Wireless Monitoring and Management of Energy Consumption and Power Quality Events

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***Abstract*—This paper describes the design, implementation and testing of a distributed wireless system conceived for residential consumers which allows remote monitoring of energy consumption and power quality events from multiple electrical appliances. The system can be operated by the user from a central computer, which receives the collected data from a wireless sensor network based on the IEEE 802.15.4 and ZigBee standards. The development of the system involved the design and implementation of the hardware of the wireless sensor nodes; the software embedded in the network nodes, which manages the acquisition and transmission of data from the sensor nodes to the computer; as well as the user interface software in the central computer. Performance tests show that the developed prototype is able to provide measurements with very good accuracy and precision, for both voltage and current.**

***Index Terms*— Smart Meters, Power Quality, Smart Grid, ZigBee, Wireless Sensor Networks.**

I. Introduction

Nowadays, there is a growing change in the pattern of energy consumption of residential consumers, driven by economic, political and environmental factors, as well as stringent regulations for power quality (PQ) and energy efficiency certification of housings. This trend can be seen in the increasing demand of electrical appliances with lower energy consumption, lower cost and less environmental impact. The International Energy Agency (IEA) refers that agriculture, commercial, public services, and residential sectors together demand most of the electricity consumption, about 57% on a global scale. According to the same agency, electricity demand is projected to grow at an average annual rate of 2% per year in the period of 2015 to 2030 [1]. Electrical power grid PQ problems are also seen as responsible for significant energy waste.

According to Targosz et al. [2], the total PQ costs to the European economy exceed 150 billion euros per year. PQ is degraded by nonlinear loads (e.g., electric motor drives, personal computers, television sets and cell phone chargers) connected to the power grid. Since these appliances are part of the consumers' everyday life in modern societies, it is necessary to compensate these PQ problems, as well as to contribute to the improvement of energy efficiency [3].

A study of the European Union states that the energy efficiency of residential facilities can be improved in 13% [4]. In order to respond to the challenge of reducing the electricity consumption and making the electric system more efficient, a new economic niche was born: the development of smart, reliable and efficient solutions that help consumers to reduce their electricity consumption and are competitively priced in the current market.

The starting point for reducing electricity consumption is to be aware of how much and how it is consumed. An example of a feasible solution is the development of monitors to measure and report to the consumer the entire energy consumption history of an electrical load connected to the power grid [5], [6]. These measurements are mainly being made by distribution networks companies, using different technologies, such as power line communication [7], ZigBee [8], and GSM [9]. Likewise, energy management for residential consumers is increasing as result of advances in electrical power grid technologies [10]. According to [11], the use of electric energy monitors increases the householders' knowledge and confidence about the amount of electricity they consume.

In manufacturing facilities, the energy efficiency is also a must. Traditionally, energy consumption is not considered as a manufacturing strategy; however, it is becoming a matter of concern and a criterion for facilities planning and operation strategies. Power and energy monitoring equipments are essential for an accurate quantification of the energy efficiency, and also allow the measurement of a wide variety of additional statistics related to PQ [12], [13]. In buildings, energy efficiency (and consequently, energy monitoring) is also a matter of concern and object of research [14], [15].

The current market of residential electric energy monitors focuses primarily on products that provide visual information regarding the instantaneous electricity consumption, and accumulated measurements for one week or month, alerting users in real time to the resulting economic cost. An interesting feature is the forecast of the monthly and annual consumption. These monitors range from simple products that display locally the power consumption on a plug to distributed systems which measure

Manuscript received March 2, 2015. This work has been supported by FCT (Fundação para a Ciência e Tecnologia) in the scope of the project: PEst-OE/EEA/UI04436/2015.

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electric energy consumption at various points of a residence and send the data to a host device.

The prices of electric energy monitors can be very high. Jansson et al. [16] propose a power monitor that uses a Rogowski coil as current sensor and RS-232 for communication with a PC. This paper, on the other hand, proposes a distributed wireless solution based in a much cheaper current sensor, which aims to contribute to the development of low cost residential products, in order to help consumers to reduce energy consumption in a suitable way.

