that take advantage of multiple processors/nodes based on the same or mixed architectures. Several embedded controllers can be found in the laboratory, which can be grouped into two categories. On the one hand, cRIOs running the NI LabVIEW real-time operative system (LabVIEW RTOS), NI cRIOs-9074, 9075, 9076 y 9024 can be found. On the other hand, cRIOs running NI Linux real-time (Linux RTOS), NI cRIOs-9030, 9063, 9066 are also available. This wide variety of cRIO platforms allows us to test and verify the performance under several contexts of computational load.

- Sharing data efficiently among multiple processors/nodes that are either directly connected on or remotely connected through a network. In the SGTB, variables must be published in a Web Service to share information between the cRIOs, as well as with remote devices.
- Coordinating all nodes as a single system, including the timing and synchronization between nodes. For this, all the cRIO devices are constantly synchronized with the GrandMaster XLI 1588 having the most accurate time from the PTP standard. The IEEE 1588v2 switch works as Master IEEE 1588 v2 in the local area network to assure synchronization errors lower than 1 us. In this way, even the delays due to the asymmetry of the Ethernet network can be avoided.
- Integrating different types of I/O such as high-speed digital, analog waveforms or phasor measurement measurements. Among the modules employed in this system are current and voltage input modules specialized in signal acquisition for power systems, a wireless communications module, which acts as the coordinator of a wireless sensor network (WSN) composed of distributed nodes, and the synchronization module that acts as the PTP master for the synchronization of the rest of devices using the PTP 1588 standard.

2.4. Monitoring system

The monitoring system is used for the management and supervision of the rest of systems. This system can be configured by means of one or several host computers.

For monitoring purpose LabVIEW software is used. This application is an integrated development environment from National Instruments to measure and automate collecting data from the physical world. LabVIEW allows creating virtual instruments (VI), running under cRIO platforms and host computers, to display the status of the data acquisition equipment and the measurement taken, thus acting as an enterprise SCADA systems.

3. Application in a grid-connected photovoltaic plant

The SGTB presented in the above section can be configured with different control architectures and monitoring systems for testing in the laboratory if those characteristics are suitable for operating in DER situations. In this paper, the application of SGTB in a GCPV is presented as a case study. The system was tested, first, in an emulated laboratory scale scenario at the University of Córdoba and secondly, in a real installation. Concretely, the SGTB's performance was analyzed in a Grid-Connected Utility-Scale PV Power Plant with a nominal power of 6.1 MW located in Cordoba, Spain, and a property of the Magtel Operaciones SL company.

In this case study, the requirements have been defined for processing all needed information in the monitoring of a dispatchable photovoltaic plant. For a PV system of this type one of the first needs is to have the PV system perfectly characterized, providing an accurate knowledge of the operational status of all components that it comprises (Trillo-Montero et al., 2014). To fully characterize the GCPV, detailed information of all values of the different parameters that define the operation of the facility is given. Specifically, a monitoring system that records environmental measures, electricity production measures, and PQ measures, is proposed. To process all measurements recorded with the same timestamp is vital to consider two fundamental aspects, the synchronization of the information recorded by the acquisition devices, and on the other hand, the transmission, and analysis it.

In order to give more details about the SGTB proposed, Fig. 2 will be used, where the configuration scheme for monitoring in real time a large-scale photovoltaic plant connected to the grid can be observed. The structure of the developed system comprises sensors, programmable controllers, and a monitoring and supervision system, along with the different relationships between them. In this section, the above-mentioned methods and parameters selected for the implementation of the monitoring system PV-on time for the solar system are addressed in details.

3.1. Modeling a wireless sensor network (WSN) for a solar facility

A WSN to capture and coordinate measures in various geographically distant points was modeled. Specifically, they were added to register environmental magnitudes, as well as the currents generated by the PV modules into solar field.

The WSN platform consisting of three main components: nodes, gateways, and programmable controllers. The nodes were spatially distributed and comprised the interface with sensors to monitor the selected variables. The acquired data were then transmitted by nodes to the gateway, which connects to a host system which collects, processes, analyzes and presents the measurement data using the LabVIEW software. The employed nodes were the NI-WNS3226 model, having direct connectivity to four sensors at the same time. The programmable controller that was used as the NI-WSN coordinator was the NI cRIO-9075 and configured to collect and process data from wireless nodes distributed field. This required the installation of the NI 9795 module in the cRIO, which acts as the network coordinator responsible for the authentication of the nodes, data transfer management and message storage.

3.2. Modeling a real-time PQ monitoring system in inverters

The measurement of the DC voltage and current generate in the PC field was monitored by mean of various sensors installed at the input of each inverter. Likewise, the AC voltage and current signals are measured with sensors located at the three-phase output of each of the four inverters. In the proposed system (Fig. 2), cRIO equipment is located in each inverter measuring all the parameters required for performing power and energy calculation.

Furthermore, thanks to the three-phase voltage and current measuring points, an analysis of the PQ can be carried out at the point of injection to the grid, which will allow analyzing how the PV plant itself affects the quality of the signal injected into the electrical grid. In order to carry out a complete analysis of the operation of a PV installation, it should be pointed out that having additional equipment, besides the inverters, provides the ability to record possible events and disturbances in the electrical signal generated, especially in the case of large PV installations, or when the number of distributed PV installations is increasing.

The electrical quantities monitored in each inverter compliance with UNE-EN-50160 (UNE-EN 50160, 2007) and IEC 61000-4-30 standards (IEC 61000-4-30, 2003) and can be grouped into power and energy measurements, electrical measurements, voltage and current unbalance measures, voltage event measurements, and harmonic measurements. All of them addition information about the voltage and current injected into the grid. In addition, using all the data recorded from the solar field and the inverters, a series of normalized magnitudes or performance indices can be calculated, allowing an assessment of the production, efficiency, and losses in each component of the PV field (Trillo-Montero et al., 2014).

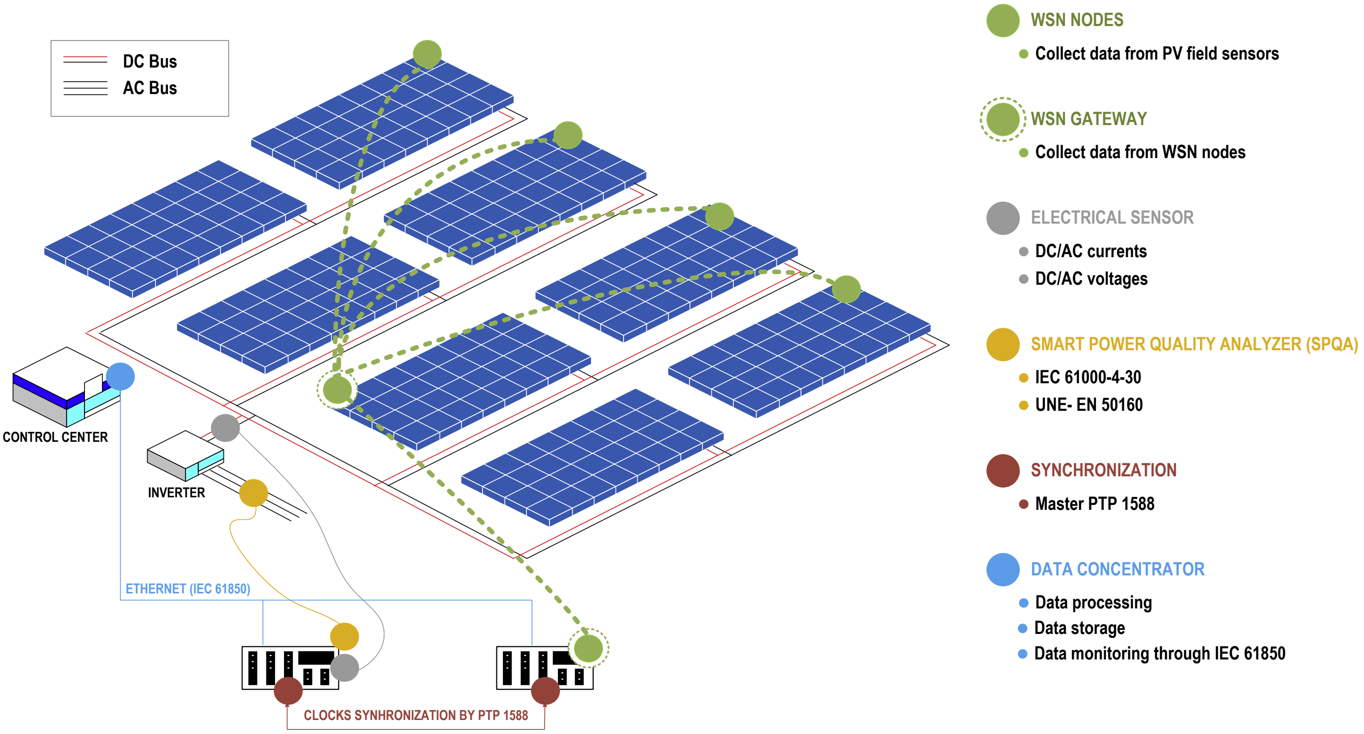


Fig. 2. Proposed scheme for real-time monitoring of a grid-connected PV plant.

