Develop, implement and characterize an electric energy monitoring device

Bernardo Ribeiro de Matos
Instituto Superior Tecnico
Lisbon, Portugal
bernardo.de.matos@tecnico.ulisboa.pt

***Abstract*—This project consists in developing, implementing and characterizing a small size energy monitoring device to be used in the long-term monitoring of the energy consumption of a single mains connected device.**

Nowadays, the number of electronic devices are increasing, as well as the need for smaller, more accurate and low consumption energy metering systems. The electromechanical meters are still widely used to measure the overall consumption of a power utilities client. Currently, they are being replaced due to their limitations and their replacements are electronic meters that, in addition to performing the same functionalities of electromechanical, are capable of distinguishing between hourly rates, store data and remotely transfer it to the electricity provider. The objective of the prototype to be developed in this work is not to replace the electromechanical meters or to provide a new device to measure the overall power consumption of a client. The developed device objective is to monitor the power consumption of one single mains connected device (for example, a TV, a refrigerator or a washing machine).

The proposed energy metering solution includes: i) voltage and current sensors to interface with the mains; ii) an energy metering specific integrated circuit and a microcontroller. A resistive voltage divider is used as a voltage sensor and a Shunt Resistor is used to sense the current. To process the data from the metering IC, a PIC is used. This microcontroller controlls the flow of data from the energy metering IC to the user, storing data in a flash memory, implements a remote communication protocol. The system is powered by an AC/DC capacitive power supply and in case of a power failure, a battery is used to acquire the last values of power consumed before the failure.

The acquired information is stored in a microSD memory card, using the FAT filesystem. Using this interface the data saved in memory card can be read in a computer. Alternatively, to analyze the power consumption, an Android Application is used. This app communicates via Bluetooth and displays the information the user wants to analyze.

***Keywords*—Energy metering, Power, Energy, Power Supply, Signal Conditioning, Microcontroller.**

I. INTRODUCTION

The increase of electronic devices and consequent increase in energy consumption leads to a greater need in service and measurement quality [1]. Electronic meters fulfill many needs, as they add some features such as automatic counting, ease in implementing new features, power failure detection and power factor measurement [2].

To monitor the consumption of a single device, the electromechanical meter isn't practical since its big dimensions and high cost difficult its implementation. In addition to the difficulty in reading the value of the active power consumed by a low power consumption device.

In this project the development of a small sized energy meter is described. The energy metering device developed will perform an intensive consumption monitoring of a single electronic equipment connected to a Schuko connector. It can be used with devices with currents up to 16 A. To communicate with the user, a wireless communication protocol is used to exchange data between the device and user. This communication allows to obtain data about voltage, current, instant and accumulated power consumption.

The device acquires the required data every 10 second, so, the sample frequency is 0.1 Hz. The device is connected to the electric grid, being the input voltage 230 V. The Schuko connectors used limit the current to 16 A. To store the desired information a 2 GB microSD is used and to transmit the information to the smart phone, the Bluetooth Low Energy protocol is used.

Measurement of electric power consumption requires the measurement of the current and voltage supplied to a load.

The power is divided into three components. The active power (P) that represents the actual work done by a circuit in form of heat, light and motion, which is expressed in kilowatts (kW). The reactive power (Q) represents the stored energy and doesn't produce work and is expressed in kilovolt ampere reactive (kVAR). The apparent power (S) is the total power required including active and reactive power and is represented in kilovolt ampere (kVA) [3].

Depending on the load, the apparent power can be a complex number, where the real component is the active power and the imaginary component is the reactive power. So, the apparent power is

$$\overline{S} = P + jQ. \quad (1)$$

For a given sinusoidal voltage and current, active, reactive and apparent powers remain constant and the representation can be performed using vectors, these vectors form a triangle as shown in Figure 1.

Mathematically, apparent power is defined by

$$S^2 = P^2 + Q^2. \quad (2)$$

Apparent power is greater or equal to active power. In order to be equal, the power factor must have a unitary value.

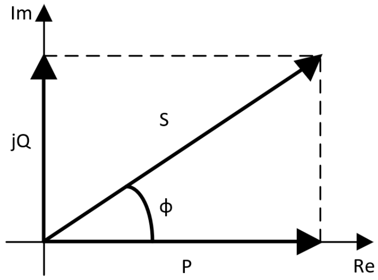

Fig. 1. Power vectors triangle.

A power factor different from the unitary value means that exists a phase shift between the voltage and current signals. To have a maximum energy transference and hence the work is performed with a lower current value, the power factor must be as closest to unitary as possible. With the increase of phase shift the power factor decreases [4].

Power factor is defined by the ratio between active power and apparent power, where the apparent power is the product of RMS value of voltage with RMS value of current in sinusoidal regime. In sinusoidal regime

$$S = V_{RMS} \times I_{RMS}, \tag{3}$$

and the power factor is

$$PF = \frac{P}{S} = \cos(\phi), \tag{4}$$

where ϕ is the angle between active power and apparent power vectors in absence of harmonics. To compensate a low power factor and consequently higher losses in the transmission lines, it is possible to use capacitors or coils banks, contradicting the reactance of the load.

Active power is

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt. \tag{5}$$

It is possible to measure the reactive power by shifting either the voltage or current signal by 90°. So, the reactive power is

$$Q = \frac{1}{T}\int_0^T v(t)i_{90^\circ}(t)dt. \tag{6}$$

Voltage and current signals aren't purely sinusoidal since they suffer distortion. So, in addition to the fundamental, there are harmonics at integer multiple frequencies of the fundamental.