Others systems that also use wireless communication have been developed to control electrical loads in home appliances. Song et al. [17] present a prototype of a wireless-controllable power outlet system which uses ZigBee modules to create a network of remotely controllable power outlets. However, this solution only allows remotely switching on/off the power on the equipments connected to the outlet.

Another wireless system for remote controllable power outlets, presented by Lien et al. [18], uses different technologies to control and measure the electric energy consumption of home appliances. In this system, each power outlet allows the connection of up to six electric equipments. For each one, the user can acquire the values of energy consumption and switch them on/off. The user has three different ways to communicate with the power outlet: Bluetooth [19], GSM [9] or Ethernet [20]. All the relevant data are stored on an SD card in the power outlet. This system does not detect power quality events.

The system proposed in this paper is supported by a wireless sensor network (WSN) [21] implemented using the IEEE 802.15.4 [22] and ZigBee [23] protocols. The IEEE 802.15.4 standard defines the physical (PHY) and the medium access control (MAC) layers of the network, whereas the ZigBee standard defines the upper layers of the protocol stack, including the network layer (NWK) and application layer (APL). A ZigBee network is characterized by low cost and low power consumption devices, low data transfer rates (250 kbps in the frequency band of 2.4 GHz), as well as support for multihop wireless communications, which increase the network coverage. The wireless sensor network implemented in the proposed system consists of measuring devices (sensor nodes) attached to the electrical loads, a coordinator device (base station) and, optionally, dedicated routers to forward information across the network.

This system measures several relevant electrical parameters (such as current, voltage, frequency, active power, and power factor) associated with each monitored electrical load, using a sensor node, and sends the data wirelessly to the base station, which is connected to a PC. The data is available to the user through a graphical user interface (GUI) application: the monitoring UI. The sensor node is capable to act remotely on the electrical load, either cutting or supplying the power according to a command sent from the PC. The monitoring UI provides to the user information on the measured electrical parameters, along with the date and time of acquisition, the cumulative energy consumption in kWh, as well as the respective monthly and annual electrical energy cost in euros. This system also presents alarms when PQ events occur.

II. System Implementation

The proposed system is structured in four parts: the sensor node hardware; the base station hardware; the embedded software at the network nodes; and the PC software (monitoring UI). The main component of the WSN is the CC2530 System on Chip (SoC). This chip integrates an 8051 microcontroller, a high performance RF transceiver compatible with the IEEE 802.15.4 standard in the 2.4 GHz band, 8 kB of RAM and up to 256 kB of Flash memory. The CC2530 is used in all network nodes (base station, sensor nodes and routers).

A development kit was used during the initial development of the WSN. This kit provides two boards that work together and are attached to each other by two connectors: an RF evaluation module, which contains a CC2530, a connector to an external antenna and auxiliary components; and an evaluation board, which provides power to the node, contains several peripherals useful for testing, and allows the programming of the embedded code into the CC2530. For the final prototype, three new boards were developed: two boards for the sensor node and one for the base station. These boards, described below, suit the functionalities desired for the system and replace the boards of the kit.

A. Sensor Node Hardware

The developed sensor node is adapted to the characteristics of the electrical power grid at residences in Portugal: AC input voltage 230 V-50 Hz and maximum current of 16 A. As shown in Fig. 1, the sensor node contains: an ADE7753 IC, which processes the data received from the sensors; a current sensor; a voltage sensor; a relay, to connect and disconnect the load; a DC power supply, to feed the circuit; and a CC2530 RF module for data processing and communication.

The power supply extracts energy from the power grid, which is readily available at the site, since the power grid is connected to the load being monitored by the sensor node. In the developed prototype, the ADE7753 is powered with 5 V provided directly by the DC power supply, while the CC2530 module is powered with 3.3 V through a voltage regulator.

In the event of power failure, the MAX630 IC switches the power supply from the grid to the 3.6 V battery, allowing the sensor node to continue to operate and send information about this PQ event. This IC also provides the 5 V requested by the sensor node through its voltage step-up feature.

