# Power Quality Measurements Embedded in Smart Lighting Systems

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***Abstract*—Considering the three main infrastructure of the actual power system (generation, transmission and distribution), where the latter receives least attention towards the modernizing grid. However, in the new context of smart grid, the distribution network plays an important role and topics related to monitoring of the power quality parameters are of great relevance to achieve the so called smart distribution network, providing valuable and reliable information to be used in control and protection schemes and also representing an important asset which aids distribution utilities and consumers to diagnose and fix the system's problems besides enabling regulators with tools for measuring the quality of services supplied by utilities. In this way, the proposed work aims at the development of a modular and smart device to be attached in public lighting systems, enabling the control and management of the lamp's parameters as well as to measure some power quality indicators from the distribution system and providing a communication infrastructure for the information exchange with a supervisory system.**

***Keywords—Local measurements, Power quality parameters, Signal processing, Smart lighting device, Street lighting system***

## I. INTRODUCTION

The power quality parameters have been a central point of study to many researchers group due to its importance for factories, power distribution companies and final consumers. There are some standards to classify and measure the electromagnetic events related to the power quality and amongst them it is cited the IEC 61000 standard [1].

According to the IEC standard, these events can be classified by duration, signal amplitude and its spectral content. The common events found in the electrical system and that are discussed in this work are the harmonics, interharmonics, interruption, short and long voltage variations. These disturbances cause various degrading effects on the power grid, such as overload in the capacitors, power loss and reduction in equipment life-span [2].

As can be seen in [3], almost all street lighting systems are composed by obsolete equipment as well as by old techniques. Additionally, the current street lighting system does not have a communication network infrastructure [4]. In this sense, to obtain useful information from the luminaire, such as energy consumption and defective lamp, is not easy. However, owing the fast development of devices and computational process, using smart features and communication technologies, the street lighting is evolving from a conventional to a more intelligent system, increasing its capability to transmit on-line data and providing, in this way, opportunities for monitoring and automating the system.

The attractiveness revolves around the possibility to perform dimming remotely, acquire data regarding fault conditions and energy consumption [5]. Nevertheless, it is necessary a luminaire that offer flexibility and high efficiency, which in this context, the technology that meets all necessary requirements besides having several advantages over others is the LED [6].

Some papers were published in order to overcome modernization of the lighting and distribution systems through the usage of available devices and resources as well as to maximize its cost saving. For instance, in [7] is discussed a web-based system to be used to manage urban road lighting aiming for power-saving utilization of public lighting systems and in [12] is proposed a remote monitoring unit to be attached in distribution transformer to evaluate the power quality parameters of the distribution network. Note that since the distribution system is more complex and with more ramifications, the implementation of a communication infrastructure to provide data exchange and analysis is not trivial.

Concerning the power quality parameters, there are several equipment available commercially in order to monitor the quality features of the electrical systems. As discussed in [11], nowadays, the power quality monitoring of the distribution system is usually accomplished with smart meters, protection relays, fault recorders, among others and they do not measure all the power quality parameters specified by common standards. Additionally, these devices are expensive, sometimes inaccessible or have limitations to identify certain problems. Due to this fact, in this work is proposed a modular and smart device capable to be integrated in any lighting system, allowing the control and management of the lamp's parameters as well as to measure the electromagnetic events of the power grid, representing in this way a powerful tool for utilities as well as for consumers.

This paper is organized as follows. In Section II, the necessary requirements for the processing and communication network as well as a detailed description of the proposed smart device are presented. In Section III is discussed the signal processing methodology used for estimating important

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parameters for power quality monitoring. In Section IV are shown the developed hardware, the simulation and experimental results. Finally, in Section V are given the conclusions of this work.

## II. Concept of the Smart Lighting Device

The general and global concept of the smart lighting device and all components that work together with it, are discussed in [10]. The main idea of the proposed smart system is shown in Fig. 1. This smart module is connected between the luminaire and the power grid. The status information of both grid and lamp are sent to a central supervisory system, which is responsible for saving the data in a certain period of time, analyze and monitor possible failures as well as to send commands.