The current is then defined by the Fourier Series

$$i(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega t - \phi_n) \tag{7}$$

and the voltage is

$$v(t) = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega t - \theta_n). \tag{8}$$

Replacing (7) and (8) in (5)

$$\begin{aligned} P = \frac{1}{T}\int_0^T &(V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega t - \theta_n)) \\ &(I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega t - \phi_n)) = \\ &V_0 I_0 + \sum_{n=1}^{\infty} \frac{V_n I_n}{2}\cos(\phi_n - \theta_n). \end{aligned} \tag{9}$$

According to (9) there is only active power consumption when there are terms of the Fourier Series of voltage and current at the same frequency.

The RMS current and voltage are

$$I_{RMS} = \sqrt{I_0^2 + \sum_{n=1}^{\infty}\frac{I_n^2}{2}} \tag{10}$$

$$V_{RMS} = \sqrt{V_0^2 + \sum_{n=1}^{\infty}\frac{V_n^2}{2}}. \tag{11}$$

Using (10) and (11) in (4), the power factor is

$$PF = \frac{V_0 I_0 + \sum_{n=1}^{\infty}\frac{V_n I_n}{2}\cos(\phi_n - \theta_n)}{\sqrt{I_0^2 + \sum_{n=1}^{\infty}\frac{I_n^2}{2}} \times \sqrt{V_0^2 + \sum_{n=1}^{\infty}\frac{V_n^2}{2}}}. \tag{12}$$

The presence of harmonic content increases the RMS value of current and voltage. However, the mean value of the power may not increase.

II. State of the Art

A. Electronic Meters

Over the years, the electromechanical meters became antiquated and the need to develop new types of meters that allowed communication with the costumers and less susceptible to the unauthorized alteration of the recorded power consumption increased. These meters have advantages over the electromechanical, such as a small size, high accuracy over a large current range, greater capacity to handle high currents, low power consumption, greater reliability and robustness and the absence of gears avoids mechanical wear and possible failures in counting the number of rotations [5].

The newest electronic energy meters use digital signal processing, converting the acquired voltage and current signals from analog to digital using ADC's, usually SAR or Sigma Delta type. After conversion, the signals can be multiplied, filtered and integrated by microprocessors or integrated circuits to obtain power information.

B. Voltage Sensor

Since the load is connected to the electric grid the signal must be reduced so an ADC can read its value correctly. For the voltage sensor there are two main alternatives: voltage transformer and resistive divider. When using a transformer, galvanic isolation is guaranteed and the circuit is protected from grid peaks. The primary of the transformer is connected to the electric grid between the phase and the neutral and the measurement is made in the secondary. Although the circuit is protected from the electric grid, this topology has an high cost and considerable volume.

The resistive divider consists on dividing the grid voltage into a smaller voltage using resistors . The sensor is placed in parallel with the load to have the same voltage. The measurement is performed as shown in Figure 2.

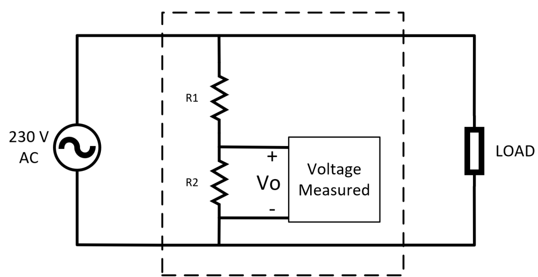

Fig. 2. Voltage sensor circuit based on a resistive divisor.

The measured voltage is

$$V_O = \frac{R_2}{R_1 + R_2} V_{AC}, \tag{13}$$

The resistor values are chosen to have an adequate voltage in the input of the circuit that will process the signal. The resistors must also have a high value so that the power consumption is low.

Resistor R_1 is replaced by a set of resistors of equal value connected in series so that the set of resistors has the same value of R_1. In this way, it is guaranteed a protection of the system since in case of a malfunction of one resistor the system isn't compromised. Also, the power is distributed by all resistors, each consuming less than the total power consumption. If only one SMD resistor is used, there is a voltage drop of 230 V in 2 or 3 mm, which is dangerous.

This type of sensor has the advantages of a reduced size and low cost of components. On the other hand, it has the disadvantage of not isolating the system from the grid.

For the voltage sensor because of its dimensions and price the resistive divider is used.

C. Current Sensors

Unlike voltage, the current has a wide dynamic range and because of the harmonic content of the current signal, the sensor has to handle a higher frequency range. Thus, there are several topologies of current sensors, among them Shunt Resistor, Current Transformer, Hall Effect Sensor and Rogowski Coil Sensor [6].

The Shunt Resistor consists of a highly stable low value resistor, placed in series with the load as shown in Figure 3. The voltage across the shunt resistor is proportional to current, so since the value of the resistor is known, it is possible to calculate the current according to Ohm's law [7].

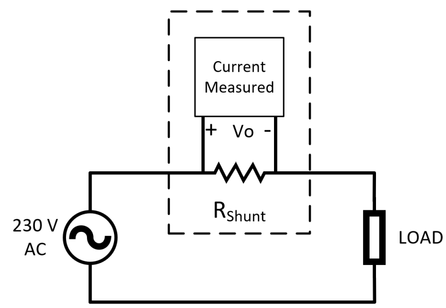

Fig. 3. Current sensor using a Shunt Resistor circuit.

This type of sensor has some advantages such as good accuracy, low cost and the measurement process is simple. However, it has the disadvantage of parasite induction and dissipated power. As this sensor is resistive, the power will be dissipated by heat and this heating is proportional to the square of the current that flows through the resistor so it has to have a small value to minimize the heat. Thus, for high currents values another type of sensor is usually implemented [6].

The current transformer converts the current in the primary, connected in series with the load, into a lower current in the secondary. This is the topology mostly used in high currents. The magnetic properties of this type of sensor are highly linear over a wide range of primary current and temperature. This type of sensor has the advantages of measuring high currents and having low power consumption. Its disadvantage is the possibility of saturation due to the material typically used in the core (ferrite) and a nonlinear phase response at low currents and large power factors. After being magnetized, the core will undergo hysteresis and accuracy will worsen unless it is demagnetized again. Saturation can occur when the current is higher than that allowed by the sensor or when there is an high DC component. To prevent saturation from occurring a material with high permeability is used.