The ADE7753 is a low cost and low power single-phase multifunction power metering IC. The typical power consumption of the ADE7753 is around 25 mW. This device provides two input channels with a programmable gain amplifier in each one, through which the current and voltage signals are acquired. Each channel has a high precision 24-bit second-order Σ-Δ analog-to-digital converter (ADC). The ADE7753 also contains a digital signal processor that performs calculations, based on the measured current and

ISBN: 978-988-19253-4-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

voltage, to determine the active, reactive and apparent power, the signal period and the RMS values of the voltage and current. The collected information is stored in internal registers which can be read by a microcontroller using the SPI (Serial Peripheral Interface) communication interface. Writing operations are also available, for tasks such as the configuration of the ADE7753 operating mode or the calibration of parameters like gain and offset correction.

The current sensor used in the sensor node is an AC1015 current transformer. The nominal current on the primary side of the transformer is 15 A, the maximum current is 60 A and the turn ratio is 1000:1. The secondary of the current transformer is connected to a load resistor R_L. This resistor provides a voltage proportional to the current, which is read by the ADE7753. The R_L resistance used in the developed prototype has the value of 22 Ω.

The voltage sensor is implemented using a resistive voltage divider. The resistors values used in the developed prototype, in order to ensure that the measured voltage is within the limits required by the ADE7753, were 650 kΩ and 1 kΩ. The monitored appliance is powered from the grid through a relay, which enables the user to remotely interrupt or provide power to the appliance.

The CC2530 version used in the developed prototype system is the CC2530F256, which has 256 kB of flash memory. The CC2530 module contains also an external antenna, two connectors that provide access to the pins of the CC2530 and auxiliary components. The communication between the CC2530 and the ADE7753 is performed through the SPI interface.

Fig. 2 presents the top, side and bottom views of the sensor node board, identifying the corresponding blocks shown in Fig. 1.

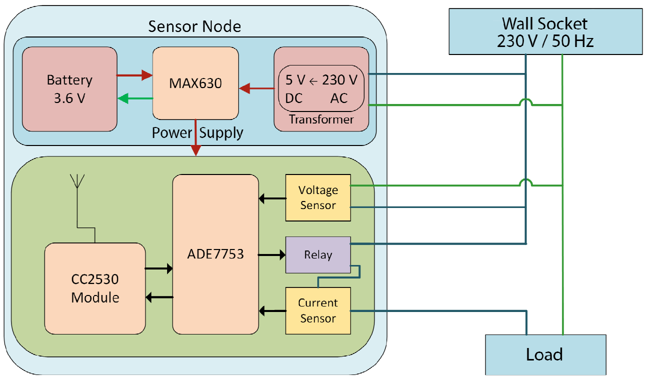

Fig. 1. Block diagram of the sensor node hardware.

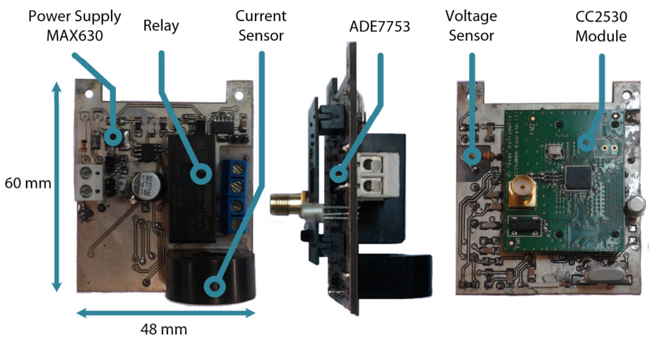

Fig. 2. Top, side and bottom views of the developed sensor node board.

A CC2530 board with integrated antenna was developed as a more compact replacement to the original CC2530 module, which uses an external antenna. This board has 40 mm x 40 mm and contains a CC2530 and an inverted F antenna integrated in the PCB [24]. Fig. 3 (a) presents the front view, with the PCB antenna at the top and the CC2530 near the center, and the rear view (b), with the two connectors at the bottom. The cost of this board is significantly lower than the cost of the original CC2530 module. The total cost of the developed sensor node, including all the required components, is 42.47 euros. This cost is based on prices of the components for retail sale in small quantities. On a commercial, wholesale scale, it is expected the total cost to be much lower.