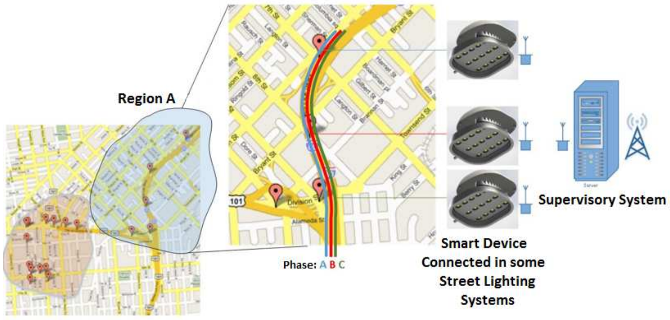



Fig. 1. Concept of the proposed smart management and control system.

The present work aims to describe in more detail all the processing and communication requirements, focusing on the algorithm to estimate the power quality parameters, according to the IEC standard. In this sense, all the methodology to acquire and process the received signal is described. Moreover, it is also presented in this section all the necessary requirements to embed the smart module in any luminaire that has the same communication protocol, providing, in this way, other functions to the conventional lighting system.

### A. *Processing Requirements*

Aiming for the correct detection of power system events and monitoring of power quality parameters, there are some requirements that need to be attended by the signal processing hardware. According to the IEC 61000-4-30 [1], for a class "A" equipment, it is advised to measure at least to the harmonic 50 of the 60 Hz fundamental frequency with a resolution of 5 Hz in the Discrete Fourier Transform algorithm.

As can be seen in (1), the resolution is dependent to the system's fundamental frequency (represented by f) and the number of cycles (represented by Nc). It is noteworthy that the specified resolution can be met by analyzing 12 cycles of a 60 Hz fundamental frequency or 10 cycles for 50 Hz.

$$\Delta f = \frac{f}{N_C} \qquad (1)$$

It is known that to be able to represent frequencies up to 3000 Hz (harmonic 50 of the 60 Hz signal), the sampling rate of the acquisition hardware must be equal to at least 6000 samples per second or 100 samples per cycle of the fundamental, which is twice the maximum representable frequency [13]. Sampling 12 cycles with this acquisition rate would result in a vector of 1200 samples. However, the Fast Fourier Transform works optimally with vectors with lengths with a power of two dimensions. So the near value which is greater than 1200 samples and also a power of two is 2048 samples within 12 cycles. Therefore, the number of samples per second can be calculated by 2048/12 multiplied by 60.

To conclude the processing requirements, the acquisition hardware must work with a minimum sampling rate of 10240 Hz and compute the DFT for each vector of 2048 samples.

### B. *Communication Requirements*

The communication between the smart lighting devices and the software supervisor is accomplished by a ZigBee interface, due to the fact that this interface has low power consumption, low cost and is possible to connect up to 65000 nodes [8]. Moreover, the physical topology of the ZigBee interface allows the construction of mesh topologies without hard configuration on each luminaire.

The communication between the smart lighting device and the luminaires itself is provided by a DALI data frame. This standard was firstly introduced in the project NumeLite for street lighting applications and a detailed discussion of this project is discussed in [9].

### C. *Concept of the proposed device*

The proposed equipment, called by Smart Module or just SM, is able to manage and operate the luminaire as well as provide information concerning the power grid. The schematic of the system is shown in the Fig. 2. Besides, each smart device contains a real time clock in order to provide time synchronization between the coupled sensors and network, a power supply with backup battery ensuring an uninterrupted and isolated power source, a control interface to send control signals for the luminaire and acquire information from the sensors.