3.3. *Modeling a synchronization and communication system for distributed measurements*

One of the main requirements for monitoring a GCPV is to ensure a proper temporal correlation of all measurements. For this aim, a GPS module was integrated into one of the cRIOs controllers. This module did not only allow us to obtain a timestamp for this device, but this cRIO was also acting as a master, implementing the PTP, for synchronizing the clocks of others cRIO, installed in the same facility, which were working as PTP slaves. This conception is illustrated in Fig. 3 where the application of the supervision, control and synchronization devices to a generation and transport system is shown. The main difference between the SGTB located in the laboratory and this one is the usage of a GPS module for the synchronization of the PTP master unit (IEEE 1588 v2), which guarantees similar levels of accuracy as those observed in the controlled environment. Moreover, the GPS synchronization is not a high computational demanding task, so additional features can be integrated into the system as it might be a module acting as the coordinator of a wireless sensor network responsible for collecting remote measures in a large installation.

The usage of the NI cRIO platform together with the NI LabVIEW software allows the development of real-time applications that were able to integrate multifunctional processing technologies, synchronization and communication tasks, all of them essential in a distributed system. Specifically, using the high-speed and instrumentation system, the developing time were drastically reduced since the tasks were programmed in a high level of abstraction.

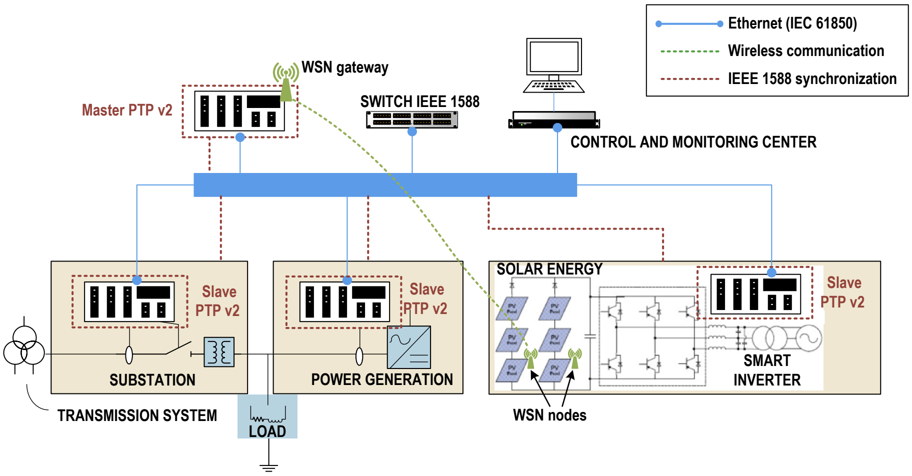


Fig. 3. Synchronization system setup.

Table 1
Link quality levels of the WSN nodes.

Enumerated Values	Numeric Values
Excellent	87 to 100
Good	71 to 86
Fair	55 to 70
Poor	35 to 54
Poor	0 to 34

Furthermore, the enclosure of the NI cRIO devices is suitable for industrial environments, which reduced, even more, the time between development and the application of the technology in the GCPV.

4. Results

In order to validate the proposed SGTB, the results from the case study presented in the above section are presented. These studies revealed the ability of the developed SGTB for testing in the laboratory systems whose characteristics are suitable for operating in DER situations. Therefore, It has succeeded in developing a stable monitoring application that supervises all the sensors distributed in a GCPV and has the processing capacity to calculate production data in real time.

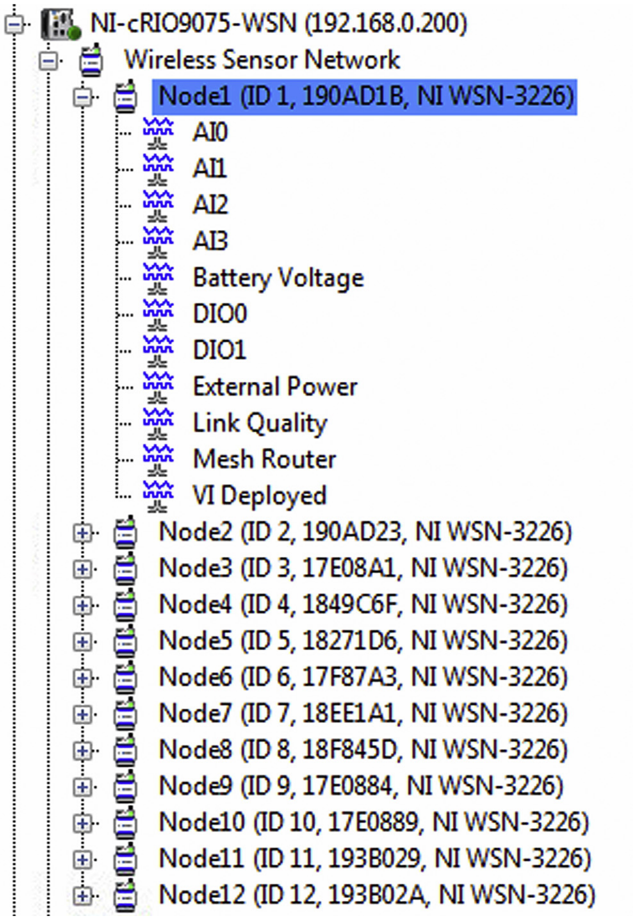
The two implementation stages are addressed in the following sections. First, the results of the laboratory scale implementation of the acquision equipment is presended. Subsequently, its application in the selected GCPV is exposed highlighting the coordination between devices, and the data synchronization as the novel features.

4.1. *Simulation of a real-time monitoring system for a GCPV in the laboratory*

A procedural test of the SGTB configuration was performed in the laboratory to validate the design prior to its deployment in the GCPV. The designed monitoring system was configured with the LabVIEW platform and the cRIOs. A DELL server executed the LabVIEW project that receives the information acquired by different cRIOs and processes the measurements to determine production data, losses, performance, etc. In this system, the calculated measurements could be monitored in a supervisory control and data acquisition (SCADA) application and stored in a database (DB), both processes being performed in real time. Given the magnitude of the project, some results related to the configuration of the cRIO platforms are shown. Moreover, a test for analyzing the influence of data-related factor on the use of IEC 61850 is described.

4.1.1. *Evaluation of the WSN network*

11 spatially-distributed wireless nodes were installed in the laboratory in order to evaluate the link quality of this technology. NI-WSN parent devices (routers and gateways) can only have a maximum of eight end nodes connected to them at a given time. This limitation could be a problem when a node configured as an end node might not be able to join a device node. Therefore, to avoid this and ensure the communication quality, three nodes were configured as mesh routers.



- NI-cRIO9075-WSN (192.168.0.200)
  - Wireless Sensor Network
    - Node1 (ID 1, 190AD1B, NI WSN-3226)
      - AI0
      - AI1
      - AI2
      - AI3
      - Battery Voltage
      - DIO0
      - DIO1
      - External Power
      - Link Quality
      - Mesh Router
      - VI Deployed
    - Node2 (ID 2, 190AD23, NI WSN-3226)
    - Node3 (ID 3, 17E08A1, NI WSN-3226)
    - Node4 (ID 4, 1849C6F, NI WSN-3226)
    - Node5 (ID 5, 18271D6, NI WSN-3226)
    - Node6 (ID 6, 17F87A3, NI WSN-3226)
    - Node7 (ID 7, 18EE1A1, NI WSN-3226)
    - Node8 (ID 8, 18F845D, NI WSN-3226)
    - Node9 (ID 9, 17E0884, NI WSN-3226)
    - Node10 (ID 10, 17E0889, NI WSN-3226)
    - Node11 (ID 11, 193B029, NI WSN-3226)
    - Node12 (ID 12, 193B02A, NI WSN-3226)

Fig. 5. Configuration of the WSN nodes in the LabVIEW project.

The WSN was tested in the laboratory, verifying the correct configuration of both the data acquisition part and the communication system. The operation of the nodes was monitored in LabVIEW for about a month. For this, the WSN nodes were declared in the LabVIEW project with a simple interval of transmission of 5 s. LabVIEW monitors the status of the nodes and the list of digital and analog signals belonging to each node as shown in Fig. 5.

For the first one, temperature sensors were connected to each of

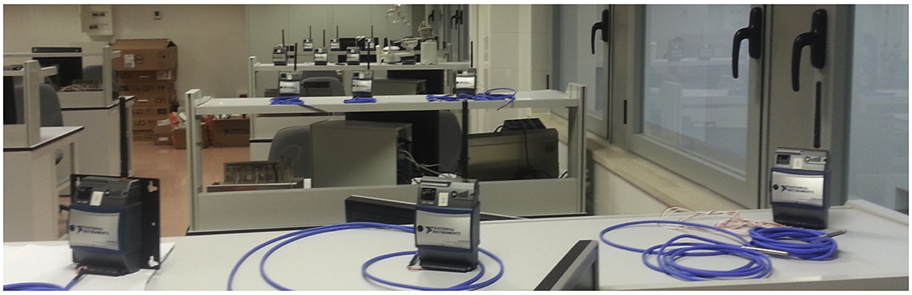


Fig. 4. Calibration of the WSN nodes in the laboratory.

node asserting that the received data matched the expected one. As far as the communication was regarded, the quality link indicator sent by the nodes was also recorded an evaluated. NI sets five ranges for signal quality (Table 1). During the laboratory test, the link quality of all the nodes was always monitored at the maximum range.