There are two main types of Hall Effect sensors implementations, open-loop and closed-loop. Usually the Hall Effect sensors used for energy metering have an open-loop implementation, so the cost of the system is lower. These sensors have the advantage of a good frequency response and good high current measurement capability. Their disadvantages are the high variation with temperature and a stable external current source is required [6].

The Rogowski Coil sensor consists of a coil that has a mutual inductance with the conductor conducting the current. The Rogowski Coil is typically made with a core of air so that there is no hysteresis, saturation or non-linearities. This sensor being based on the measurement of a magnetic field is susceptible to external magnetic fields. The output signal is derived from the voltage and an integrator is required to process the signal [6].

After analyzing the characteristics of the current sensors the Shunt Resistor was chosen for the energy metering device. Its small dimensions, low cost, good linearity and the fact that it doesn't suffer saturation or hysteresis problems were the factors that led to this option.

D. Power Supply

There are several ways to convert an AC voltage into a DC voltage needed to supply the microcontroller and other devices. Typically, a transformer is used along with a rectifier circuit. However, in small sized applications that involve only a microcontroller and a few low-current devices, this topology isn't appropriate. This is due to the high price of the transformer as well as the space occupied. Despite the cost and size, a transformer based power supply has the advantage of isolating the electrical grid from the output of the power supply.

Transformerless power supplies provide a low-cost and small alternative to a transformer-based power supply. There are two basic transformerless power supplies topologies, resistive and capacitive. The simplest circuit of a transformerless power supply is the resistive with half wave rectification, as shown in Figure 4 [9].

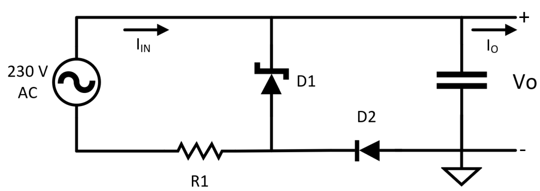

Fig. 4. Resistive transformerless power supply circuit.

Resistor R1 is used as a current limiter and the output voltage is constant when the output current is less than or equal to the input current. All the current that flows through R1 can become output current. While the grid voltage is smaller than the zener diode voltage drop, the output voltage is defined by the grid voltage. Since the zener isn't conducting, the output capacitor stores charge, allowing the load to draw current from it as needed. When the grid voltage exceeds the zener voltage, the output voltage is defined by the zener diode, being constant and equal to the difference of the zener (D1) and diode (D2) voltage drop. So, the voltage across R1 is the subtraction of the grid voltage with zener voltage drop [8]. Since the circuit has a half wave rectifier, the average current through R1 represents the maximum average output current that the power supply can generate.

The region where the zener diode conducts is represented as shaded in Figure 5. The average voltage across R1 is

$$v_{R1,average} = \frac{1}{\pi - 0}\int_{\sin^{-1}\left(\frac{V_{D1}}{V_{peak}}\right)}^{\pi-\sin^{-1}\left(\frac{V_{D1}}{V_{peak}}\right)} (V_{peak} sin\theta - V_{D1})d\theta, \tag{14}$$

where V_{D1} is the voltage drop in D1 and V_{peak} is the maximum grid voltage ($\sqrt{2} \times 230$ V).

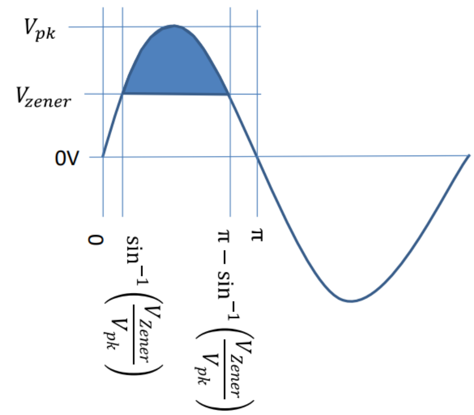

Fig. 5. Zener diode in conduction zone represented as shaded.

As the value of $sin^{-1}(\frac{V_{D1}}{V_{peak}})$ is very low (14) can be simplified into

$$v_{R1,average} = \frac{1}{\pi - 0}\int_0^{\pi} (V_{peak} sin\theta - V_{D1})d\theta, \tag{15}$$

since the circuit perform half wave rectification, the maximum average output current is approximately

$$i_{out,max} = \frac{\left(\frac{1}{\pi-0}\int_0^{\pi}(V_{peak} sin\theta - V_{D1})d\theta\right)}{2R1}. \tag{16}$$

Since the source doesn't have a transformer to reduce the grid voltage, the voltage drop in the resistor is high and an high power will be dissipated as heat. This topology has the advantages of reduced size and cost compared to transformer-based power supply and capacitive transformerless power supply. However, it has the disadvantage of not isolating the voltage which can introduce safety problems. This topology is also less efficient than the capacitive due to dissipation of energy as heat in the resistor [8].

The other basic topology is the capacitive power supply, where a capacitor is added in series with the resistor, so the current is limited by the reactance of the capacitor. The resistor is kept to limit the inrush current, so its value can be smaller. The inrush current happens when a capacitor is connected directly to the grid and at the instant the AC voltage is at a peak value, the capacitor will behave as a short circuit, producing an high current [9]. The capacitive transformerless power supply topology is shown in Figure 6.