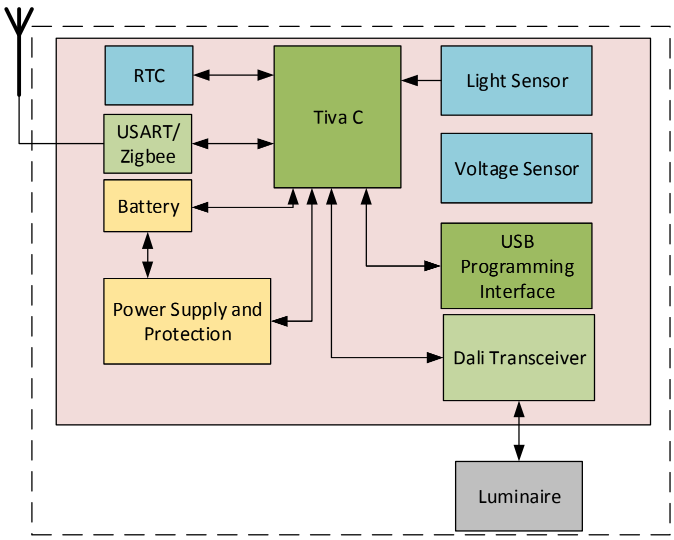



Fig. 2. Schematic of the proposed device.

To acquire the grid status information and detect the events, it is necessary to couple in the main module a voltage sensor, which needs to follow certain requirements, such as signal conditioning for proper analysis in an embedded system as well as to provide isolation and protection of the hardware in case of fault conditions in the grid. The schematic of the voltage sensor is shown in Fig. 3. As can be noted, the voltage signal is conditioned to provide a determined output range values to the smart device processor.

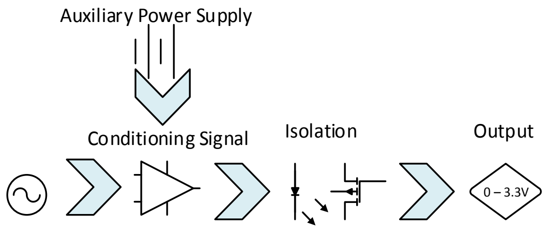



Fig. 3. Schematic of the voltage sensor.

## III. SIGNAL PROCESSING METHODOLY

In this section is described the signal processing methodology used in the proposed smart device. The power quality application algorithm is shown in Fig. 4. Firstly, it is performed the signal sampling and it is verified if the oscillography time is reached. In case of positive response, 12 cycles are sent to the supervisory system. In case of negative response, it is performed the calculation of the RMS voltage value and verified the existence of disturbances in the power grid. This RMS voltage value is calculated in each cycle and updated every zero crossing passage, i.e. every half cycle, as recommended by the IEC standard. The equations of the RMS voltage and the number of samples in half cycle are presented in (2) and (3), respectively.

$$Vrms_{\left(\frac{1}{2}\right)} = \sqrt{\frac{1}{N_S} \cdot \sum_{i=1}^{n} {v_i}^2} = \sqrt{\frac{{v_1}^2 + {v_2}^2 + \cdots + {v_n}^2}{N_S}} \quad (2)$$

$$N_S = \frac{f_s}{2 \cdot f} \quad (3)$$

Where $N_S$ is the number of samples in a half cycle, $f_s$ is the sampling frequency, $f$ is the fundamental frequency and $v_i$ is the voltage value in a determined sample of the main voltage signal.

It is noteworthy that the acquisition of a new sample is always compared with the previous sample in order to check the zero crossing passage, once it indicates the end of a half cycle. While the half cycle has not completed, the samples are used to increment the sum of (1). When the computing process of RMS voltage of a half cycle is completed, this value is added to the previously value stored in the buffer, resulting in a RMS value of a full cycle, which is updated every half cycle.