Fig. 4 shows an image of the layout of the WSN nodes in the laboratory.

4.1.2. *Configuration for measurements on inverters*

The acquisition of the measures for the analysis of the PQ is made through software implementation called virtual instruments (VIs) developed with the graphical programming tool NI LabVIEW. These code blocks are run in real time and with a high level of determinism in the cRIO platforms.

For the acquisition of these signals, the project was configured in a way that allowed having an embedded application running on each cRIO, and the FPGA and the processor to be handled in real time (Fig. 6 (a)). This was possible thanks to the installation of the FPGA and real-time modules in the cRIO chassis. The next step was to configure the I/O modules in each chassis and integrate that action into the project. LabVIEW includes the advanced auto-detection functionality of the I/O modules, so the configuration of the NI RIO modules was simplified (Fig. 6 (b)). The various acquisition channels were then configured, one to capture 3 AC voltages and 1 DC voltage and the other to capture 3 AC current and one DC current, matching the above-discussed signal to be monitored in each inverter.

In the VIs of each cRIO, routines devoted to determine the PQ of the generated electrical signal in real time were implemented for each inverter. For this aim, the communication with the FPGA was done through a critical priority loop included in the RTOS whereas the processing of the PQ measurements was performed in parallel to the data acquisition loop. In this way, the measurement acquisition and the PQ calculations were carried out with a high level of determinism. Fig. 7 shows a calibration test of the measurement system performed in the SGTB.

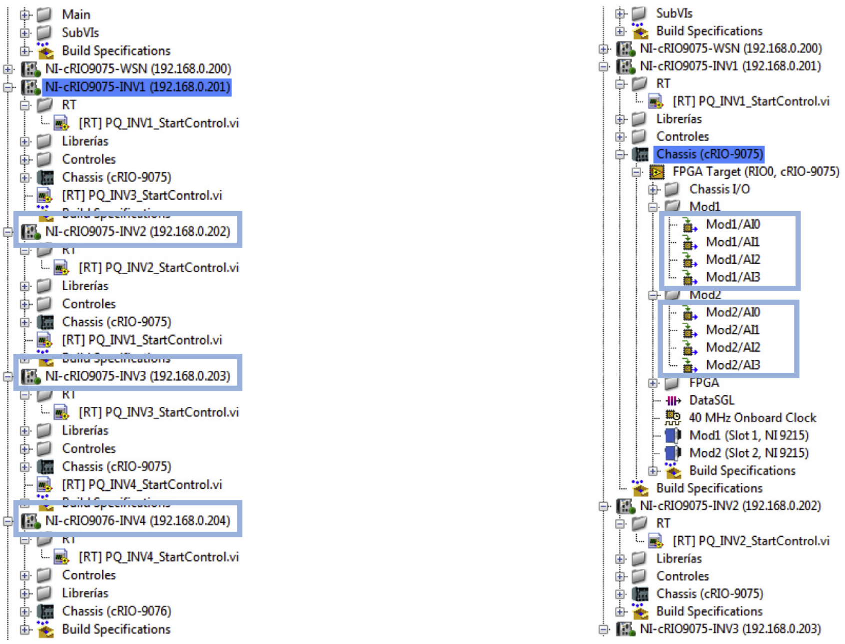
An analysis of the processing capacity of the NI cRIO-9075 and the NI cRIO-9024 models was performed. In both cRIO platforms, a real-time deterministic processing of all information and data was possible by means of the LabVIEW RTOS integrated into their chassis. Furthermore, in addition to the tPQ events and the steady state signal variations, such as harmonics and voltage unbalance, the power and energy production were determined in the RTOS from measurements, performed according to several electromagnetic compatibility standards (IEC 61000-4-30, 2003; UNE-EN 50160, 2007; IEC 61000-4-7, 2002; IEC 61000-4-15, 2010).

From all the processing tasks, the most critical ones are those related to PQ analysis that took place directly in the controllers. Thus, the performances of both sets of equipment for this process were determined and collected in Table 2. The NI cRIO-9075 supposes a more economical solution but it has lower processing capabilities than the NI cRIO-9024, which prevents the registering of some events such as rapid voltage changes or unbalance factors. Therefore, and according to objectives of the case study, the NI cRIO-9075 was selected for monitoring the inverters in the PV plant.

4.1.3. *Test of communications based on the IEC 61850 standard*

The last trial considered for testing of the SGTB was the integration of the IEC 61850 standard so the communications performance can be analyzed in the laboratory. For this aim, National Instruments provides the NI Industrial Communications for IEC 61850 software, which implements a library with a wide range of VIs and properties. By means of this software and LabVIEW, it is feasible to develop IEC 61850 applications for the IEDs. Between some of the possibilities that this system offers it should be pointed out that the VIs can be programmed either using GOOSE (Generic Object Oriented Substation Event) or MMS (Manufacturing Message Specification) properties and therefore they can implement both communication services.

This case study focused on the measurement of the transfer



(a) (b)

Fig. 6. Configuration of the cRIOs in the LabVIEW project: (a) Detail of cRIOs's configuration; (b) Detail of the acquisition module in a cRIO.

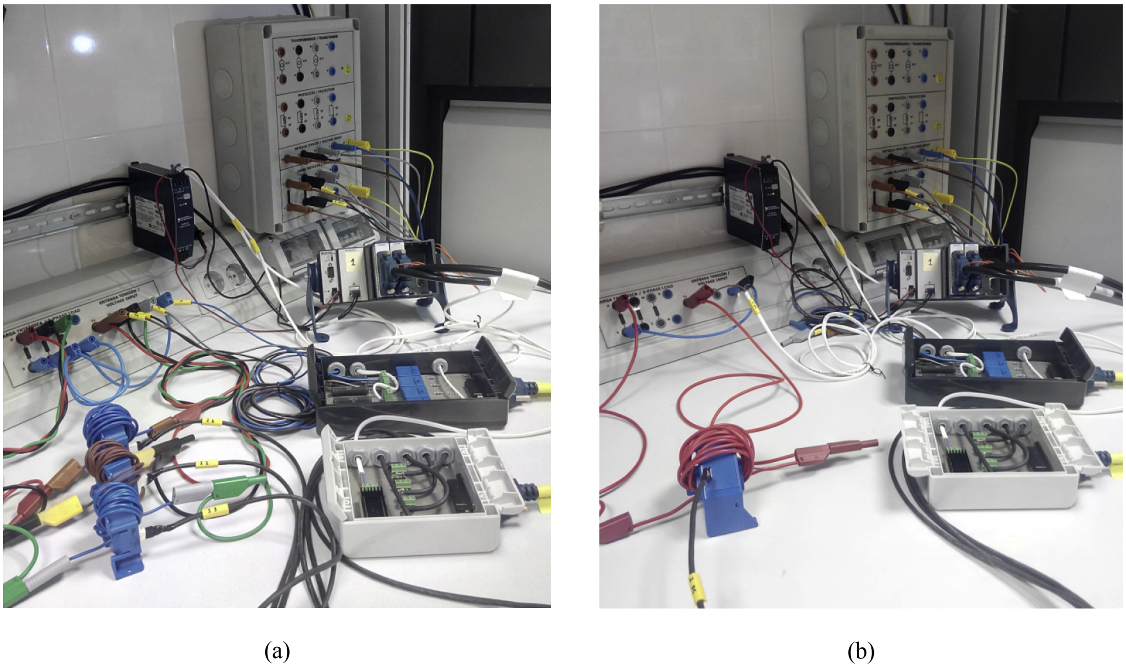


Fig. 7. Calibration of the conditioning circuits developed jointly to the CompactRIO programmable controller (cRIO): (a) AC test; (b) DC test.

times when the GOOSE messaging is employed. In order to avoid the influence of other factors, which have been previously studied by others authors, such as the network topology, the bandwidth or the traffic, a simplified architecture was selected composed of two cRIO devices connected by means of a Moxa PT-7710 switch. One of the devices was acting as publisher, whereas the other was a subscriber as it can be observed in Fig. 8. Due to the restrictions of the communication library, only those cRIO models which are able to implement the GOOSE communication services were used. Specifically, the NI cRIO-9066, with a dual-core process running at 667 MHz and an FPGA Artix-7, and the NI cRIO-9030 with a central processing unit (CPU) dual-core at 1.33 GHz and the 70T FPGA were chosen. Both devices were also equipped with NI-9402 modules composed of 4 bidirectional digital channels. In Fig. 8 the Ethernet connections are represented with dashed red lines, whilst the solid blue line illustrates the digital TTL (Transistor-Transistor Logic) connections between the publisher and the subscriber. Such basic configuration contributes to minimizing the influence of the network time.

