Design and implementation of a plug-in power metering device

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Abstract

This project focuses in developing and implementing a device capable of monitoring the electric power consumption of an appliance connected to the 230 V, 50 Hz power grid. The device presents a Schuko CEE 7/4 to connect to the grid and on the other end a Schuko CEE 7/3. The appliance maximum current is 16 A. A specific energy metering Integrated Circuit (IC) is used and sensing circuitry is included for voltage and current, to attenuate the grid amplitude to the Analog-to-Digital Converter (ADC)'s input range of the IC and convert current drawn into a differential potential, once again taking into consideration the input range. The system includes a non-volatile memory where measured values are stored. The files format will be readable by any modern device, for example a smartphone or a computer. The system also comprises a wireless communication module, to offer system management (e.g. period between saved values) and data analysis options (e.g. graphs) to the user without interrupting the data acquisition. Avoiding the necessity to take the Secure Digital Card (SD Card) out of the metering device to view the results, which requires the system to be halted. The device is based on a Peripheral Interface Controller (PIC) microcontroller from Microchip, which manages data processing and communication with the energy metering IC, SD Card and bluetooth module.

Keywords: Energy metering, Single Phase, Embedded System

1. Introduction

1.1. Purpose and motivation

The XIX century was marked by the spread of electric energy starting with street lighting and later on in households, to power telegraphs, telephones, radios and televisions succeeded by modern appliances, such as fridges and washing machines. The demand for electric energy will only tend to increase as the world moves to a more interconnected society with data centers working around the clock [1]. This consumption of the modern era comes as a service and with it came the need to meter it for billing purposes. Two centuries passed by and nowadays the need to monitor the electric energy consumption goes beyond billing. This includes balancing the power grid based on demand in real time and patterns from previously logged information. Furthermore, the need of better knowing the load patterns of an equipment; where it can be a steady load or its consumption may be arranged in short bursts, lead to the development of more advanced plug-in power meters.

The primary objective of this work is to develop a compact device able to monitor the electrical power consumption of an Alternate Current (AC) equipment. The energy metering device will work as a man-in-the-middle; where the device is connected to the mains, and the load to a Schuko connector present on the developed device. The project must acquire data for a long period of time and register on non-volatile memory, connect to the mains through a Schuko CEE 7/4 connection and pass-through to the metered equipment with a Schuko CEE 7/3 connection. A metering IC [2], current and voltage sensing circuitry is required for the measurement. As for processing unit, the embedded system must be based on a PIC [3]. A wireless interface [4] in conjunction with a smartphone Application (APP) shall be integrated for live monitoring and download of the acquired data, improving the user experience. As such, the goals for this project are to develop: embedded measurement system, firmware capable of performing processing and routing of data, metering IC, conditioning circuit, power supply, integration of non-volatile memory, wireless interface and smartphone APP.

1.2. Electric Power

In the XIX century a battle between two electric...
energy standards for mass distribution took place, between Thomas Edison (Direct Current (DC)) and Nikola Tesla (AC). The high distribution cost of DC, mainly linked to power losses in the line that forced the presence of a power plant no further than 1 mile away from the end user, as well as the high cost and at the time lack of step-up and step-down voltage technology for DC [5] encouraged three-phase AC to be implemented. [6]

A load with an impedance purely resistive is when all power consumed by the user is transformed into transformed energy, light, mechanical, sound, etc. However, not all loads are resistive, and thus may hold a reactive component, either capacitive and/or in most cases inductive (motors, transformers). A reactive component generates a phase shift on the sine wave of current that feeds the load.