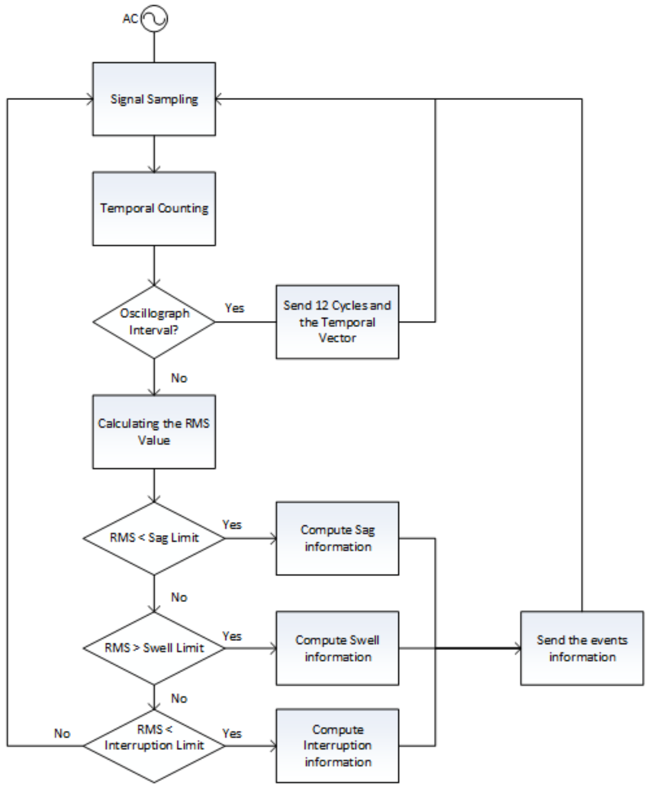



Fig. 4. Algorithm for the power quality parameters estimation and disturbances detections.

This buffer is initialized with a null value, precluding that the first iteration results in a RMS voltage value of a complete waveform. However, from the second iteration, it is possible that the algorithm output results in the RMS value of a complete cycle and updated every half cycle.

Note that for the correct zero crossing detection of a signal corrupted by noise, it is necessary that the input signal of the voltage sensor is filtered, avoiding improper counts. The chosen filter is the SWRDFT, acronym for Sliding Window Recursive Discrete Fourier Transform, due to its faster attenuation near of the fundamental frequency and removal of harmonics content [14]. The SWRDFT transfer function is shown in (4).

$$H(z)_{SWRDFT} = \frac{1 - Z^{-L}}{1 - e^{j2k\pi/L} Z^{-1}} \quad (4)$$

Where L is the window size and k is the desired harmonic. To filter the fundamental component from the corrupted signal, k should be chosen as one, but in order to avoid complex number calculations in hardware, and to guarantee stability of (4), for fixed point implementation, k is chosen equal to zero. The magnitude response for k=0 is shown in Fig. 5. It can be observed that the developed filter is a low pass with harmonic cancelation.

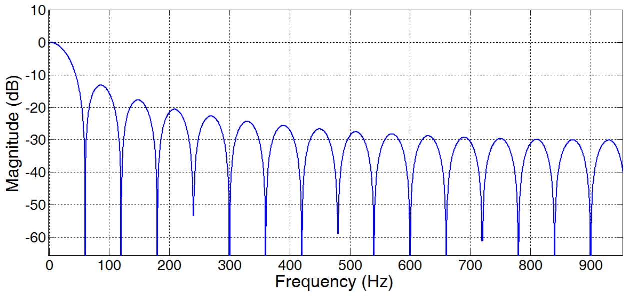



Fig. 5. Magnitude response of the recursive DFT with k equal to zero.

In order to shift the fundamental component to the pass band of the filter, it is necessary to modulate the original signal with fundamental frequency and then filter. The modulator is fixed, since the frequency deviation is expected to be around ±0.5 Hz. The output will be the DC component, or in other words, the amplitude of the fundamental signal. In order to obtain the fundamental component from the corrupted signal, the filter's output needs to be modulated once again with the same frequency. This modulation structure is represented in the Fig. 6.

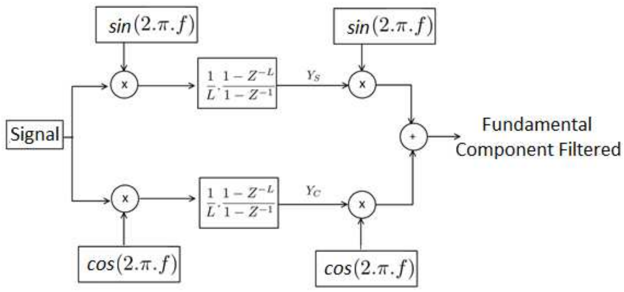



Fig. 6. Filter structure based on SWRDFT.