The methodology followed for measuring the performance was similar to the one proposed in (Gonzalez-Redondo et al., 2016), by means of digital signals. In the publisher side, a digital output is activated just before the transmission of the data is performed, and remains in this state until the VIs responsible for this transmission

Table 2
Performance of programmable controllers for PQ measurements.

Measurements	Computed	Intervals	NI cRIO-9075	NI cRIO-9024
One-cycle fundamental power values	3-phase	1c[a]	Yes	Yes
Power values	3-phase	10c	Yes	Yes
Energy values	3-phase	10c	Yes	Yes
Aggregated frequency 10 s values	1-phase	10c,3s,10s,10m	Yes	Yes
Voltage RMS values	3-phase	10c,3s,10s,10m	Yes	Yes
Current RMS values	3-phase	10c,3s,10s,10m	Yes	Yes
Vrms-under	3-phase	10c,3s,10s,10m	Yes	Yes
Vrms-over	3-phase	10c,3s,10s,10m	Yes	Yes
Voltage events	3-phase	1c	No	Yes
Rapid voltage changes events	3-phase	1/2 c	No	Yes
Voltage THD	3-phase	10c,3s,10s,10m	Yes	Yes
Voltage THDG	3-phase	10c	No	Yes
Voltage THDS	3-phase	10c	No	Yes
Current THD	3-phase	10c	No	Yes
Pst	3-phase	10c	No	Yes
Plt	3-phase	2h	Yes	Yes
Voltage unbalance factor	1 value for 3-phase	10c	No	Yes
Fundamental voltage unbalance factor	1 value for3-phase	10c,3s,10s,10m	Yes	Yes
Fundamental voltage symmetrical components	1 value for 3-phase	10c	No	Yes
Current unbalance factor	1 value for 3-phase	10c	No	Yes
Fundamental current unbalance factor	1 value for 3-phase	10c	No	Yes
	Processing time		140 ms	90 ms

[a] Cycle.

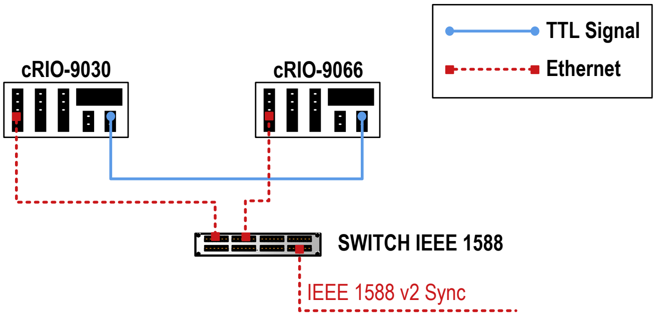


Fig. 8. Setup details of the IEC 61850 test.

are finalized. This signal is wired to the subscriber so it can identify the instants when the transmission processing started and finished. The processing time in the subscriber side was calculated using the absolute timestamp of the instants that indicated the beginning and the end of the processing for receiving the datagram. In Fig. 9 the different times defined by the IEC 61850 standard are shown. These times are the publisher processing time (T_a), the subscriber processing time (T_c), and the total transfer time (T_t) that includes T_a, T_c, and the network time (IEC 61850-5, 2013). In addition, the parameter T_1 was defined that indicates the time elapsed between the beginning of the transmission and the time in which the first data was received by the subscriber.

Based on this configuration several tests could be run in order to analyze the communications performance. One of these tests was to assess the influence over the transfer time of the number of object being transmitted. For this aim, 10 scenarios were tested, transmitting and increasing number of objects in each one. For each scenario, 1000 samples of the time parameters were recorded for later processing. The mean values of the test were used in the comparisons.

The selected data type for the test scenarios was the BOOL (Boolean) type. The first test was conducted for one BOOL data, the second one for two and so on. All the objects were included in the same logical node. The obtained results are shown including the mean values of T_t and T_1 for each scenario.

As it can be observed in Fig. 10, where the time magnitude is represented along with the number of object being transmitted, the number of data being transmitted directly affect the transfer times (T_t) since the frame length is increased. This relationship seems to be almost linear. However, in the case of T_1 the time measured was similar for all the tests.

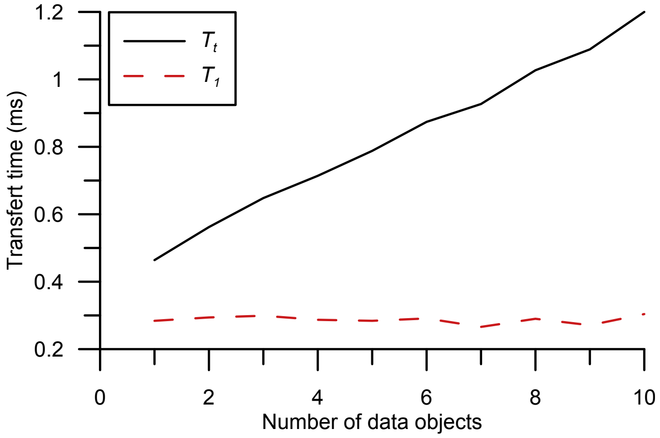


Fig. 10. Influence of the number of data over the transfer time.

4.2. Deployment in the grid-connected photovoltaic plant selected

In this section the results regarding the deployed of the previously tested SGTV in the selected GCPV are addressed. First, the installation of the WSN network is described. Secondly, the synchronization procedure of the cRIO equipment is exposed. Finally, some performance results of the plant are discussed.

Fig. 11 shows an aerial photograph of the GCPV selected. The implemented monitoring system has been installed in the transformation center of one of the 8 clusters in which the plant is divided. In the figure, this is indicated by a shaded area that highlights the region of the solar trackers monitored by the SGTB. In the analyzed TC four photovoltaic sections of 100 kW converge, being each one composed of 22 solar trackers which inject its power to the grid through an inverter.

In the PV plant described, the previously commented wireless sensors that climatological parameters and the direct current generated by each group of panels forming a solar tracker have been distributed.

In the area where the inverters are located, the sensors that measure the voltage and current from the solar field, as well as the value of these quantities transformed at the output of each inverter were deployed. In each inverter, a cRIO has been located to analyze the quality of the signal generated by the inverter. In addition, each cRIO has been configured with the PTP protocol to establish a correct temporal correlation of the data measured by the different sensors. To this end, a fifth cRIO has been installed operating as a

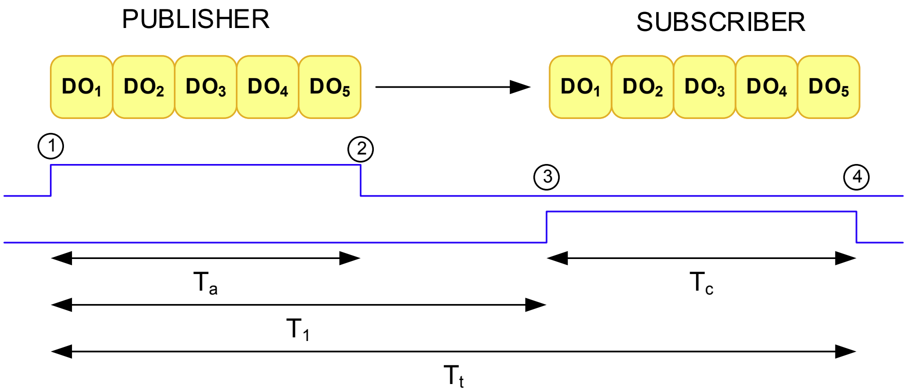


Fig. 9. Setup details for measuring the transfer times of the IEC 61850 test.

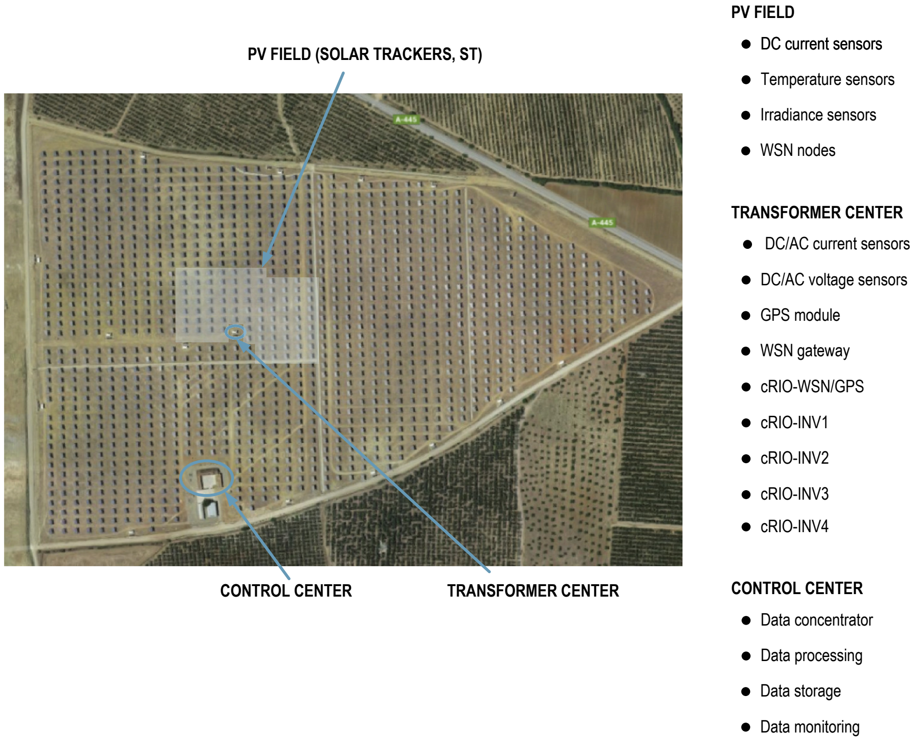


Fig. 11. Aerial photography of the monitored GCPV.

