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Implementation of a Smart Grid Inverter through Embedded Systems

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Abstract—**This paper focuses on the integration of the inverter into the Smart Grid environment. This work consists of developing an Intelligent Electronic Device (IED) which can perform measurement and protection functions. Our work focuses on the development of a platform for the real-time monitoring, measurement of power quality and electrical parameters, the implementation of the main functions of a protective relay and the detection of power quality events, in particular sags, swells, transients and faults. This IED becomes part of the inverter electronic equipment as an embedded system. The following work presents the proposed IED architecture for multifunctional processing, synchronization and communication in order to fulfil the requirements of Distributed Generation grid connection. The main goal here is detection and evaluation of voltage disturbances with higher-order statistics. Different types of disturbances are tested and results obtained are successful.**

Index Terms—**Power quality, power system measurements, power system protection, smart grids.**

I. INTRODUCTION

Led its expansion by the boom of the photovoltaic market, the inverter has consolidated as a key piece for the integration of Distributed Energy Resources (DER) in the grid. A review of the different topologies and control systems can be found in [1], [2]. Although important steps have been taken to develop more efficient and reliable inverters, it is still necessary to redouble the efforts to reach the levels achieved by this equipment in other sectors. This paper focuses on inverter aspects such as communication compatibility with international standards, power quality protection and predictive tools for equipment self-diagnosis and maintenance. This work follows the legislation and international standards related to grid interconnection of renewable energy sources presented in [3].

We are still in a transition scenario wherein, despite the normative efforts made in the scope of the interconnection, there still exist numerous barriers which prevent a real increase of the DER presence [4], [5]. This is the reason why the work continues with plans of performance which were recently established. An inverter oriented to work in a Smart Grid environment has not being developed at all. The designed inverter must communicate the measurements and the necessary parameters of operation [6], [7], in real or deferred time, so that the diagnosis algorithms and functions can be run. Therefore, we stand before a scenario in which the communication technologies play a fundamental role for the development of systems which allow the management and control of the integration of DER [8]. It is necessary a deep analysis of the requirements of each communication subsystem, synchronization between nodes and scalability in distributed or centralized networks, facing the election of the optimal technology for each one. In this sense, the new standards of wireless communication arisen in the last years [9], [10] open up many possibilities that must be explored as an effective alternative solution to other technologies traditionally used in the sector.

The following section proposes an Intelligent Electronic Device (IED) design which can be embedded into the inverter equipment. This IED provides the inverter with measurement and protection functions, making it ready to be used in the new model of Smart Grid with the characteristics described in [11], i.e. fast registration of the events, transmission to the power network control system, smart relay protection devices, etc.

II. IED ARCHITECTURE

A high capacity IED that guarantees the computational accuracy needed to detect critical events is proposed to monitor the power quality (PQ) and establish a protection system. Fig. 1 shows the architecture of the system and Fig. 2 shows a block diagram which represents the IED procedure that involves sampling, processing and detection. The chosen architecture for designing the system is CompactRIO (cRIO), manufactured by National Instruments (NI), which has already been successfully used for PQ monitoring [12].

The system combines a real-time processor with a FPGA core which has direct access to input/output modules. The acquisition and control software has been developed using NI LabVIEW. Fig. 3 shows the system interface.

Platform's features have been defined taking into account PQ, protective relay functions and synchronization standards. The system controller is a NI CompactRIO 9074,

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which supports compatibility with NI voltage and current input modules NI 9225 and NI 9227. Voltage and current in the three lines of a three-phase system are measured simultaneously in these modules. Having a sampling rate of 50 kS/s not only can they measure voltage and current (and hence power) but they can also be used to determine some PQ parameters like harmonics, frequency, noise, etc.