The method to calculate the maximum output current is similar to the resistive power supply but replacing the resistor R1 by the combined impedance of the resistor in series with the capacitor.

$$i_{out,max} = \frac{2V_{peak} - V_{D1}}{2\pi \quad \sqrt{(R_1)^2 + (\frac{1}{2\pi f C_1})^2}}, \tag{17}$$

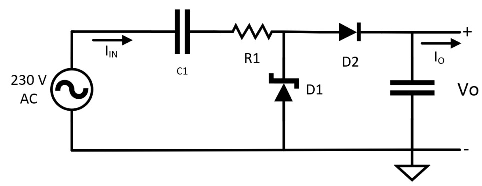

Fig. 6. Capacitive transformerless power supply circuit.

Like the resistive power supply, the capacitive version has the advantage of a reduced size and price when compared to the transformer-based power supply, in addition of a higher efficiency comparing to the resistive version. On the other hand it is also not isolated from the grid and the cost is slightly higher than the resistive [9]. To improve the efficiency, a rectifying bridge can be used to rectify both cycles of the input signal. This topology is represented in Figure 7.

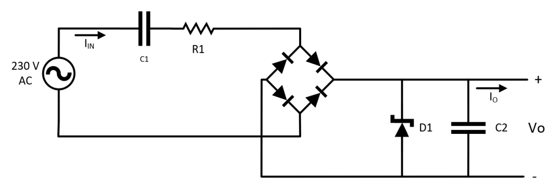

Fig. 7. Capacitive transformerless power supply with full wave bridge rectifier.

The maximum output current is

$$i_{out,max} = \frac{2V_{peak} - \pi V_{D1}}{\pi \sqrt{(R_1)^2 + (\frac{1}{2\pi f C_1})^2}}, \tag{18}$$

This topology has the advantage of being more efficient, the output voltage is more stable and the output current is higher. As a disadvantage the cost is slightly higher [8].

A relay controlled by the PIC is added to protect the circuit from high current values and the resistor R2 in parallel with the capacitor creates a filter to attenuate the electromagnetic interference back to the line, discharging the capacitor avoiding shocks due to the capacitor charge [9].

E. Wireless Communication - Bluetooth Low Energy

There are several wireless technologies that can be used to connect devices remotely. The ZigBee standard, is a simple technology that uses a protocol of data packets with specific characteristics. The main characteristic of this technology is the number of nodes that reach more than 64000 nodes in the same network [10]. Wi-Fi standard is a technology that allows networks to connect with computers and other compatible devices, like smart-phones or tablets. The Wi-Fi standard has a typical maximum range of 100 m and a higher data rate than ZigBee and Bluetooth being that the main advantage in using this technology [11]. Bluetooth is a technology developed for short-range devices, this technology has the advantage of being compatible with most modern devices as a smart-phone, tablet or personal computer [12].

In this project the Bluetooth wireless technology is chosen since it doesn't need additional components and doesn't depend on the Wi-Fi network, also the number of nodes required is low.

Bluetooth is a wireless technology that allows data exchange between devices over short distances.

Data protocol stack is divided in host and controller. The controller is responsible for the link layer and physical layer and to filter data packets. The host consists in the Logical Link Control and Adaptation Layer (L2CAP) that is the protocol that allows the communication between host and controller, its main function is to group and ungroup data packets. The Generic Access Profile (GAP) that defines generic procedures used to pair and link the device. The Security Manager (SM) that authenticates and encrypts the data. The Attribute Protocol (ATT) to transmit small packets in an optimized way. The GATT is responsible to describe the service frameworks and communicate with the application layer [13].

Figure 8 represents the architecture of the BLE protocol.

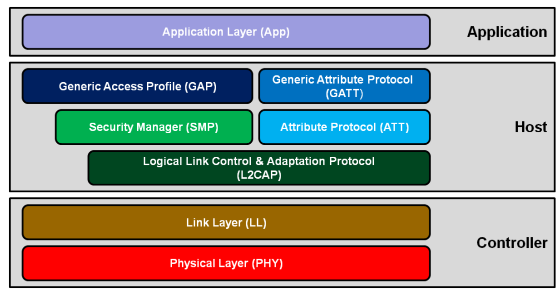

Fig. 8. BLE protocol stack architecture. Extracted from [13].

The Bluetooth Low Energy physical layer consists in the analog communications circuitry responsible for translation of digital symbols. The radio divides the 2.4 GHz band in 40 physical channels with a 2 MHz bandwidth. These channels can be one of two types: 3 advertising channels that are used for the transmission of advertising packets prior to a connection and discover other devices and 37 data channels used for transmission of data during a connection. BLE has a data rate that theoretically can reach 1 Mb/s, however this value can be reduced by some factors like bidirectional traffic, protocol overhead, CPU and radio limitations and software restrictions [13].

The Link Layer interfaces with the physical layer and is responsible for advertising, scanning and creating connections. A frequency hopping scheme is implemented in this layer to remap a packet from a bad channel to a good channel where the interference from other devices is reduced.

There two types of packets, the data packets and the advertising packets. These packets have only one format as shown in Figure 9. These packets have a 1 Byte preamble to synchronize transmission timing between systems, 4 bytes for an access code generated randomly by the RF channel, 2 to 257 bytes for the Protocol Data Unit (PDU) and 3 bytes for CRC (Cyclic Redundancy Check) to check for accidental changes to raw data.

Preamble	Access Address	Protocol Data Unit (PDU)	CRC
1 Byte	4 Bytes	2-257 Bytes	3 Bytes

Fig. 9. BLE packets format. Extracted from [13].

The difference between the advertising and data packets is in the Protocol Data Unit, where the advertise packets only have a 2 Bytes header and a payload up to 37 Bytes, whereas the data packets have a payload that can has up to 255 Bytes plus a 2 Bytes header.

Because of its low power consumption, BLE has some limitations such as a lower Data Transfer Rate that on classic Bluetooth can reach 3 Mbps and on BLE 1 Mbps. For continuous transmission of large amounts of data the BLE is not the advised device. In this project there is no need to continuously transfer data, so the BLE option is a better solution.