PTP master and performing the function of recording the measurements performed by the WSN nodes.

Finally, the server where the LabVIEW project in charge of performing the control is integrated was deployed in the control center of the plant. In this project, the measures are processed to obtain the previously commented information about the operation of the plant. The quantities recorded allowed determining production data, losses, performance, etc. Furthermore, the calculated measurements are monitored in an application and stored in a DB, both processes being performed in real time.

4.2.1. *WSN network*

The WSN nodes were installed according to the structure of the Utility-Scale PV Power Plant shown in Fig. 12 The solar trackers are distributed in parallel and the distance between them can be either 14 or 20 m. An image of a WSN node installed in the cabinet under the tracker is also shown in Fig. 13.

During plant operation, the WSN gateway Link Quality signal with the WSN nodes was significantly lower than the laboratory tests. As proof of this, Fig. 14 shows the Link Quality values for three nodes. Table 3 shows the Link Quality status for all nodes installed. Nevertheless, as shown in Fig. 13 the enclosure in which the nodes were installed can drastically have affected the wireless signal.

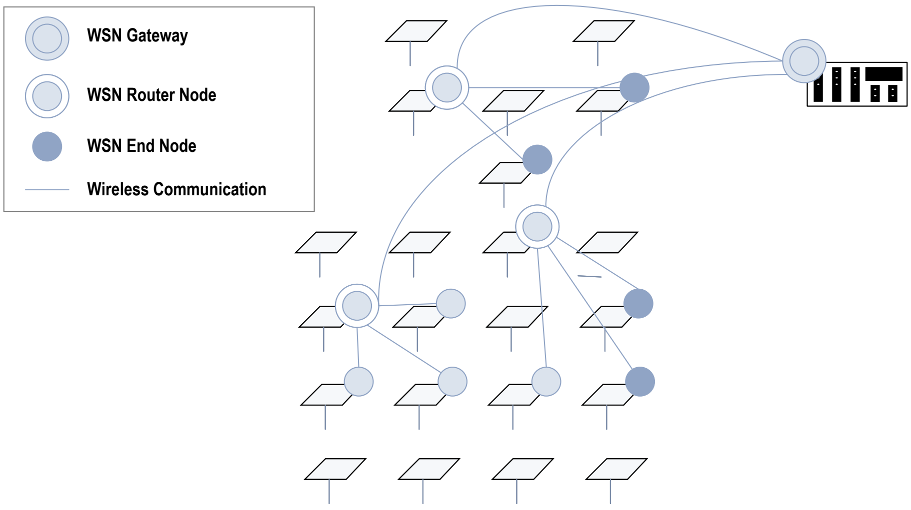


Fig. 12. Wireless sensor network (WSN) nodes configuration.

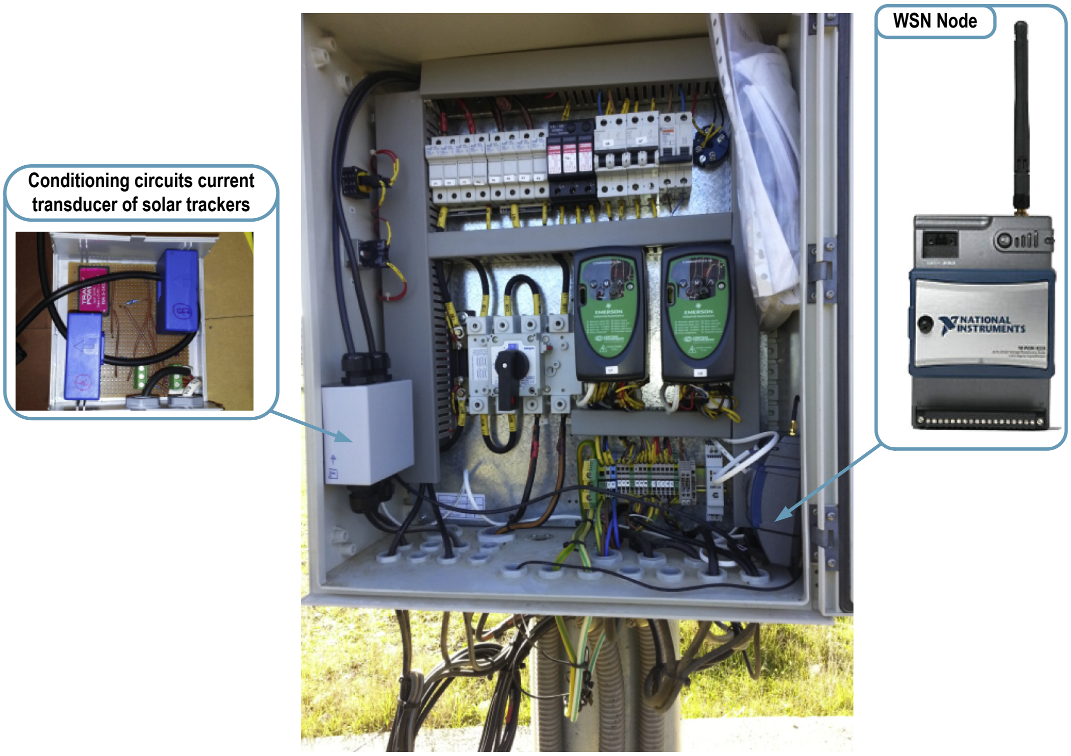
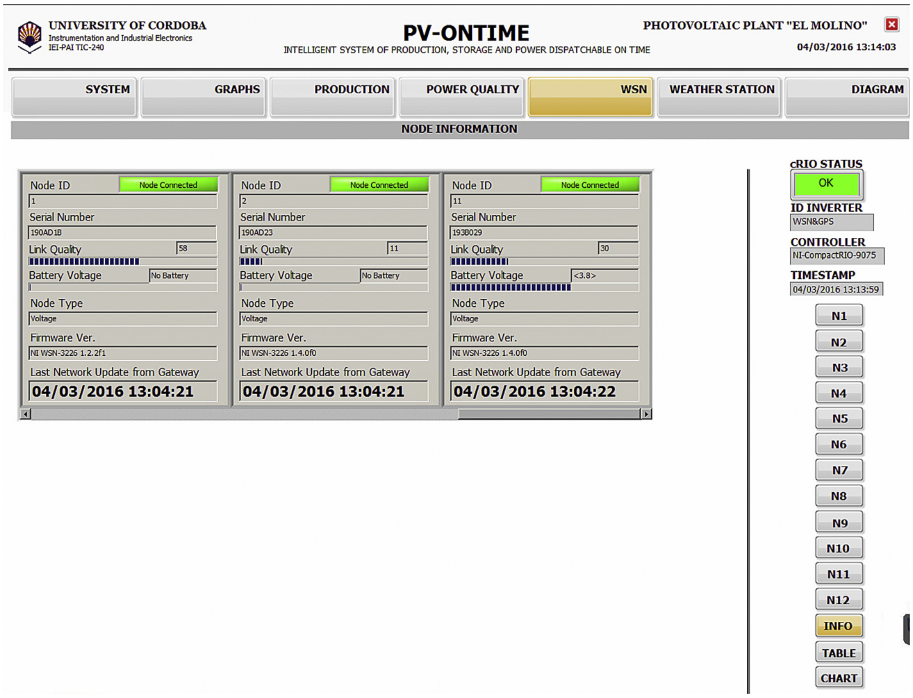


Fig. 13. WSN node in solar trackers in grid-connected PV plant.

4.2.2. *Synchronization of acquisition equipment deployed in plant*

This hierarchy between the master PTP (cRIO-WSN) and the four PTP slaves (cRIO-INV1, cRIO-INV2, cRIO-INV3, and cRIO-INV4) is set with a priority parameter. The cRIO which acts as master PTP must be configured with the lowest priority and the rest of cRIOs, which would act as slaves, must be configured with a higher priority. Once established the synchronization hierarchy, the clocks of each slave are aligned with the master.