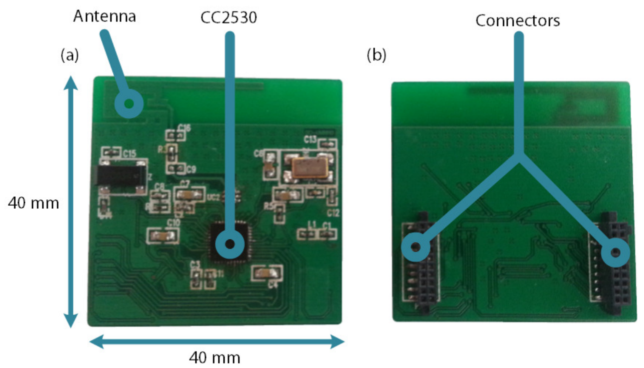

Fig. 3. Developed CC2530 board with integrated PCB antenna: (a) Top view; (b) Bottom view.

B. Base Station

The base station has the role of coordinator of the ZigBee network and is connected to a PC, through a USB connector. Fig. 4 presents the developed base station, which replaces the two original boards of the development kit (the much larger evaluation board and CC2530 module). The main component of this board is the CC2530. A FT232 chip provides an USB to UART interface. Virtual COM port drivers make the base station board appear as an additional serial port available to the PC, allowing the developed PC software to communicate with the CC2530. The board has a standard-A USB plug for connecting to the PC, which is used for data transfer and also to power the base station. This board has also an antenna connector and other auxiliary components.

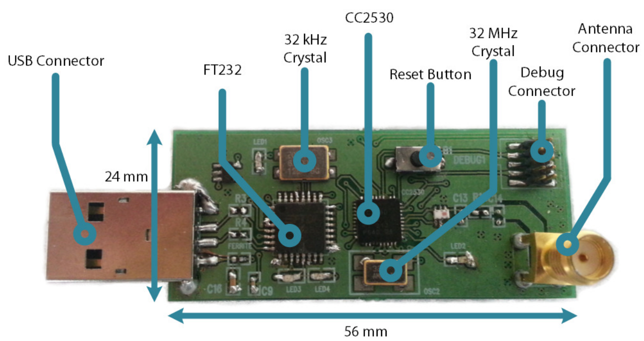

Fig. 4. Developed base station board.

C. Embedded Software

The ZigBee software platform used in the developed prototype is called Z-Stack. The Z-Stack software is

ISBN: 978-988-19253-4-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

organized on the following components: OSAL (Operating System Abstraction Layer); HAL (Hardware Abstraction Layer); ZigBee and IEEE 802.15.4 stack; Application component; and MT (Monitor and Test) interface. The OSAL component consists on the operating system provided to control all the running tasks, which provides an API (Application Programming Interface) for communication and synchronization between tasks. The HAL provides an API to access the peripherals available in the evaluation board. The ZigBee and IEEE 802.15.4 stack provides the implementation of the ZigBee layers. The Application component refers to the set of applications running on the device.

The developed embedded software is executed in the CC2530 microcontrollers of the nodes. It consists of three different applications, one for each type of node: sensor node, base station and router. The main tasks of the sensor node application are: configuration of the operating parameters and sensor data acquisition from the ADE7753 (both through the SPI interface); and wireless data transfer using the ZigBee protocol. The base station application sends the data received from the sensor nodes to a PC, through the serial port, and vice-versa. The basic tasks required for the operation of the ZigBee network, such as association, routing, medium access control and error control, are performed by the Z-Stack code.

The sensor nodes generate two types of data packets: a periodic packet and an event packet. The event packet is sent sporadically in response to the occurrence of a PQ event: voltage sag, current surge, voltage surge (swell) or momentary failure. Each periodic packet contains 19-byte payload with measurements of current, voltage, signal period, active power and apparent power, which is encapsulated by the ZigBee and IEEE 802.15.4 protocol headers and trailers, resulting in a packet length of 50 bytes. The periodic packets are sent at intervals of one minute; therefore, the traffic load generated by each sensor node is just 6.67 bps, which is much lower than the ZigBee data rate (250 kbps). Such low traffic conditions enable the support of a very large number of sensor nodes without foreseen issues due to contention.