The power dissipated in terms of resistive component is called Active Power (P) expressed typically in kilowatts (kW), and the reactive component, Reactive Power (Q) expressed in kilovolt ampere reactive (kVAr). The later, is considered a loss, since it is not converted into other form of useful energy to the load. Apparent power (S) expressed in kilovolt ampere (kVA) is the amount of electric energy required to distribute a given (P); thus S could be equal or higher than P. For a given sinusoidal voltage and current, apparent power, described by active and reactive power (1 and 2) as represented in Figure 1, remains constant [7].

$$\vec{S} = P + jQ.$$  \hfill (1)

And

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

Power factor (PF) is the ratio (3) between P and S,

$$PF = \frac{P}{S}. \hfill (3)$$

Where for sinusoidal waveforms, PF has a direct relationship with the phase shift ($\phi$) between voltage and current, given by

$$PF = \cos(\phi). \hfill (4)$$

\( S \) (5) is given by the Root Mean Square (RMS) value of voltage and the RMS value of current,

$$S = V_{RMS} \times I_{RMS}. \hfill (5)$$

From (4), a null power factor is characterized by 90 degrees phase shift either from a capacitive load (-90 °) or an inductive load (90 °).

2. State of the Art

2.1. Voltage Sensor

The national residential electric grid has an RMS voltage value of 230 V, and ADCs require lower input voltage; thus there is a need to create a conditioning circuit. There are three methods that could be implemented: Hall effect voltage transducer, Voltage Transformer (VT) and resistive divider.

On an Hall effect based voltage transducer, a primary winding is fed by a current proportional to the voltage to be measured, generating a magnetic flux. Separated by a small air gap there is a Hall effect sensor which senses this flux, causing a potential difference at the output. The output can be connected in a open loop where the output of the Hall Effect sensor is the system output; the core can be easily saturated and is characterized with greater nonlinearity in terms of error with respect to the closed loop. In a closed loop the Hall Effect sensor output feeds current to a secondary winding, amplified by a high-gain Operational Amplifier (OPAMP) and translated into voltage by a resistor with exactly the same waveform of the primary current. [8]

This setup offers galvanic isolation between the high voltage line and the data acquisition system, providing remarkable linearity and bandwidth compared to transformers [8]. Although, its working principle makes it susceptible to false readings due to external magnetic fields [9].

A voltage transformer offers a simple solution to step-down the voltage to a suitable range; based on induction between a primary and a secondary winding. Galvanic isolation can be guaranteed but considerable volume and high cost must be taken into account. The voltage at the secondary is

$$V_s = \frac{n_P}{n_S} \times V_P, \hfill (6)$$

where \( V_P \) is the voltage in the primary (RMS 230 V), \( V_S \) the output voltage in the secondary winding, \( n_P \) and \( n_S \) the number of turns in the primary and secondary winding, respectively [7].
A resistive divider is a series of resistors to create an attenuation network placed in parallel with the source. Resistors should be high valued to pull the least current possible; diminishing its effect on the source. This setup is described by the source voltage, the series of resistors and the desired output voltage defined by

\[ V_{\text{out}} = \frac{R_2}{R_1 + R_2} \times V_{\text{AC}}. \] (7)

This configuration is the cheapest of them; although it requires \( R_1 \) to be a series of multiple resistors to share the dissipated power across them. The occupied area is small, especially if Surface Mounted Device (SMD) resistors are used but lacks the advantage of isolating the output from the mains.

2.2. Current Sensor

The load voltage does not vary much contrary to current; thus it is required a wider measurement dynamic range and frequency range due to rich harmonic contents in the current waveform. There are several current sensor topologies, such as: Low resistance current shunt, Current Transformer (CT), Hall effect sensor and Rogowski coil. [10]

A shunt resistor is the cheapest solution for current sensing; with highly stable low values available in the range of \( \mu \Omega \) to \( m \Omega \). This resistor should be placed in series with the load. The voltage across the resistor is proportional to the current flowing through it

\[ I = \frac{U}{R}. \] (8)

Two disadvantages to take into consideration is parasitic inductance and dissipated power. When performing high precision current measurements even at line frequency, the inductance is generally in the order of \( n \)H but its effect in the phase can be significant enough to cause an error in case of a low power factor. The heat dissipated by the resistor is proportional to the square of the current flowing and the smaller its value lesser the heat generated [7] [10].