For the installation, a priority of 80 has been assigned to NI cRIO-WSN, to act as a master in the synchronization of cRIOs. The remaining modules maintained the same priority, 128, except for the equipment located in the cRIO-INV2 inverter that was



Node ID: 1 (Node Connected)
Serial Number: 190AD1B
Link Quality: 58
Battery Voltage: No Battery
Node Type: Voltage
Firmware Ver.: NI WSN-3226 1.2.2f1
Last Network Update from Gateway: 04/03/2016 13:04:21

Node ID: 2 (Node Connected)
Serial Number: 190AD23
Link Quality: 11
Battery Voltage: No Battery
Node Type: Voltage
Firmware Ver.: NI WSN-3226 1.4.0f0
Last Network Update from Gateway: 04/03/2016 13:04:21

Node ID: 11 (Node Connected)
Serial Number: 193B029
Link Quality: 30
Battery Voltage: <3.8>
Node Type: Voltage
Firmware Ver.: NI WSN-3226 1.4.0f0
Last Network Update from Gateway: 04/03/2016 13:04:22

cRIO STATUS: OK
ID INVERTER: WSN&GPS
CONTROLLER: NI-CompactRIO-9075
TIMESTAMP: 04/03/2016 13:13:59

Fig. 14. Link Quality monitored for three nodes.

Table 3
Link quality levels of the WSN nodes.

ID Node	Link Quality	Value
1	58	Fair
2	11	Poor
3	37	Poor
4	54	Poor
5	44	Poor
6	28	Poor
7	47	Poor
8	41	Poor
9	50	Poor
10	25	Poor
11	30	Poor

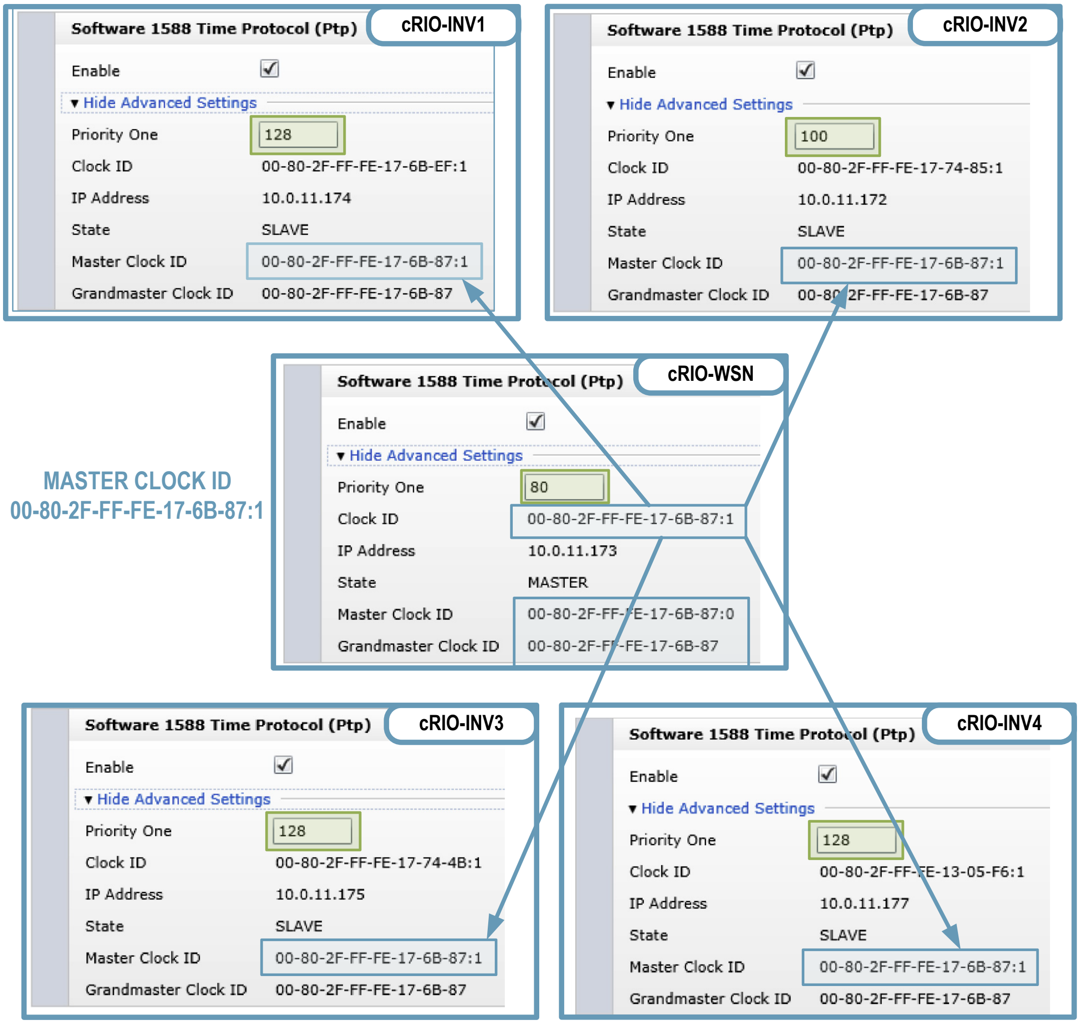
configured with priority 100. This can act as a substitute for the master clock, especially in the situation of loss of communication improving the reliability of the system.

In Fig. 15 the identification of the master located in the PV plant can be observed. The reference ID can be displayed on the "GrandMaster Clock". In addition, it also identifies the ID "Master Clock" with the same reference. In addition, the figure shows the configuration achieved by the cRIOs located in the inverters. In all cases, the "Master Clock" ID can be displayed as a reference. Synchronization ensures simultaneous capture and correlation of measurements of all parameters.

4.2.3. GCPV performance analysis through the data monitored by the SGTB

Among the different PQ parameters evaluated by this system, an experimental testing concerning the effect of the irradiance in the quality of the signal injected into the grid has been carried out. For this aim, PQ parameters at the output of an inverter, the active power (P_a) and the voltage THD (THD_V), has been compared with the solar irradiance (G_i). The research was based on data recorded in the DB of the developed monitoring system for three cases: a clear day (Fig. 16), a cloudy day (Fig. 17) and a day with sunny spells (Fig. 18). The results depicted that there is an effect of solar radiation in the PQ of the signal produced by the inverter.

The left graphs, 16(a), 17(a) and 18(a), show the active power and the solar irradiance. For the three cases studied, the active power P_a produced by the inverter is linearly dependent with the solar irradiance G_i. The right graphs, 16(b), 17(b) and 18(b), show the 9th harmonic voltage amplitude registered at the output of the inverter. Each horizontal line of these graphs corresponds to one channel or phase. As shown in these graphs, a high harmonic distortion is produced when the inverter starts and ends to produce energy. The spikes on the THD_V in the three phases are easily visible. These instants match with sunrise and sunset, low solar irradiance



cRIO-INV1
Software 1588 Time Protocol (Ptp)
Enable ☑
▾ Hide Advanced Settings
Priority One: 128
Clock ID: 00-80-2F-FF-FE-17-6B-EF:1
IP Address: 10.0.11.174
State: SLAVE
Master Clock ID: 00-80-2F-FF-FE-17-6B-87:1
Grandmaster Clock ID: 00-80-2F-FF-FE-17-6B-87

cRIO-INV2
Software 1588 Time Protocol (Ptp)
Enable ☑
▾ Hide Advanced Settings
Priority One: 100
Clock ID: 00-80-2F-FF-FE-17-74-85:1
IP Address: 10.0.11.172
State: SLAVE
Master Clock ID: 00-80-2F-FF-FE-17-6B-87:1
Grandmaster Clock ID: 00-80-2F-FF-FE-17-6B-87

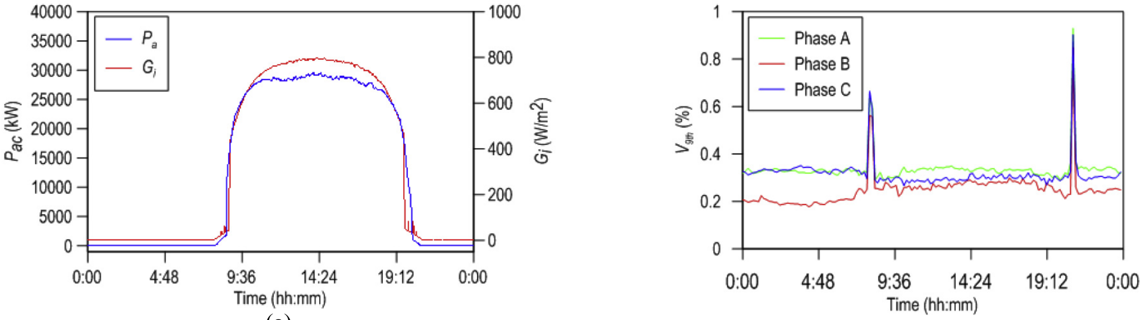
cRIO-WSN
Software 1588 Time Protocol (Ptp)
Enable ☑
▾ Hide Advanced Settings
Priority One: 80
Clock ID: 00-80-2F-FF-FE-17-6B-87:1
IP Address: 10.0.11.173
State: MASTER
Master Clock ID: 00-80-2F-FF-FE-17-6B-87:0
Grandmaster Clock ID: 00-80-2F-FF-FE-17-6B-87