It can be noted that the modulation is accomplished with sine and cosine functions in order to obtain the in phase and quadrature components. By adding the modulated versions of Ys and Yc, the fundamental component is filtered and therefore, being optimal for zero-crossing detection. Nevertheless, the RMS is calculated based on the original signal, thus computing the so called true RMS. Note that the filtered signal serves only for the accurate zero crossing detection for recognizing when each half cycle is over. It worth to mention that the RMS measurement from the power grid is computed in real time, and this information is used to detect unusual condition from the power grid, such as voltage sag and swell.

Other power quality parameters relevant to measure from the power grid are the harmonic distortion and spectral analysis from the signal. It is noteworthy that these analyses do not need to be performed in real time, since it demands higher computational effort. In this sense, the data acquired from the smart device containing the 12 cycles and time stamp are sent via the communication network to a supervisory system, which will run the necessary algorithm.

To determine and study the spectral content, the technique used in this work, which is probably the most used in this scenario, is the Discrete Fourier Transform, shown in (5).

$$X\left[e^{-\left(j\cdot 2\frac{\pi}{L}\right)k}\right] = \sum_{n=0}^{L-1} x[n]\cdot e^{-(j\cdot 2\cdot\pi/L\cdot)kn} \tag{5}$$

Where $X\left[e^{-\left(j\cdot 2\frac{\pi}{L}\right)k}\right]$ is the discrete sequence and as defined earlier, L is the window size, which needs to contain a integer number of fundamental period. In case of a wrong choice, the DFT algorithm will not provide consistent results with a real signal composition, showing the so called leakage effect.

## IV. Results

In this section is described the simulation results of the chosen filter and how it performs in filtering the fundamental component for optimal zero crossing detection as well as the results of the RMS estimation from a corrupted test signal. The results concerning the DFT algorithm in the supervisory system with a test signal generated in Matlab are also shown in this section.

### *A. Simulation Results*

In order to optimize the hardware development, all the signal processing requirements and algorithms were first tested and validated in a simulation environment. By generating a test signal corrupted with noise and/or harmonics, it was possible to validate the filter structure chosen and the algorithm to compute the RMS value of each cycle.

The noise added to the fundamental component in order to validate the SWRDFT filter has a Signal to Noise Ratio (SNR) equal to 10 dB. Note from Fig. 7 that the estimated fundamental component is very close to the actual component, which means that the zero crossing detection will be very accurate for the RMS calculation.

The RMS value of the signal was computed according to (2). To assure that the IEC standard [1] is satisfied, the algorithm calculates the RMS value for a complete cycle and updates every half cycle. The upper and lower bounds are also defined in [1] as 1.1 and 0.9 of the nominal value, respectively. If RMS is higher than the upper threshold, then a swell event is detected, and in case it is lower than the lower bound, a sag is detected. Thus, time count is started in order to specify the duration of the event. Fig. 8 shows the result for this algorithm, detecting six half cycles with sag. Note that it achieved good performance even in presence of noise, since the zero crossing detection is accomplished using the filtered signal.

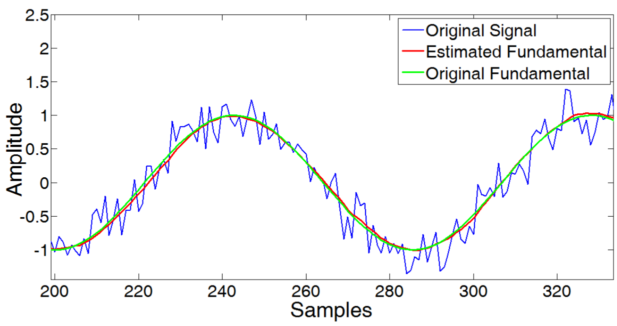



Fig. 7. Result of the filtered fundamental component utilizing the SWRDFT filter.