Fig. 5 shows the flowchart of the sensor node application. After the initialization, the algorithm is divided into three concurrent tasks. The first task processes interrupts signaling a PQ event. When an interrupt occurs, this task checks the type of event, measures the relevant data, builds the corresponding event packet and sends it to the wireless network. The second task, executed every second, calculates the average of 60 samples collected from the ADE7753 and sends periodic packet. The third task, which is triggered when the sensor node receives a packet, toggles the state of the sensor node relay. When the appliance is turned off, the task responsible for periodically transmitting the periodic packet is automatically disabled.

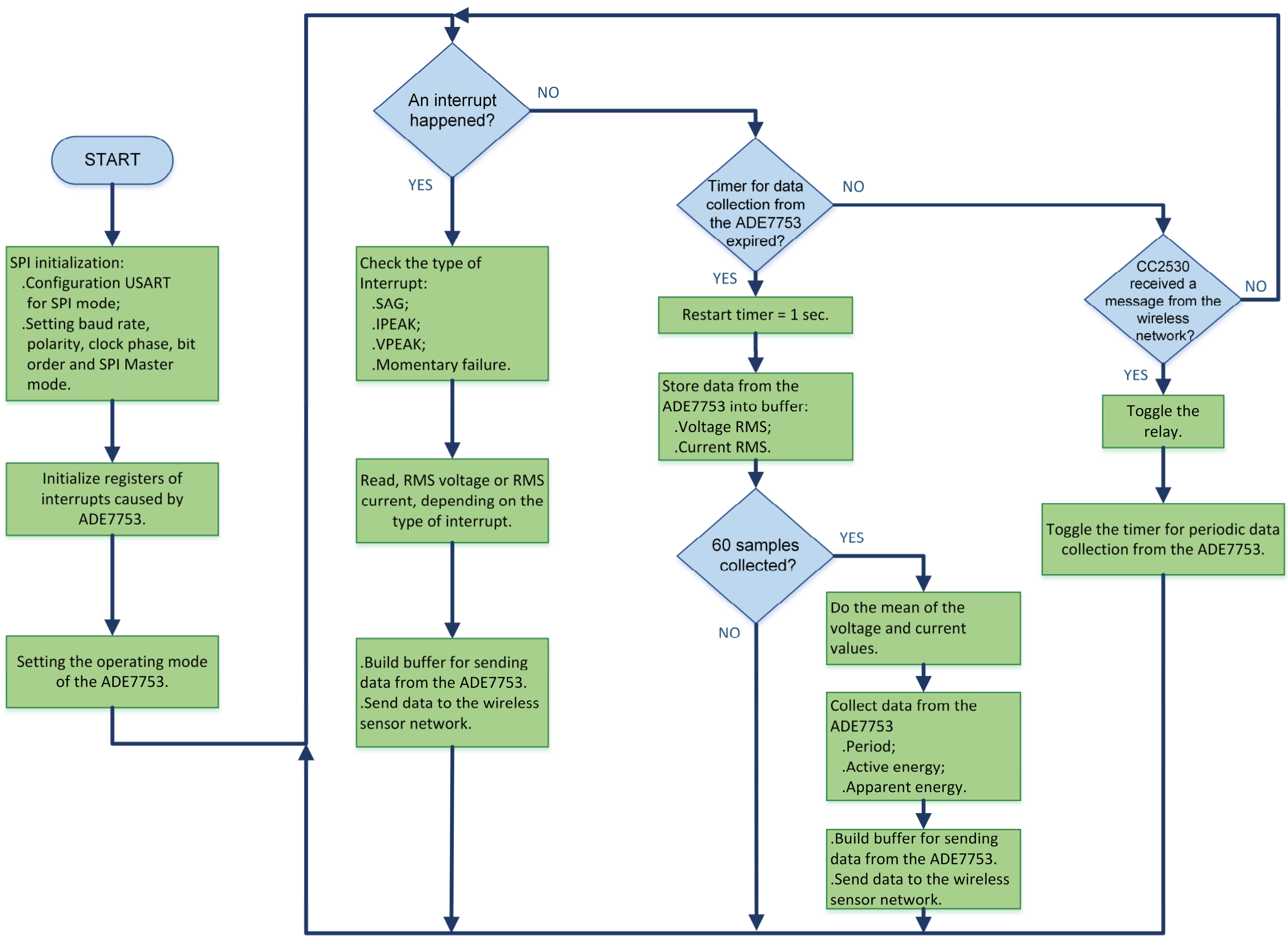

Fig. 5. Flowchart of the application developed for the CC2530 sensor node.