MASTER CLOCK ID
00-80-2F-FF-FE-17-6B-87:1

cRIO-INV3
Software 1588 Time Protocol (Ptp)
Enable ☑
▾ Hide Advanced Settings
Priority One: 128
Clock ID: 00-80-2F-FF-FE-17-74-4B:1
IP Address: 10.0.11.175
State: SLAVE
Master Clock ID: 00-80-2F-FF-FE-17-6B-87:1
Grandmaster Clock ID: 00-80-2F-FF-FE-17-6B-87

cRIO-INV4
Software 1588 Time Protocol (Ptp)
Enable ☑
▾ Hide Advanced Settings
Priority One: 128
Clock ID: 00-80-2F-FF-FE-13-05-F6:1
IP Address: 10.0.11.177
State: SLAVE
Master Clock ID: 00-80-2F-FF-FE-17-6B-87:1
Grandmaster Clock ID: 00-80-2F-FF-FE-17-6B-87

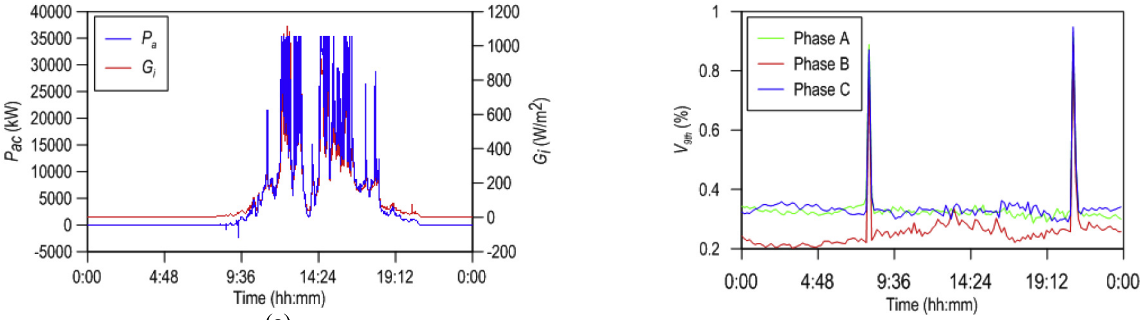
Fig. 15. Configuration of the synchronization system.



(a)

(b)

Fig. 16. Clear day.



(a)

(b)

Fig. 17. Cloudy day.

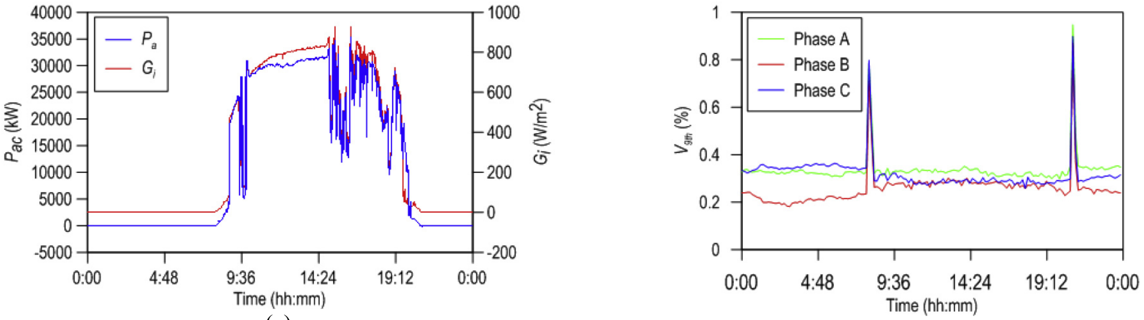
conditions, so the THD_V is also strongly influenced by the solar irradiance G_i.

5. Conclusions

The present study provided a real-time laboratory scale test bench to emulate different scenarios in the Smart Grid. The proposed platform, based on a high computational capacity ES, was designed to implement a multifunctional and flexible architecture. It consisted of a configurable power system and an advanced supervisory and control system that enabled the acquisition and the processing in real time. Moreover, a high precision synchronization system, as well the IEC 61850 communication standard, was incorporated, main features that differentiate this system compared to the ones previously developed. These capabilities have proved to be useful to test Smart Grid technologies, such as protection, PQ monitoring, communication or DER integration, providing great benefits in order to achieve a more secure and reliable power system.

A case study has been presented to show the performance of the system such as the verification of the monitoring system for a grid-connected power plant. This system was characterized by including a wide range of measurements from distributed devices that are processed in real time, with strict temporal correlation conditions. The use of the SGTB platform was also essential to validate in the laboratory the real-time processing, synchronization, and communication systems, as well as the logging of all the records in a DB before the final deployment of the system in the photovoltaic plant.

The implementation of the proposed methodology in the grid-connected PV plant selected using controllers with RTOS allowed the establishment of priorities so that the acquisition and processing of a wide range of measurements of operation and management with a high degree of stability, coordination, and



(a)

(b)

Fig. 18. Sunny spell day.

synchronization in real time. Due to the use of a WSN network in the PV modules and solar trackers, it was possible to calculate the state of production and the wiring losses. Thanks to the added sensors in the inverters and the RTOS controllers, it was possible to obtain more information than the provided by inverters, detecting and classifying PQ measurements, as well as obtaining information about their performance. The information recorded by the deployed system can be considered relevant for operators of grid-connected PV plants because it allows them to monitor in real time the state of production, the quality of the injected signal into the grid and the performance of the generation equipment. Moreover, results show the effectiveness of the proposed platform to establish the same timestamp in a DER framework. As demonstrated in the paper, the platform was equipped with an adaptable hardware and a configurable management architecture that enabled it to emulate technologies focused on the future energy system in order to increase its resilience and security.

Acknowledgments

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References

Abikarram, J.B., McConky, K., 2017. Real time machine coordination for instantaneous load smoothing and photovoltaic intermittency mitigation. J. Clean. Prod. 142, 1406–1416. http://dx.doi.org/10.1016/j.jclepro.2016.11.166.

Amini, M.H., Nabi, B., Haghifam, M.-R., 2013. Load management using multi-agent systems in smart distribution network. In: 2013 IEEE Power Energy Soc. Gen. Meet. IEEE, pp. 1–5. http://dx.doi.org/10.1109/PESMG.2013.6672180.

Amini, M.H., Karabasoglu, O., Ilic, M.D., Boroojeni, K.G., Iyengar, S.S., 2015. ARIMA-based demand forecasting method considering probabilistic model of electric vehicles' parking lots. In: 2015 IEEE Power Energy Soc. Gen. Meet. IEEE, pp. 1–5. http://dx.doi.org/10.1109/PESGM.2015.7286050.

Amini, M.H., Frye, J., Ilic, M.D., Karabasoglu, O., 2015. Smart residential energy scheduling utilizing two stage Mixed Integer Linear Programming. In: 2015 North Am. Power Symp. IEEE, pp. 1–6. http://dx.doi.org/10.1109/NAPS.2015.7335100.

Amini, M.H., Moghaddam, M.P., Karabasoglu, O., 2017. Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks. Sustain. Cities Soc. 28, 332–342. http://dx.doi.org/10.1016/j.scs.2016.10.006.

Baghaee, H.R., Mirsalim, M., Gharehpetian, G.B., Talebi, H.A., 2017. A decentralized power management and sliding mode control strategy for hybrid AC/DC microgrids including renewable energy resources. IEEE Trans. Ind. Inf. http://dx.doi.org/10.1109/TII.2017.2677943, 1–1.

C37.118.1a, 2014. IEEE Standard for Synchrophasors for Power Systems, 0_1-57.

Cardenas, J.A., Gemoets, L., Ablanedo Rosas, J.H., Sarfi, R., 2014. A literature survey on Smart Grid distribution: an analytical approach. J. Clean. Prod. 65, 202–216. http://dx.doi.org/10.1016/j.jclepro.2013.09.019.

Celeita, D., Hernandez, M., Ramos, G., Penafiel, N., Rangel, M., Bernal, J.D., 2016. Implementation of an educational real-time platform for relaying automation on smart grids. Electr. Power Syst. Res. 130, 156–166. http://dx.doi.org/10.1016/j.epsr.2015.09.003.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2016. Photovoltaic energy systems with battery storage for residential areas: an economic analysis. J. Clean. Prod. 131, 460–474. http://dx.doi.org/10.1016/j.jclepro.2016.04.157.

Cucinotta, T., Mancina, A., Anastasi, G.F., Lipari, G., Mangeruca, L., Checcozzo, R., Rusina, F., 2009. A real-time service-oriented architecture for industrial automation. IEEE Trans. Ind. Inf. 5, 267–277. http://dx.doi.org/10.1109/TII.2009.2027013.

Dufour, C., Belanger, J., 2014. On the use of real-time simulation technology in smart grid research and development. IEEE Trans. Ind. Appl. 50, 3963–3970. http://dx.doi.org/10.1109/TIA.2014.2315507.

Eidson, J., 2002. IEEE 1588 standard for a precision clock synchronization protocol for networked measurement and control systems. In: 2nd ISA/IEEE Sensors Ind. Conf. IEEE, pp. 98–105. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1159815 (accessed 12 June 12 2015).

Gonzalez-Redondo, M.J., Moreno-Munoz, A., Pallares-Lopez, V., Real-Calvo, R.J., 2016. Influence of data-related factors on the use of IEC 61850 for power utility automation. Electr. Power Syst. Res. 133, 269–280. http://dx.doi.org/10.1016/j.epsr.2015.12.028.