A current transformer translates the current flowing through the primary winding, which is connected in series with the load, into a lower current in the secondary. Among high currents measurements, this topology is the most common. It’s a low power sensor, having little impact on the measured current and deals great with high currents. It presents a low phase-shift if calibrated although in extreme cases of current or substantial presence of DC component it may saturate due to the core characteristics. After the ferrite core is magnetized, it will show hysteresis with negative repercussions on its accuracy, until demagnetized [10].

As in Hall effect voltage transducers there are open-loop and closed-loop implementations. The first being the option with lower cost. The system withstands measuring very large current and has a good frequency response. On the other hand, the output of the Hall effect sensor is sensitive to temperature and usually requires a stable external current source [10].

A Rogowski coil is an inductor which has mutual inductance with the conductor carrying the current to be measured. This phenomena makes that a change in the current passing through the wire causes an induced electromagnetic force in the coil, due to the magnetic field generated. Rogowski coil typically has a core of air, so in theory there is no hysteresis, saturation or non-linearity. Its low inductance allows for fast response to current changes and the lack of an iron core makes it respond linearly even at high currents. These characteristic as well as its smaller size and cost compared to a CT make it a better option for high current applications, such as, in electrical power transmission. Its output is proportional to the time derivative of the current

\[ V_{\text{out}}(t) = -\frac{1}{RC} \int v_{\text{in}}(t) \, dt, \] (9)

therefore requires an integrator with an OPAMP. [10]

2.3. Wireless Communication

Wireless communication offers further flexibility to the system by removing the need of a cable and by making it more versatile in terms of to what it can connect to. Smartphones lack ethernet ports and even some laptops nowadays. For the device in development, a short range wireless connection is ideal for system management since all data is saved locally there is no need to constantly upload it elsewhere. Embedded systems in general implement short range wireless communication such as Bluetooth, Bluetooth Low Energy (BLE), WiFi or ZigBee [11].

WiFi would be useful for an Internet of Things (IoT) approach since it would be the only standard implementation that would easily connect to an existing Access Point (AP) connected to the internet. Although it is the fastest option and with high range, there is no benefit to include the system in a Local Area Network (LAN) if there is no desire to implement a server to make it accessible outside (Wide Area Network (WAN)). The current implementation of this project looks to include a wireless interface but not to make it remote accessible since
it would increase the total system cost and complexity. ZigBee is a low power, highly resilient wireless network type, with range that could match WiFi and can be further expanded through a mesh topology. But it isn’t commonly offered on smartphones and laptops, external modules would need to be acquired [12].

Bluetooth or BLE offers enough range for the purpose of the developed system, it is low cost, low power and is available in virtually any device making it ideal in terms of versatility.

2.4. Non-volatile memory - SD Card

A non-volatile memory allows the metering system to be independent in terms of data logging. SD Card offers a good price per GB ratio, enough capacity for long term logging, basic and fast communication through Serial Peripheral Interface (SPI). Furthermore, its popularity made available a number of abstraction libraries to simplify the programming necessary for the interaction between the embedded system and the SD Card. These abstraction layers also implement a filesystem such as File Allocation Table (FAT); making the SD Card compatible with a broad range of devices (computers, smartphones, tablets, etc.) [13].

3. System Architecture

The developed system is comprised by current and voltage sensors, an energy meter IC, a non-volatile memory unit, a wireless communication interface and a PIC microcontroller.

![Figure 2: System block diagram.](image)

3.1. Microcontroller

Microchip’s PIC24 family of Microcontroller Units (MCUs) features a 16 MIPS core and enhanced on-chip peripherals [14]. It communicates through SPI1 module with the SD Card, SPI2 module with the energy meter IC and Universal Asynchronous Receiver-Transmitter (UART) with the Bluetooth module. Other features worth mentioning is the availability of another UART, two Inter-Integrated Circuit (I2C) peripherals, a Real Time Calendar-Clock (RTCC), five timers and interrupts based on external inputs, timers or peripherals.