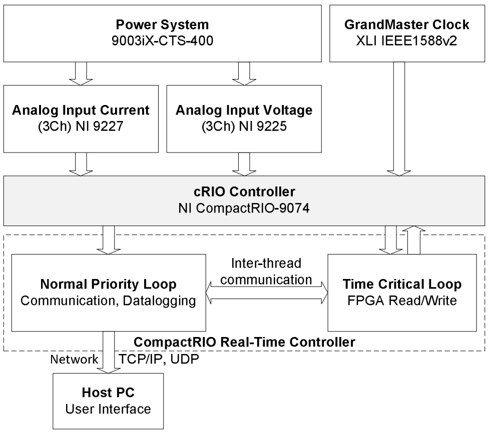


Fig. 1. Platform architecture.

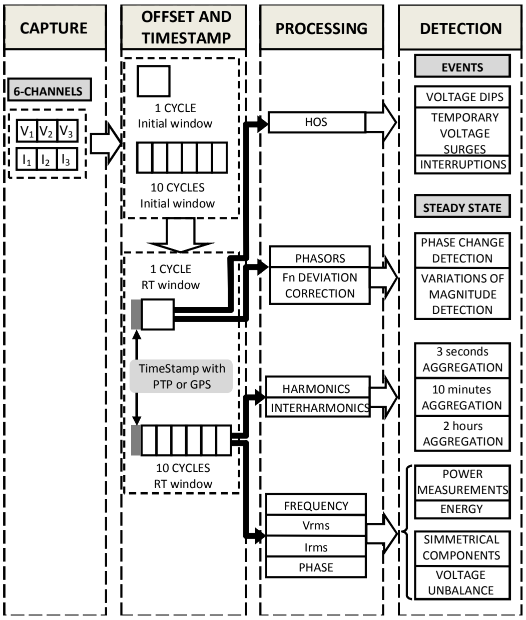


Fig. 2. IED functional design.

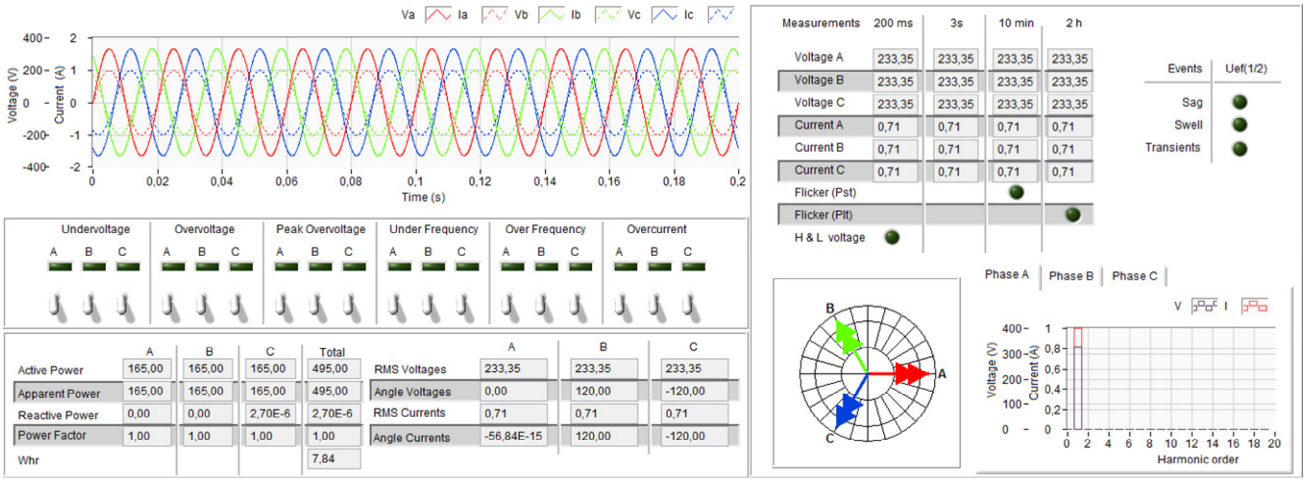
The AC programmable power source 9003iX CTS 400, manufactured by California Instruments, was selected to test the platform. This power system integrates a transient network analyzer and a three-phase output; it can also run several standardized PQ tests (voltage sags, swells, flickers, etc.).