Gudzius, S., Markevicius, L.A., Morkvenas, A., 2011. Characteristics of fault detection system for smart grid distribution network. Electron. Electr. Eng. 112, 123–126 (accessed 11 March 2015). http://www.eejournal.ktu.lt/index.php/elt/article/view/461.

Guo, F., Herrera, L., Murawski, R., Inoa, E., Wang, C.-L., Beauchamp, P., Ekici, E., Wang, J., 2013. Comprehensive real-time simulation of the smart grid. IEEE Trans. Ind. Appl. 49 http://dx.doi.org/10.1109/TIA.2013.2240642.

IEC - Smart Grid Standards Map, (n.d.). http://smartgridstandardsmap.com/ (accessed 17 May 2017).

IEC 61000-3-2, 1995. Limits - Limits for Harmonic Current Emissions (equipment input current up to and including 16 A per phase.

IEC 61000-3-3, 1994. Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection.

IEC 61000-4-1, 2006. Testing and Measurement Techniques - Overview of IEC 61000-4 Series.

IEC 61000-4-15, 2010. Electromagnetic Compatibility (EMC) - Part 4-15: Testing and Measurement Techniques - Flickermeter - Functional and Design Specifications. International Electrotechnical Commission. http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/44482 (accessed 6 October 2014).

IEC 61000-4-30, 2003. Electromagnetic compatibility (EMC). Part 4-30: testing and measurement techniques. Power quality measurements methods. Int. Electrothecnical Com.

IEC 61000-4-7, 2002. Electromagnetic Compatibility (EMC) - Part 4-7: Testing and Measurement Techniques - General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto. International Electrotechnical Commission. http://webstore.iec.ch/webstore/webstore.nsf/ArtNum_PK/29073?OpenDocument (accessed 6 October 2014).

IEC 61727, 2004. Photovoltaic (PV) systems —Characteristics of the utility interface. Int. Electrothecnical Com.

IEC 61850-5, 2013. Communication Networks and Systems for Power Utility Automation - Part 5: Communication Requirements for Functions and Device Models. IEC Webstore. https://webstore.iec.ch/publication/6012.

IEC 61850-7-2, 2010. Communication Networks and Systems for Power Utility Automation - Part 7-2: Basic Information and Communication Structure - Abstract Communication Service Interface (ACSI). IEC Webstore. https://webstore.iec.ch/publication/6015 (accessed 4 April 2016).

IEC 62116, 2014. Utility-interconnected photovoltaic inverters – test procedure of islanding prevention measures. Int. Electrothecnical Com.

IEEE 1159, 2009. IEEE Recommended Practice for Monitoring Electric Power Quality c1–81. http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=5154067 (accessed 10 March 2014).

IEEE 929, 2000. IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems i-.

IEEE Std 1588, 2011. IEEE Draft Standard Profile for Use of IEEE Std. 1588 Precision Time Protocol in Power System Applications, pp. 1–67.

IEEE Std 2030, 2011. IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-use Applications, and Loads, pp. 1–126.

Ilic, M., 2014. Integration of heterogeneous small test beds for emulating large-scale smart power grids the emphasis on cyber architectures. In: 2014 Work. Model. Simul. Cyber-physical Energy Syst. IEEE, pp. 1–8. http://dx.doi.org/10.1109/MSCPES.2014.6842394.

Kamyab, F., Amini, M., Sheykhha, S., Hasanpour, M., Jalali, M.M., 2016. Demand response program in smart grid using supply function bidding mechanism. IEEE Trans. Smart Grid 7, 1277–1284. http://dx.doi.org/10.1109/TSG.2015.2430364.

Lund, P.D., Mikkola, J., Ypyä, J., 2015. Smart energy system design for large clean power schemes in urban areas. J. Clean. Prod. 103, 437–445. http://dx.doi.org/10.1016/j.jclepro.2014.06.005.

Meng, L., Savaghebi, M., Andrade, F., Vasquez, J.C., Guerrero, J.M., Graells, M., 2015. Microgrid central controller development and hierarchical control implementation in the intelligent microgrid lab of Aalborg University. In: 2015 IEEE Appl. Power Electron. Conf. Expo. IEEE, pp. 2585–2592. http://dx.doi.org/10.1109/APEC.2015.7104716.

Moreno-Garcia, I.-M., Moreno-Munoz, A., Domingo-Perez, F., Pallares-Lopez, V., Real-Calvo, R.-J., Santiago-Chiquero, I., 2013. Implementation of a smart grid inverter through embedded systems. Electron. Electr. Eng. 19, 3–6. http://dx.doi.org/10.5755/j01.eee.19.3.1378.

Moreno-Garcia, I.M., Moreno-Munoz, A., Gil-de-Castro, A., Real-Calvo, R., Palacios-Garcia, E.J., González-Redondo, M.J., 2015. Grid-tied smart inverter safety functionality: fast power quality event detection. Inf. Midem J. Microelectron. Electron. Components Mater. 45 (3), 204–2015.

Moreno-Garcia, I., Palacios-Garcia, E., Pallares-Lopez, V., Santiago, I., Gonzalez-Redondo, M., Varo-Martinez, M., Real-Calvo, R., 2016. Real-time monitoring system for a utility-scale photovoltaic power plant. Sensors 16, 770. http://dx.doi.org/10.3390/s16060770.

Moreno-Munoz, A., De la Rosa, J.J.G., Real-Calvo, R.J., Pallares, V., 2010. Embedding measurement in distribution automation systems. In: 2010 IEEE Int. Symp. Ind. Electron. IEEE, pp. 3722–3727. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5637698 (accessed 25 February 2014).

Moreno-Munoz, A., Pallares-Lopez, V., Gonzalez de la Rosa, J.J., Real-Calvo, R., Gonzalez-Redondo, M., Moreno-Garcia, I.M., 2013. Embedding synchronized measurement technology for smart grid development. IEEE Trans. Ind. Inf. 9, 52–61. http://dx.doi.org/10.1109/TII.2012.2209659.

Smart Grid Ready Instrumentation - National Instruments, (n.d.). http://www.ni.com/white-paper/14529/en/ (accessed May 8, 2017).

Neukirchner, L., Görbe, P., Magyar, A., 2017. Voltage unbalance reduction in the domestic distribution area using asymmetric inverters. J. Clean. Prod. 142, 1710–1720. http://dx.doi.org/10.1016/j.jclepro.2016.11.119.

Pallares-Lopez, V., Moreno-Munoz, A., Gonzalez-Redondo, M., Real-Calvo, R., Moreno-Garcia, I.M., Flores Arias, J.M., de Castro, A.G., de la Rosa, J.J.G., 2011. Synchronism with software-based IEEE 1588–2008 for smart grid. In: 2011 IEEE Int. Symp. Ind. Electron. IEEE, pp. 1237–1242. http://dx.doi.org/10.1109/ISIE.2011.5984335.

Real-Calvo, R.J., Moreno-Munoz, A., Pallares-Lopez, V., Gonzalez-Redondo, M.J., Moreno-Garcia, I.M., 2012. Design of an intelligent electronic device to control a private microgrid. In: 2012 IEEE Second Int. Conf. Consum. Electron. IEEE, Berlin, pp. 99–101. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6336492 (accessed 17 April 2015).

Real-Calvo, R., Moreno-Munoz, A., Gonzalez-De-La-Rosa, J., Pallares-Lopez, V., Gonzalez-Redondo, M., Moreno-Garcia, I., 2016. An embedded system in smart inverters for power quality and safety functionality. Energies 9, 219. http://dx.doi.org/10.3390/en9030219.

Salehi Pour Mehr, V., Mohammed, A., Mazloomzadeh, A., Mohammed, O., 2013. Laboratory-based smart power system, Part I: design and system development. In: 2013 IEEE Power Energy Soc. Gen. Meet. IEEE. http://dx.doi.org/10.1109/PESMG.2013.6672643, 1–1.

Shomali, A., Pinkse, J., 2016. The consequences of smart grids for the business model of electricity firms. J. Clean. Prod. 112, 3830–3841. http://dx.doi.org/10.1016/j.jclepro.2015.07.078.

Trillo-Montero, D., Santiago, I., Luna-Rodriguez, J.J., Real-Calvo, R., 2014. Development of a software application to evaluate the performance and energy losses of grid-connected photovoltaic systems. Energy Convers. Manag. 81, 144–159. http://dx.doi.org/10.1016/j.enconman.2014.02.026.

UL 1741, 2010. Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources.

UNE-EN 50160, 2007. Voltage Characteristics of Electricity Supplied by Public Distribution Networks. CENELEC. http://shop.bsigroup.com/ProductDetail/?pid=000000000030139621 (accessed 6 October 2014).

V 0126-1-1, 2013. Automatic Disconnection Device between a Generator and the Public Low-voltage Grid. VDE.

Zhou, S., Brown, M.A., 2017. Smart meter deployment in Europe: a comparative case study on the impacts of national policy schemes. J. Clean. Prod. 144, 22–32. http://dx.doi.org/10.1016/j.jclepro.2016.12.031.