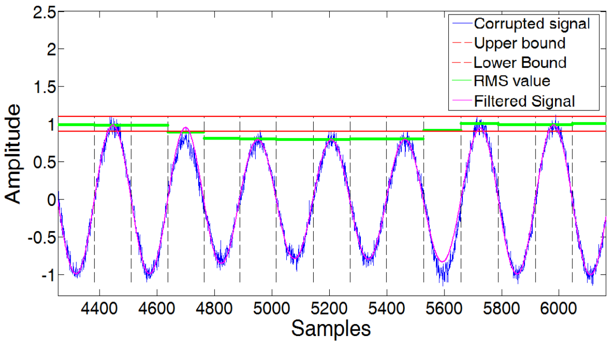



Fig. 8. Simulation result for the computation of the test signal RMS value.

The other power quality parameter that the proposed device is able to estimate is the spectral distribution and consequently the harmonic distortion. In order to do so, the vector containing the 12 cycles sampled at 10240 samples per second is used to run the FFT algorithm. The vector's length and the sampling frequency were chosen to meet the IEC standard requirements of resolution and maximum frequency representation in the spectral estimation. These power quality parameters are not computed in real time. Actually, they are sent via control module to a supervisory server. The test signal containing the third and sixth harmonic and its spectral content estimated by the supervisory system are presented in Fig 9 and Fig 10, respectively.

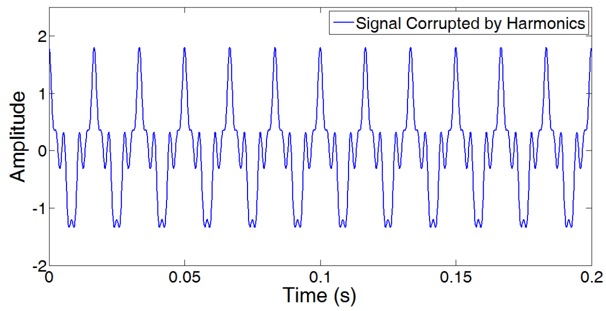



Fig. 9. Signal corrupted by third (50% energy) and sixth (30% energy) harmonics.

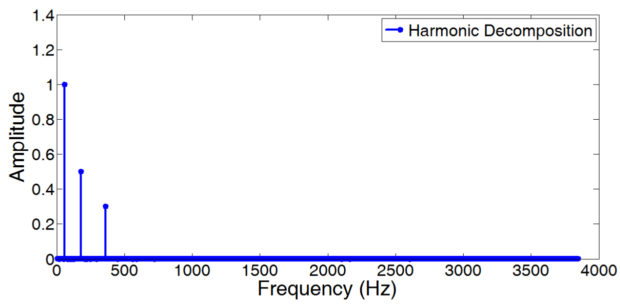
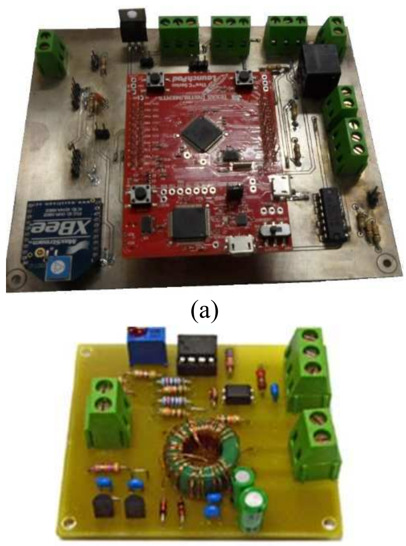



Fig. 10. Spectral estimation performed by the supervisory system showing harmonic decomposition.

## B. *Experimental Results*

The Smart Module developed in this project is presented in Fig. 12 (a). As can be seen, this device has an interface to the voltage sensor, presented in Fig. 12 (b).