The cRIO controller runs as an IEEE 1588 slave to the GrandMaster Clock XLI IEEE1588v2, which works as a Precision Time Protocol (PTP) master to synchronize the event measurements [13].

A full real time operating embedded system (ES) is configured using LabVIEW. The ES integrates two parallel loops, a time critical loop and a normal priority loop. The real time controller runs the time critical loop to communicate with the FPGA, time critical routines must be allocated in this loop. Voltage and current signals acquisition and their processing are included in this high priority loop. The time critical loop is executed with the maximum priority every 10 ms. The normal priority loop is used to set communication with the remote PC host, data visualization and additional analysis. Four loops which run in parallel have been implemented. The first loop is executed every 100 ms with the second priority level. This loop runs window generation functions, it uses two sliding windows of one and ten cycles (50 Hz) which are updated every half cycle (IEC 61000 4 30). The other three loops are executed every 200 ms (third priority level). One of them is used to perform PQ measurements; another loop deals with power and energy measurements and the last one is in charge of disturbance detection.

PQ features are processed depending on their deterministic or stochastic nature, as it was shown in Fig. 2. PQ events like voltage dips or surges change the Gaussian behavior of the normal 50/60 Hz sinusoidal waveform. The PQ stochastic events detection is based on higher order statistics (HOS), skewness (third order) and kurtosis (fourth order), which are employed to recognize non-Gaussian processes [14]. Results section shows several tests with HOS analysis. Apart from PQ events, the system can also measure and detect steady state signal features such as harmonics and interharmonics, voltage unbalance and power and energy measurements.

Several voltage and current parameters such as average



Measurements	200 ms	3s	10 min	2 h
Voltage A	233,35	233,35	233,35	233,35
Voltage B	233,35	233,35	233,35	233,35
Voltage C	233,35	233,35	233,35	233,35
Current A	0,71	0,71	0,71	0,71
Current B	0,71	0,71	0,71	0,71
Current C	0,71	0,71	0,71	0,71
Flicker (Pst)			●	
Flicker (Plt)				●
H & L voltage	●			

Events	Uef(1/2)
Sag	●
Swell	●
Transients	●

	A	B	C	Total
Active Power	165,00	165,00	165,00	495,00
Apparent Power	165,00	165,00	165,00	495,00
Reactive Power	0,00	0,00	2,70E-6	2,70E-6
Power Factor	1,00	1,00	1,00	1,00
Whr				7,84

	A	B	C
RMS Voltages	233,35	233,35	233,35
Angle Voltages	0,00	120,00	-120,00
RMS Currents	0,71	0,71	0,71
Angle Currents	-56,84E-15	120,00	-120,00

Fig. 3. Virtual instrument graphic user interface.

peak and RMS values are calculated in order to simulate the functionality of the protective relay. The protection functions which have been integrated in the ES are the most typical: over/undervoltage (59, 59N, 27, 27N), peak overvoltage (5911), over/under frequency (810, 81U) and overcurrent (50, 50N, 51VC2, 51N) [15].

III. RESULTS

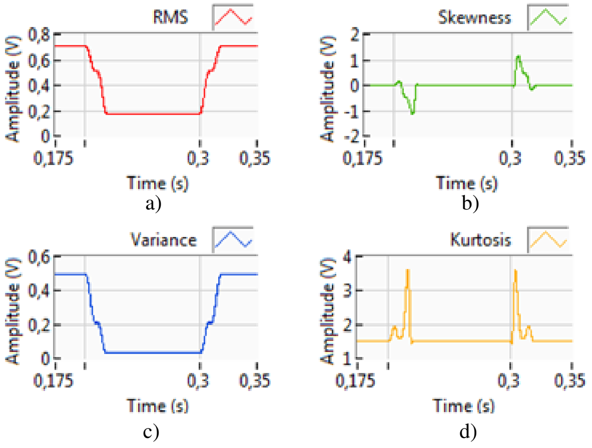
A HOS analysis was performed to the electrical disturbances of Table I. Intensity, initial time and duration time are shown in the table.