An Fast Internal Oscillator (FRC) feeds a clock source of 8 MHz and with the integrated Phase-Locked Loop (PLL), it reaches 32 MHz, maximizing the peripherals clock at 16 MHz.

The system was designed so that by tweaking three properties, namely the UART clock, enable/disable predefined CTS and RTS pins and customize the termination character, any UART capable bluetooth module can be used. PIC’s UART module has a register controlled baud rate generator ($UBRG_X$), which values can be calculated depending on the selected mode set by $BRGH$. [3]

The baudrate was set at 115.2 kHz delivering an error free and more stable communication with the bluetooth module.

In addition to the three serial peripherals used to access the SD Card, transmit/receive data over Bluetooth and communicate with the energy meter IC, the integrated RTCC is set to append timestamps to the acquired samples. Furthermore, three interrupts are active, two of which are triggered by external inputs and the third one by the UART module. These external inputs are configured as such to detect the insertion of the SD Card leading to its initialization and to sense the zero-crossing output (ZX) from the energy meter IC thus synchronizing the reading of the registers [2]. UART interrupts allows the system to fetch the streamed data from the Bluetooth module to a software buffer as soon as it’s available without polling; received strings can be later processed when the system is free of other more critical tasks (e.g. retrieving samples from the IC, free buffer space by flushing samples to the SD Card).

3.2. Energy meter IC - ADE7753

The Analog Devices’s ADE7753 is an energy meter IC with a high accuracy, compliant with the following International Electrotechnical Commission (IEC) standards: IEC 60687/61036/61268 and IEC 62053-21/62053-22/62053-23. The IC is intended for single phase applications with all the signal processing required to perform active, reactive and apparent power calculation. It can also measure RMS voltage and RMS current. This energy meter resorts to two second-order $\Sigma – \Delta$ ADCs to acquire the analog inputs. The IC’s sensing inputs are comprised of two fully differential voltage input channels with a maximum voltage range of $\pm 0.5$ V and user defined gains of 1, 2, 4, 8 and 16 to adapt for
a smaller input range. Furthermore, channel 1 also has a full-scale input range selection for its ADC. The IC power consumption tops at 25 mW with a 5 V supply. The ADE7753 is compatible with SPI to read data and allows calibration for power, phase and input offset with on-chip registers. [2]

The zero-crossing detection circuit generates its output in regards to the channel 2 input; ZX signal is logic high when a rising flank crosses zero and logic low on a falling edge crossing zero. This output is used to generate interrupts and synchronize readings, as well as for calibration purposes. The channels sampling rate can be user selected (MODE register) between 3.5 kSPS, 7 kSPS, 14 kSPS or the default and used in this project, 27.9 kSPS. The RMS values are then simultaneously calculated for both channels by

\[
V_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} V(i)^2} \quad (10)
\]

and saved in their corresponding registers (V/RMS, IRMS). All conversions from the registers values to Volts (channel 2) and to Amps (channel 1) must be done in the microcontroller; taking into account the selected input range and gains for the ADCs, as well as the designed voltage and current sensor circuits.

The average power over a defined integral number of periods \( n \) is given by,

\[
P = \frac{1}{nT} \int_0^{nT} p(t) dt = VI, \quad (11)
\]

where \( T \) is the line cycle period, \( V \) is the RMS voltage and \( I \) the RMS current.

The average reactive power over a selected integral number of lines cycles \( n \) is given by,

\[
RP = \frac{1}{nT} \int_0^{nT} R\phi dt = VI \sin(\phi), \quad (12)
\]

where \( \phi \) is the phase difference between the voltage and current channel.