III. System Architecture

An electronic energy meter is normally composed of voltage and current sensors, power supply unit, energy measurement unit, microcontroller, memory and communicating system unit [14].

The developed system has to acquire the information regarding the power from the energy metering IC, store this information in a non-volatile memory and send it via Bluetooth protocol when requested. As the system is connected to the electric grid, the power supply is supplied by the grid. To measure power, it is needed to measure the voltage and current, these measurements are performed by means of sensors. The system architecture is represented in Figure 10.

This system has a memory unit composed by a SD Card and the communication unit composed by two SPI modules that are used to communicate with the energy meter and the memory unit and a UART module to communicate with the Bluetooth module.

A. Microcontroller

The microcontroller controls the communication with the energy metering IC, process the data received, communicate with the memory and the bluetooth module.

To process the data from the energy metering IC, Microchip Technology PIC24FJ128GA010 microcontroller was chosen. This microcontroller is small and fast enough for the required operations, in addition to integrate several functionalities such as specific communication protocols and an internal oscillator.

This microcontroller has various options of oscillators, internal and external. The oscillators are two crystals, two external clocks with the option of dividing the clock by two at the output, a FRC with an output frequency of 8 MHz that can be software divided until 31 kHz, a phase-locked loop available for the external oscillator and for the FRC internal oscillator that can reach frequencies up to 32 MHz and a fixed 31 kHz internal oscillator. In this project the FRC oscillator is chosen at a frequency of 8 MHz.

The PIC has several modules for communication with peripherals including two SPI modules, two UART modules and two I_2C modules. These modules are useful since the communication between the energy metering IC and the microcontroller is done using SPI as well as the communication with the memory. The UART is used for communication with the Bluetooth module [15].

B. Energy Metering Integrated Circuit

For energy metering the Analog Devices' ADE7753 was chosen because it has an high accuracy over large variations in environmental conditions and incorporates all the signal processing required to perform active, reactive, and apparent energy measurements and RMS calculation on the voltage and current [16].

To measure the current and voltage, the input signals are firstly converted with $\Sigma - \Delta$ ADCs. The Channel 1 ADC includes three maximum range options in addition to the gain from the PGA. For the Channel 2, only the PGA introduces a gain that can take the same values as Channel 1 PGA.

In the current channel the digital signal is filtered with an high pass filter. Because the current is sensed into a voltage and sampled, to calculate its RMS value is used

$$V_{RMS} = \sqrt{\frac{1}{N} \times \sum_{i=1}^{N} V_i^2}. \tag{19}$$

The result value has a 24-bit length. To measure the RMS value of the voltage the process is similar.

As the Active Power is the DC component of the instantaneous power signal, to calculate it's value the current and voltage signals are multiplied to obtain the instantaneous power signal and then a low pass filter is used to extract the DC component corresponding to active power. The relationship between the power and the energy is

$$E = \int P dt = \lim_{t=0} \left\{ \sum_{n=1}^{\infty} p(nT) \times T \right\}, \tag{20}$$

The energy meter IC also registers the accumulated active power. This register has a length of 48 bits, however only the upper 24 bits are accessible, the lower 24 bits are used to delay the influence of the acquired active power values rounding.

Reactive power is defined as the product of the voltage and current when one of the signals is phase-shifted by 90° [16]. The resulting multiplication is called instantaneous reactive power, so as in active power case, to obtain the average reactive power a low pass filter is used.

The apparent power is calculated as in (3) by multiplying the RMS values of the current and voltage.

C. Power Supply

To implement the power supply, the topology from Figure 7 was used because of its small size, high efficiency and low power consumption due to the diodes bridge.

The component that requires more current is the microcontroller that has a maximum current of 32 mA at maximum

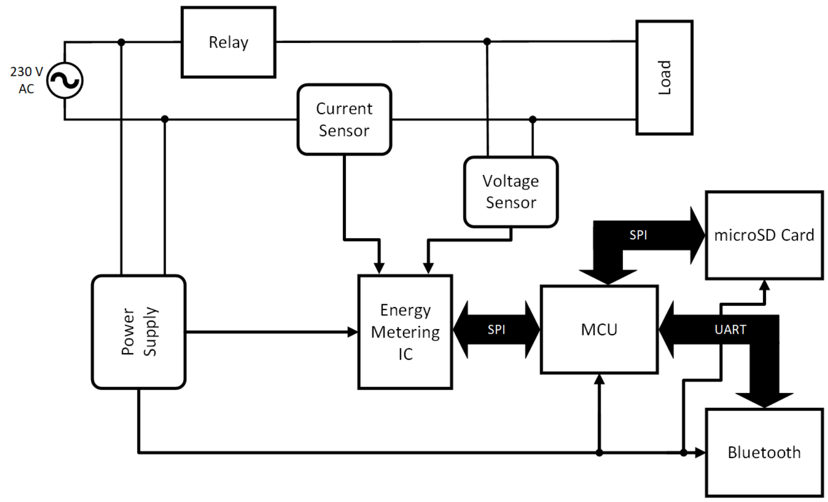

Fig. 10. System Block diagram.

frequency [15]. The other components have small currents comparing to microcontroller, with the energy meter having a current of 4 mA. So, the power supply was developed to supply up to 75 mA.