D. Monitoring User Interface

The Communication window of the monitoring UI, shown in Fig. 6, provides: at the left-hand side, the current values of the measured electric parameters; at the center, information regarding the detected PQ events; at the right-hand side, the energy cost in euros (€) and the carbon footprint. This window also allows turning on/off the appliance. The Records window (Fig.7) provides a chart with selected data (voltage, current, frequency, power or power factor). This example shows the power consumption of a residential water heater over time.

Fig. 6. Monitoring UI software: Communication window.

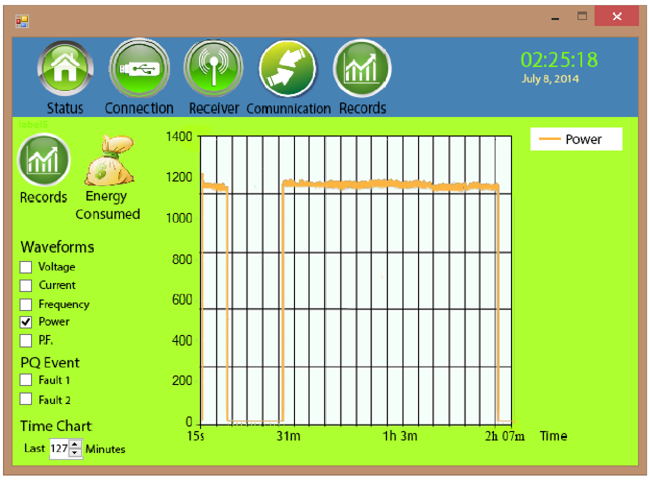

Fig. 7. Monitoring UI software: Records window.

III. Results and Discussion

Fig. 8 presents an example of the SPI communication. Channel 1 (above) displays the SPI clock, whereas channel 2 displays the MOSI (Master Output Slave Input) signal from the CC2530 to the ADE7753. The MSB (Most Significant Bit) of the first byte sent by the CC2530 defines the data transfer operation ("0" to read and "1" to write), whereas the other bits contain the address of the ADE7753 register being accessed. The value of the first byte in this case (0x89) means that it is a write operation on the 16-bit MODE register (address 0x09), which is used to configure sampling rate, filters and calibration modes. The second (0x80) and third (0xA4) bytes contain the value that is written in this register (0x80A4). The data collected by the ADE7753 is also placed in registers, which are read by the CC2530 through the SPI interface. The procedure is similar to the writing operation above described. However, in this case, after the transmission of the first byte (with "0" in the MSB), the content of the addressed register is read from the MISO (Master Input Slave Output) line.

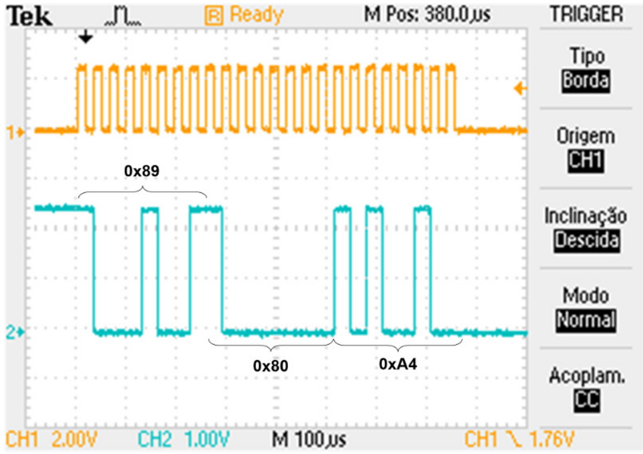

Fig. 8. SPI communication between the CC2530 and the ADE7753.