TABLE I. PQ DISTURBANCES DURING TESTS.

Event	***Intensity***	***Time reference***	***Init.***	***Dur.***
Sag	75%	Seconds	0,2	0,1
Swell	75%	Seconds	0,2	0,1
Transient	Impulsive 80%	Seconds	0,2	0,005
	Notch 80%	Seconds	0,21	0,005
Underfrequency	50%	Cycles	8	10
OverFrequency	50%	Cycles	8	10

The next figures show RMS, variance, skewness and kurtosis values for each disturbance. The PQ event detection is possible due to the differences between resulting waveforms after the HOS analysis. HOS analysis is applied in every signal cycle (20 ms).

Firstly, Fig. 4 shows the results of the sag test whereas Fig. 5 provides the swell results. The transient test is shown in Fig. 6.



a) b) c) d)

Fig. 4. Sag HOS analysis.

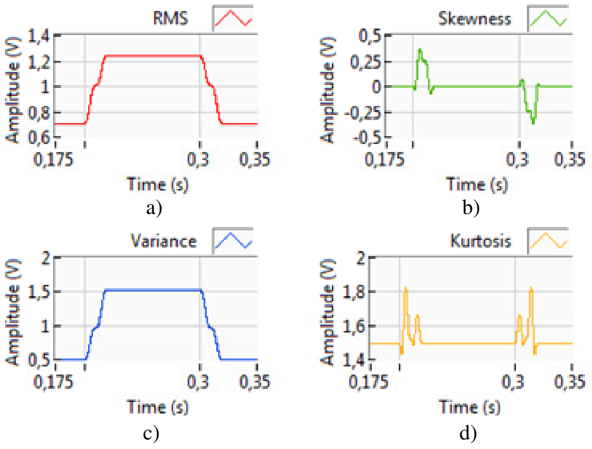


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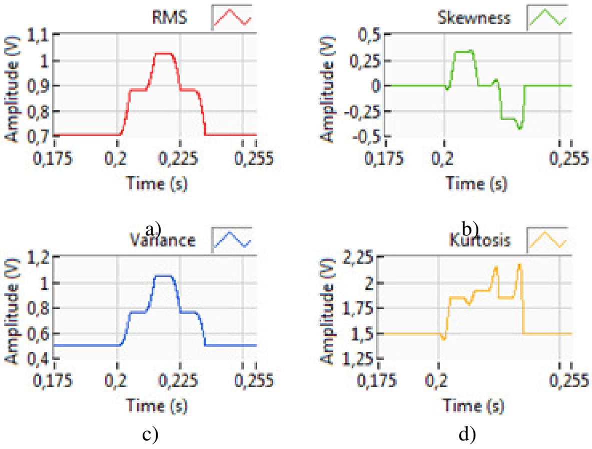
Fig. 5. Swell HOS analysis.



a) b) c) d)

Fig. 6. Transient HOS analysis.

Finally, underfrequency and overfrequency test results are shown in Fig. 7 and Fig. 8, respectively.