Apparent power, as defined in 5, is the product of the effective voltage and current delivered, independent from the phase shift \( \phi \).

3.3. Signal conditioning

A conditioning circuit is present at the input of both ADE7753’s channels to meet the IC input range, and if necessary it’s possible to amplify the resulting signal to an ideal range avoiding loss of information due to the signal amplitude or the ADCs resolution.

The choice of voltage sensor was focused on low cost and reduced footprint thus leading to a resistive divider composed of a single 1 kΩ resistor \( (R_2) \) and two 499 kΩ resistors \( (R_1) \), resulting in a ratio of

\[
\text{ratio} = \frac{R_2}{(R_1 + R_2)} = 1 \times 10^{-3}. \quad (13)
\]

For a voltage peak of 425 V \( (300 \text{ V}_{RMS}) \), the voltage sensor output is given by

\[
V_{output} = V_{peak} \times \text{ratio} = 0.425 \text{ V}, \quad (14)
\]

and maximum current is obtained from

\[
I_{output} = \frac{V_{peak}}{(R_1 + R_2)} = 0.425 \text{ mA}. \quad (15)
\]

The power consumption per resistor can be calculated from

\[
P_{max} = I_{output}^2 \times R. \quad (16)
\]

The resulting power consumption is 180 uW for the 1 kΩ and 90.3 mW for the 499 kΩ. The resistors of 1 kΩ (ERJP06F1001V) and 499 kΩ (ERJP06F4993V) used for the voltage sensor, have a power dissipation characteristic of 500 mW. This large margin in terms of power dissipation allows for cooler operation and a steadier temperature overall for the resistors, thus mitigating the resistance drift that otherwise could occur with the temperature increase. [15]

Once again, the selection for the current sensor relies on the same attributes, low cost and small footprint. A 3 W current sense chip resistor of 10 mΩ with a low temperature coefficient of ± 50 ppm/°C from Bourns is chosen. The resistor is capable of handling currents up to

\[
I_{shunt,max} = \frac{P_{shunt,\text{max}}}{R_{\text{shunt}}} = \frac{3}{0.01} = 173 \text{ A}. \quad (17)
\]

And the voltage output is within energy meter IC range, as demonstrated by

\[
V_{\text{out},\text{max}} = I_{\text{max}} \times R_{\text{shunt}} = 0.173 \text{ V}. \quad (18)
\]

3.4. Bluetooth module - Itead HC-05

Wireless communication is carried by a Bluetooth module with the task to create an abstraction layer from the wave driven transmission to the available serial communication, most of which the available solutions resort to UART.

The Itead HC-05 [4] supports Bluetooth 2.0 with Enhanced Data Rate (EDR), delivering a maximum bit rate of 3 Mbps. Connects to the PIC via
UART, it allows data to be streamed bidirectionally. Any American Standard Code for Information Interchange (ASCII) string sent to the module, either via Bluetooth from a smartphone or from the microcontroller via UART is echoed to the other device. The termination character, declaring the end of transmission, is a Carriage Return Line Feed (CRLF).

The baud rate of the unit can be configured when powered in AT mode [4]. An experiment was setup to check the stability of the selected baud rate. A string was sent repeatedly via UART to the Bluetooth module and echoed to a smartphone running a serial terminal, if any character was missing or incorrect; it was considered unstable. CTS and RTS pins are physically inaccessible in this version of the module, all tests were conducted without flow control, from which the maximum baud rate achieved for viable operation was 115.2 kHz.

3.5. Memory - SD Card

Non-volatile memory allows the system to store and keep the previously measured data even when powered down.