In order to evaluate the accuracy of the measurements performed by the sensor nodes, tests were performed in comparison with a precision power measurement device. The relative error of the measurements, which is a measure of the accuracy, was calculated according to (1). The measured value in (1) is the average value of 60 samples calculated by the node. The standard deviation of the measurements, which is a measure of the precision, was calculated according to (2), where n is the number of measurements performed.

$$error(\%) = \frac{measured\ value - reference\ value}{reference\ value} \times 100 \tag{1}$$

$$\sigma = \sqrt{\frac{\sum (measured\ value - \overline{reference\ value})^2}{(n-1)}} \tag{2}$$

To perform the aforementioned tests, a circuit was designed where three resistive loads (A, B, and C) were switched on/off along the time, in order to change the current. Fig. 9 shows the variation of the RMS value of the current along the test. Table I presents a summary of the RMS current values measured by the sensor node and by the reference power meter, as well as the relative error and the precision, which are calculated according to (1) and (2), respectively. It can be seen that the maximum relative error was 0.15% and the precision was equal or better than 0.01 A. Table II presents results regarding the RMS voltage values measured by the sensor node and by the reference power meter, the relative error and the precision. It can be seen that the maximum relative error was 0.18%, while the precision was equal or better than 0.47 V. In both sets of measurements (current and voltage) the relative error, when comparing with a reference instrument, is equal or less than 0.18%, and the precision is also very good. Therefore, the results obtained validate the use of the developed prototype for the proposed application.

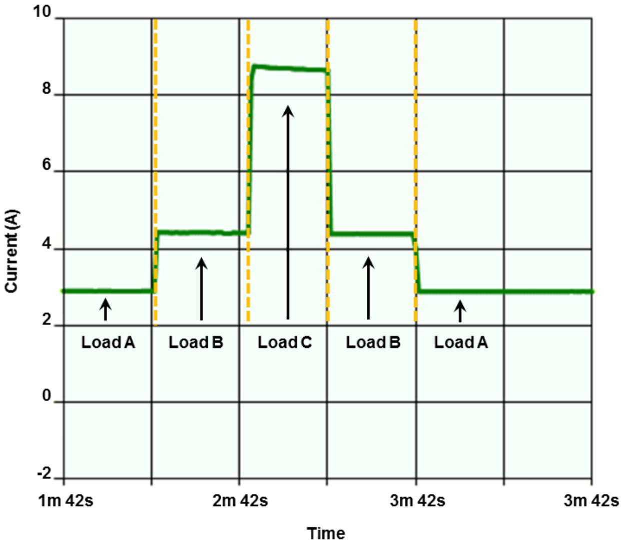

Fig. 9. RMS value of the current for different loads.

TABLE I
ACCURACY OF THE SENSOR NODE CURRENT MEASUREMENTS

Load	Measured current (A)		Error (%)	Precision (A)
	Sensor Node	Reference		
A	2.95	2.95	-0.15	0.0035
B	4.38	4.38	-0.06	0.0100
C	8.22	8.21	0.14	0.0100

TABLE II
ACCURACY OF THE SENSOR NODE VOLTAGE MEASUREMENTS

Load	Measured voltage (V)		Error (%)	Precision (V)
	Sensor Node	Reference		
A	233.05	233.20	-0.06	0.42
B	232.06	232.47	-0.18	0.47
C	229.41	228.40	0.17	0.35

IV. CONCLUSION

The low cost energy monitoring system presented in this paper, which enables the users to monitor the energy consumption and power quality problems of home appliances, meets the growing needs of residential consumers in reducing the electricity consumption, and contributes to make the electric system more efficient and to diagnose the PQ.

The proposed distributed wireless system, which is based on the ZigBee standard, is able to acquire relevant electrical parameters from each electrical load being monitored, through a sensor node. All the collected information is centralized in a base station connected to a PC, which makes the data available to the user through a GUI application. An alarm message is presented when a PQ event occurs (e.g. voltage sag or swell).

Prototypes of the sensor node and the base station were developed. The results from the measurements of accuracy and precision were very good, validating the proposed system.

Future work includes the integration of the developed system into a ZigBee-based home automation system designed to monitor and control other environmental variables at residential buildings.

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ISBN: 978-988-19253-4-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)