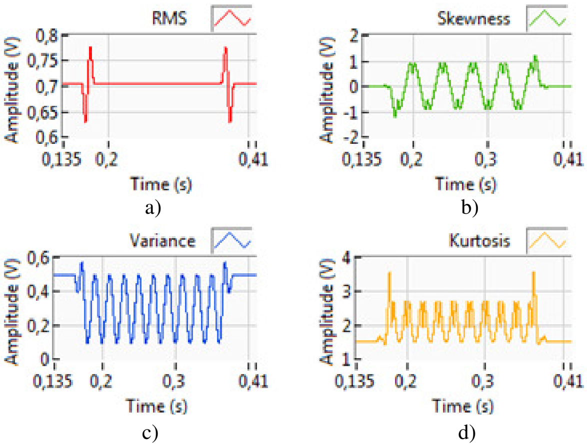


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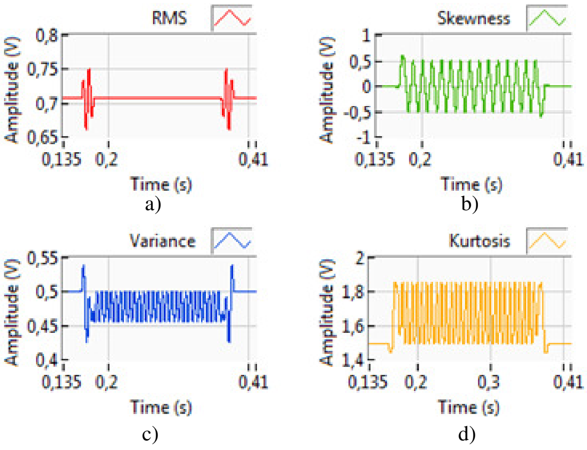
Fig. 7. Underfrequency HOS analysis.



a) b) c) d)

Fig. 8. Overfrequency HOS analysis.

Results show that amplitude variations, without altering the shape of the waveform, keep the skewness and kurtosis values, and the variance gives information of the new amplitude. Kurtosis changes with the sinusoidal shape, characterizing the signal's symmetry via the skewness.

The subjacent power-event classification technique could follow the following procedure. The first parameter to contrast is the frequency of the events. The window length (20 ms) allows a classification, resulting constant values for 50 Hz events and non-stable values for other frequencies. If the tested signal shows constant values (events of 50 Hz), skewness would be the next parameter to be tested. The skewness informs about the symmetry of the signal. Hence, 50 Hz symmetrical signals would exhibit constant skewness of 0, and 50 Hz asymmetrical signals would be associated to other constant values. Moreover, if the tested signal shows a constant skewness with value 0 (50 Hz symmetrical signal), additional information of the signal could be obtained from its kurtosis. A 50 Hz symmetrical signal with constant kurtosis valued 1.5 is associated to a sine wave. Non-sinusoidal 50 Hz symmetrical shapes have kurtosis values different from 1.5. Finally, if the tested signal shows a constant skewness valued 0 and a constant kurtosis of 1.5 (50 Hz sinusoidal signal), the event will be a sag or a swell (or healthy signal) depending on its amplitude's variation.

The algorithm is noise tolerant, behaving as expected up to a SNR = 30 dB. A practical approach has been performed using real-life signals from the IEEE working group P1159.3. Under real conditions the algorithm behaves properly with an accuracy of the 83%.

IV. CONCLUSIONS

A Smart Grid Inverter Interface for monitoring the power quality and establish a protection system has been described in this paper. Furthermore the system guarantees computational accuracy needed to real-time critical events detection and classification. It has been shown how it is possible to have measurement and protection functions in a single device with the proposed ES architecture and software. In addition, hardware and software flexibility of this technology allows the design of different types of devices with the same architecture but with different scales or levels of computing power to suit different Smart Grid applications.

Several tests have been performed with a three-phase power supply to real-time monitoring of power quality, electrical measurements and implement the major functions of a protective relay. To the HOS method, used to enhance characterization of these events, the power system was configured as single-phase which is able to run most of PQ disturbances achieving a great success in performance, proving the system to be suitable for the detection of critical events. The advantage of the proposed method is the early event detection respect to the traditional method used to this end as is the RMS case.

Future work will include experimental tests with remote data sent to the main control system and programming the FPGA to acquire signals every 10 ms so that there is a correspondence between embedded measuring and the power converter.

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