The resistor R2 has an high value, so the resulting impedance of R2 in parallel with C1 is approximately the impedance of C1. With this topology, R1 can have a small value but different from zero to avoid inrush current when the circuit is turned on, because the current is limited by the C1 reactance, so a value of 100 Ω is chosen. From (18) it is possible to calculate the value of C1,

$$C1 = \frac{1}{2\pi f} \frac{1}{\sqrt{\left(\frac{2V_{peak}-\pi V_{D1}}{\pi \quad I_{out,max}}\right)^2 - R_1^2}} = 1.003\ \mu\text{F}, \tag{21}$$

To connect a capacitor directly to the grid it is necessary a capacitor with special features. This type of capacitor is called X2, also referred as "across the line capacitor". If a X capacitor fails, one of two options can happen. Either the capacitor turns into a open circuit or a short circuit, in the last option an high current is generated and the fuse will open. After calculating the theoretical value of the capacitor, the closest value of a capacitor with these characteristics available in market is 1 μF. With the new value of the capacitor, replacing in (18), the maximum output current is 75 mA.

With this current the maximum power dissipation in resistor R1 is

$$P_{R1} = R1 \times I_{out,max}^2 = 100 \times 0.075^2 = 0.5625\ \text{W}. \tag{22}$$

So, a 1 W resistor is used. In the worst case the Zener diode should be able to dissipate a power of

$$P_Z = V_Z \times I_{out,max} = 5 \times 0.075 = 0.375\ \text{W}. \tag{23}$$

As the Zener diode as to dissipate a power of 0.375 W, a 1 W Zener diode is chosen. Each rectifier diode only conducts half of a cycle, meaning that there is only current in each diode half of the time. So, in average, the power dissipation in each diode is

$$P_D = V_D \times \frac{I_{out,max}}{2} = 26.25\ \text{mW}. \tag{24}$$

To increase the stability of the output voltage a voltage regulator was placed after the circuit of Figure 7.

D. Signal Conditioning

The energy metering integrated circuit has an Analog Input maximum range of $\pm$0.5 V, so the voltage and current signals must be reduced to fit in the IC range [16].

1) Current Sensor: For the current sensor, a small value Shunt Resistor is chosen taking into account the power and temperature coefficient. As the system has to be capable of measuring currents up to 16 A and according to Joule's Law, the power of heating generated in an electrical conductor is proportional to the square of current, a small value of 0.001 Ω is chosen for the Shunt Resistor. This way, the maximum power dissipation is

$$P_{Shunt} = I_{max}^2 \times R_{Shunt} = 0.256\ \text{W}. \tag{25}$$

From Ohm's Law

$$V_{Shunt,max} = I_{max} \times R_{Shunt} = 0.016\ \text{V}, \tag{26}$$

so, this voltage is in the energy metering IC range. As a resistor dissipates power through heat it is required that the Shunt doesn't change it's properties with an increase of temperature. With a small temperature coefficient, a linear approximation of the resistor is used.

For this project a 0.001 Ω SMD Shunt Resistor was chosen with a power rating of 1 W and with the minimum available temperature coefficient of 50 ppm/°C. With this power rating the maximum current that the sensor supports is 31 A.

2) Voltage Sensor: The voltage sensor is a resistive voltage divider and is composed by a series of ten 47 kΩ resistors and one 220 Ω resistor. Considering a maximum value of voltage of 470 V for the circuit to be capable of handle a voltage peak, the maximum input value in the energy metering is,

$$V_{Input,max} = V_{max} \times \frac{220\Omega}{10 \times 47k\Omega + 220\Omega} = 0.22 \text{ V}, \quad (27)$$

This value is in energy metering IC range. According to Ohm's Law, the maximum current consumed by the voltage sensor is

$$I_{VoltageDivider,max} = \frac{470V}{10 \times 47k\Omega + 220\Omega} = 1 \text{ mA}, \quad (28)$$

Each resistor has a maximum power consumption of

$$P_{Consumption,max} = I^2_{VoltageDivider,max} \times R. \quad (29)$$

In case of 47 kΩ resistors is 47 mW and for the 220 Ω resistor is 0.22 mW. The chosen resistors have a power rating of 250 mW.

E. Memory

To store the read data a non-volatile memory is used. This type of memory can keep the stored information even when the system isnt powered. Compared to volatile memory, non-volatile memory usually has a higher cost but a poorer performance. Although the device works with a battery in case of a power failure, this battery will run out of energy and the information stored must be kept. To implement a non-volatile memory, a microSD Card was used. In Figure 11 is presented the connection scheme.

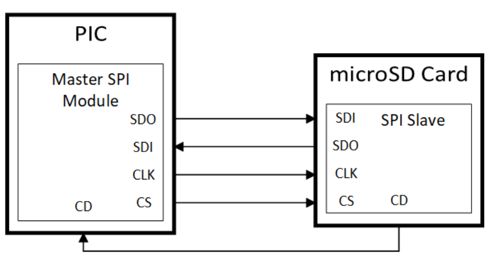

Fig. 11. Interface between the PIC and the microSD Card.

To interact with the memory card, the data cannot be stored as individual blocks of bytes, since a lot of devices dont read individual blocks of memory space. So, an abstraction layer above the memory space is needed to make sure all devices can read the data stored in the memory card. The abstraction layers, also known as filesystem, divides the memory in clusters and sectors that most devices can understand. Since the information in memory card must be read in computers a filesystem needs to be implemented. The SD card has a FAT file system implemented to be compatible with a broad range of modern and old devices.

F. Battery Management

An energy meter where the power depends on the grid voltage must present a protection in case of an energy fault. To prevent a system shut down a battery was used with an integrated circuit to monitor the voltage level and to perform the power path management.

In Figure 12 a block diagram of the battery charger is represented.

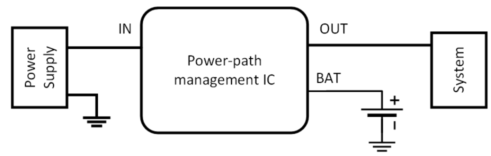

Fig. 12. Power path management block diagram.