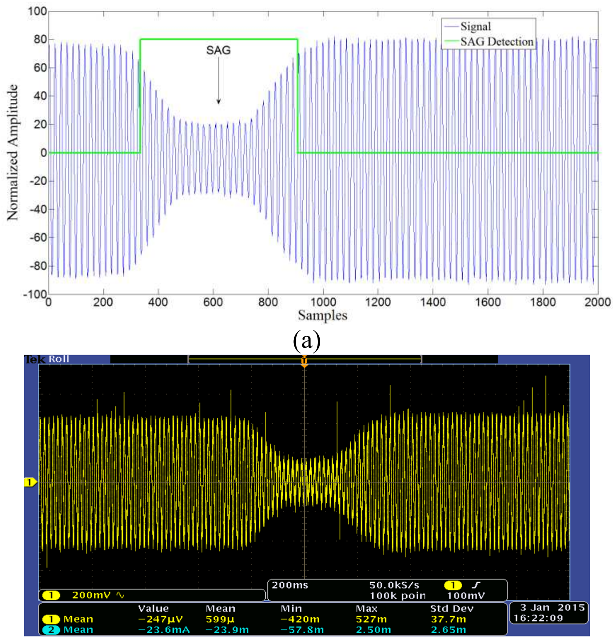



(a)

(b)

Fig. 11. Developed hardware. (a) Smart module. (b) Voltage sensor.

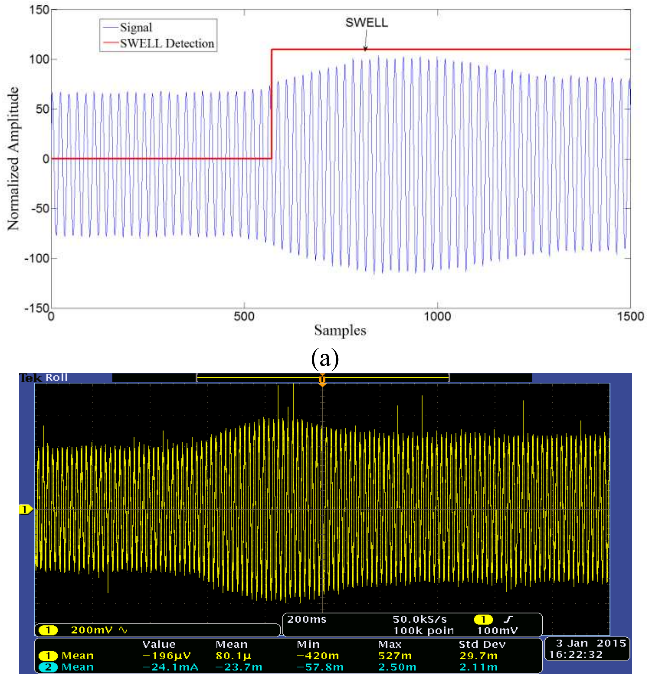
For comparison, as can be seen in the Fig. 12 (a) and Fig. 13 (a), the algorithm implemented by the prototype was capable to successfully detect the events from the power grid. The output signals of the voltage sensor, in sag and swell situations, are shown in the Fig. 12 (b) and Fig. 13 (b), respectively. In these cases, the voltage data is sent to the supervisory, which allows the event reconstruction for offline analysis, as described previously, which validates the proposed algorithm. Despite of the good fault detection, it can be noticed a little delay between the event occurrence and the indicated signal, represented by the green and red lines, which can be assigned to the filter delay used to compute the RMS value.




(a)

(b)

Fig. 12. Voltage waveforms. (a) Sag detection. (b). Voltage at output of the voltage sensor.



(a)

(b)

Fig. 13. Voltage waveforms. (a) Swell detection. (b). Voltage at output of the voltage sensor.

## V. Conclusions

The current work has presented in more details the signal processing and communications requirements for increasing observability of the distribution network, requiring only coupling power quality monitoring devices attached to a smart controller for intelligent lighting systems. All the methodology to acquire and process the received signals from the low voltage grid ensuring the IEC standard requirements were met and described in details in this work. The proposed device is capable of detecting the most common events, such as sag, swell, harmonic distortion as well as recording data for offline analysis. The results have shown that this proposed device is a promising tool for aiding the operators in fault detection and monitoring of the distribution network, turning the traditional lighting systems more intelligent and representing a big step towards the smart distribution network concept.

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