The power path management is accomplished used a BQ24070 IC from Texas Instruments, which is placed between the power supply and the system. This circuit performs the management of energy and charges the battery if needed. If the battery is fully charged and the power supply is working properly, the system is supplied from the power supply, with the battery in a stand by mode. When there is an energy outage, the power management IC swaps the supply of the system from the power supply to the battery, when the energy from the grid is restored the battery is charged.

G. Bluetooth Module

For this project the RN4871 Microchip Technology Bluetooth Module is chosen because of its small dimensions of 9 mm x 11.5 mm and its functionalities. This module is used to communicate between the device and the user. It has an integrated ceramic antenna and an ASCII Command Interface API over UART [17]. Through the ASCII Commands it is possible to configure the module since establishing connection to creating a script and enter in Low-Power Mode. The module has GPIO pins that can be configured to give some information, such as if the Bluetooth is connected. In this project a UART Transparent private service, that handles data streaming is used.

IV. Results

A. Power Supply

The voltage obtain from the Zener diode is dependent on the load and consequently on the current. So, a study on the behavior of the power supply when the load is varying is performed. The results are illustrated in Figure 13. As expected the implemented power supply provides 5 V with a minimum load of about 70 , corresponding to a maximum current of 72 mA.

B. Calibration

After obtaining the values from the energy metering chip it is required to calibrate the device. The calibration was performed by taking several measurements and compare with the values measured with a multimeter. Then, a linear regression

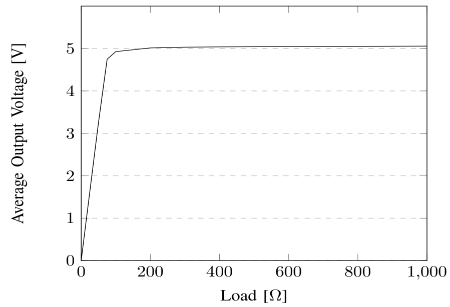

Fig. 13. Average Output Voltage with different loads.

model (y = mx + b) is used to minimize the error between the energy chip measurements and the multimeter measurements. As the energy chip has a linear behavior between FS/20 and FS (Full Scale) the linear regression model is used.

Voltage

The ADE7753 energy metering chip measurements are compared to the values obtain from the multimeter and the resultant calibration equation that minimizes the error is

$$y = 0.0140599945 \times x - 5.0493397926, \tag{30}$$

And the coefficient of determination, R^2, is

$$R^2 = 0.999. \tag{31}$$

The maximum relative error obtained was 1.77%.

Current

To calibrate the current values, the same process was executed. The outcome calibration equation that minimizes the error is

$$IRMS = 0.0002085269 \times x - 0.1278090220, \tag{32}$$

And the coefficient of determination, R^2, is

$$R^2 = 0.998, \tag{33}$$

A maximum of 2.46% relative error was obtained.

C. *Smartphone Application*

To display the acquired values, an Android Application is used. This app shows the desired values such as the active power or the voltage. This values can be displayed in two forms, live value and a chart. The chart shows the values from the last 30 days.

Figure (a) shows the home screen. In this screen it is required to connect with the Bluetooth device. In the settings screen it is possible to select which quantities to display. In Figure (b) the settings screen and the options to select is shown.

There are two more screens: live values screen (Figure (c)) and chart screen (Figure (d)). In the live values screen the instant values of the quantities selected in settings screen are presented and in the chart screen it is required to select the chart to display. The chart is refreshed when the refresh button is pressed.

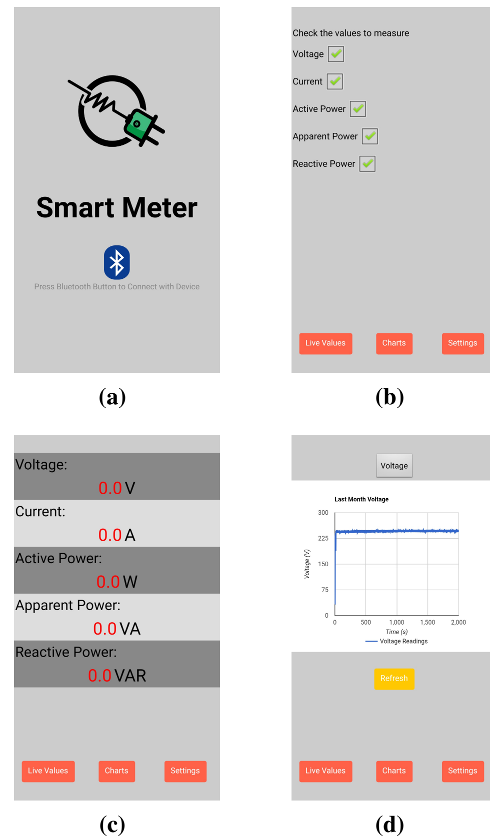

Fig. 14. Application Screens.

D. *Energy Metering*

To test the performance of the device, several linear and non linear loads where connected to the device during a period of time.

The information is saved every 10 seconds and saved in the microSD Card. To view the power consumption of a device it is required to have the Smartphone Application or remove the memory card from the device and read the values in a computer.

A refrigerator was connected to the system for 3 hours. According to its characteristics, the refrigerator works with a current of 0.6 A and is connected to the mains. Figure 15 shows that the RMS value of the voltage in refrigerator. After connecting the refrigerator it took about 10 min to power up and then remained on until it was turned off as it is shown in Figure 16. The consumed power is shown in Figure 17.

V. Conclusions

An energy monitoring device to be used in the long-term monitoring of the energy consumption of a single mains connected device was developed and tested.

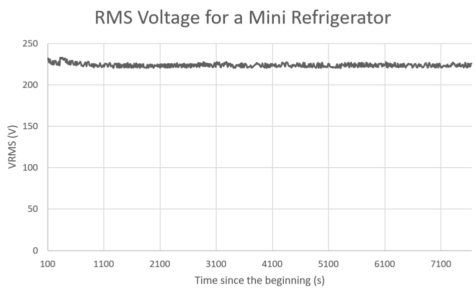

Fig. 15. RMS Voltage for a refrigerator.

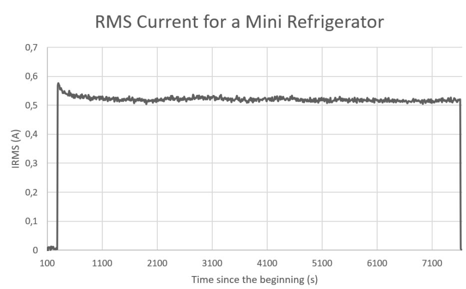

Fig. 16. RMS Current for a refrigerator.

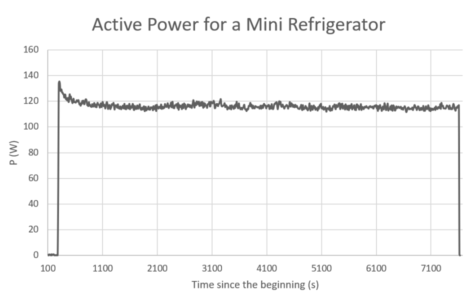

Fig. 17. Power consumed by a refrigerator.

The system is composed by a microcontroller, a memory module composed by a SD memory card, a power supply, a Bluetooth module and an energy meter IC.

To power the circuit, a capacitive transformerless power supply is used instead of a traditional power supply with a transformer, since the proposed solution is smaller and cheaper. This power supply allows the system to work without a battery as long as it is connected to the grid and an energy fault doesn't occur. In case of an energy failure the system is prepared to work on a battery to prevent from losing information and keep a record of the measurements. An analysis of this circuit was performed by varying a load in its terminals. The power supply was capable of supplying the necessary current to the system.

To measure the power consumption of a single mains connected device it is required to measure and process information about the load voltage and current. The system has a resistive voltage divider as voltage sensor and a shunt resistor to measure the current. These sensors are connected to a specific energy metering IC that processes the data performing every calculation needed to obtain the RMS values of voltage and current, as well as active, apparent and reactive power. To save the measured information a SD memory card is used to avoid the loss of data in case of both the power supply and battery won't work. The system was connected to several loads and the information about the power was stored in the memory card. In a PC was possible to verify that all the measurements were stored. To test these circuits a load was connected to system for some time and the measured values stored in the SD card, then theses values were read in a PC confirming that no information has been lost.

To communicate with the client, a Bluetooth module is used to send the collected information from the SD Card to an Android smartphone. To test this module, a load was connected to the system and the values measured were stored on the memory card, then a request from the application was sent to the device and the stored data displayed on the phone being verified that all the values from the SD card were transferred to the application.

References

[1] Natasha Wan; Kevin Manning, Exceeding 60-Year Life Expectancy from an Electronic EnergyMeter, Metering Asia Pacific Conference, February 2001.

[2] Rachel Kaplan, Frequently Asked Questions (FAQs) Analog Devices Energy (ADE) Products. [Online]. Available: http://www.analog.com/static/imported-files/applicationnotes/AN639.pdf

[3] Vinaya Skanda, Power Factor Correction in Power Conversion Using the dsPIC DSC. [Online]. Available: http://ww1.microchip.com/downloads/en/AppNotes/01106A.pdf

[4] W. Mack Grady, Robert J. Gilleskie, Harmonics and how they relate to power factor, EPRI Power Quality Issues and Opportunities Conference, November 1993.

[5] E.E.Institute, Handbook For Electricity Metering, 11th edition, 2014.

[6] William Koon, Current Sensing for energy metering, Analog Devices Inc. [Online]. Available: http://www.analog.com/media/en/technical-documentation/technical-articles/16174506155607IICPaper.pdf

[7] Direct Measurement of AC Current by Measuring the Voltage Drop on the Coaxial Current Shunt, IEEE Transctions on Intrumentation and Measurement, Vol. 58, No. 4, April 2009.

[8] Transformerless Power Supply Design, Designer Circuits, LLC. [Online]. Available: http://www.designercircuits.com/DesignNote1b.pdf

[9] Reston Condit, Transformerless Power Supplies: Resistive and Capacitive, Microchip Technology. [Online]. Available: http://ww1.microchip.com/downloads/en/AppNotes/00954A.pdf

[10] ZigBee Alliance, Understanding ZigBee Gateway, 2010. [Online]. Available: https://www.zigbee.org/zigbee-for-developers/zigbee-gateway

[11] Wi-Fi Alliance, Generational Wi-Fi User Guide, 2018. [Online]. Available: https://www.wi-fi.org/discover-wi-fi

[12] Bluetooth SIG, Radio Versions, 2018. [Online]. Available: https://www.bluetooth.com/bluetooth-technology/radio-versions

[13] Microchip, Introduction to Bluetooth Low Energy. [Online]. Available: http://microchipdeveloper.com/wireless:ble-introduction

[14] Stephen T. English, A Low Cost Watt-Hour Energy Meter Based on the ADE7757, Analog Devices. [Online]. Available: http://www.analog.com/media/en/technical-documentation/application-notes/AN-679.pdf

[15] Microchip. 64/80/100-Pin, General Purpose, 16-Bit Flash Microcontrollers. [Online]. Available: http://ww1.microchip.com/downloads/en/DeviceDoc/39747F.pdf

[16] Analog Devices. Single-Phase Multifunction Metering IC with di/dt Sensor Interface. [Online]. Available: http://www.analog.com/media/en/technical-documentation/data-sheets/ADE7753.pdf

[17] Microchip. Bluetooth 4.2 Low Energy Module. [Online]. Available: http://ww1.microchip.com/downloads/en/DeviceDoc/50002489C.pdf