All the acquired samples will be saved on this type of memory, following a specific file tree organization (e.g. /YEAR/MONTH/DAY/hour.csv). CD (Card Detect) pin doesn’t take part of the SPI interface, it’s a switch present on the SD Card holder that gets closed when a card is inserted. The microcontroller should have a pin set as input to sense the closed circuit and initialize the SD Card when inserted. To interface with the SD Card memory blocks a file system (FAT) and library module, FatFS, was implemented. Offering an abstraction layer on the programming side to create/read/edit folders and files tailored to small embedded systems, while keeping the SD Card interpretable by any device. [16]

All files and folders, for a complete thirty-one day run, are created at startup to reduce write time when flushing the acquired data into memory. But a dynamic function was also implemented, in such way that if left more than thirty-one days running, there is no major data loss since files and folder will continue to be created as needed; making the SD Card volume size the real limiting factor. Although, due to the time required for these actions to complete (file: two seconds, folder: five seconds) some data may be lost during the process of file/folder creation, depending on the selected acquisition rate. Lastly, if the user requests to stop the run prematurely, all empty files and folder are deleted.

3.6. Power Supply

The system requires two different voltage rails to work, 3.3 V and 5 V. For the implemented microcontroller family (PIC24F) and SD Card, 3.3 V is needed and 5 V for the energy meter IC (ADE7753). The Bluetooth module (HC-05) can be powered with 5 V through the module or 3.3 V if connected directly to the chip. The power source of the system is the mains AC outlet. The total system power consumption is 235 mA on the 3.3 V rail and 84 mA for the 5 V rail. [3] [2] [17] [18] 

The solution is depicted in Figure 3.

![Figure 3: Power Supply Unit (PSU) diagram.](Diagram)

A universal AC input (85 to 264 VAC [19]) switching power supply rectifies and attenuates the mains AC voltage to DC 12 V and is capable of delivering up to 1.25 A. [19] It is required to further step-down the voltage to the required levels. From 12 V to 5 V, there is a 7 V drop, power dissipation is a concern, but can be circumvented with a step-down voltage switching regulator. The LM2575-5, when powered with 12 V, can deliver up to 1 A, with a maximum working internal temperature of 150 °C, a thermal resistance characteristic of 65 °C/W and a low dissipated power,

\[
P_{\text{max}} = (V_{\text{in max}} \times I_{Q_{\text{max}}}) + \left(\frac{V_{\text{out}}}{V_{\text{in min}}}\right) \times I_{\text{out max}} \times V_{\text{sat max}} \]

\[
= 0.694 \text{ W}.
\]

For the device to shut down, it would require an ambient temperature over 100 °C, since the internal temperature rise over ambient is

\[
T_{\text{rise}} = P_{\text{max}} \times R_{\phi} = 45.12 \text{ °C}.
\]

Lastly, a linear voltage regulator is used to achieve the final step-down to 3.3 V, from the 5 V supplied by the LM2575-5 output. The MCP1825S shuts down when internal temperature reaches 150 °C, has a current limit of 500 mA and a thermal resistance characteristic of 62 °C/W. For the device to shut down, it would require an ambient temperature over 80 °C, as demonstrated by

\[
P_{\text{max}} = (V_{\text{in max}} - V_{\text{out min}}) \times I_{\text{out max}}
\]

\[
= 1.016 \text{ W},
\]

and
\[ T_{\text{rise}} = P_{\text{max}} \times R_\phi = 63 \text{ °C}. \]  

(22)

3.7. Mobile APP

A smartphone mobile APP was developed to complement the designed system. It offers the possibility to review previously acquired data (voltage RMS, current RMS, apparent, active and reactive power) in form of graphs, as well as live samples. The user can start, pause or reset the system and instantly change the acquisition rate from a list of predefined intervals. Moreover, the APP has the task to sync the system, on connect the APP automatically updates the time and date of the PIC RTCC based on the smartphone clock and calendar. An application screen is depicted in Figure 4.

![Application screen example](image)

Figure 4: Application screen example.

4. Results

4.1. Energy meter IC - ADE7753

The SPI1 peripheral was set at 4 MHz for the ADE7753 since this is the maximum frequency that could be achieved while keeping consistent results. An Hantek 4032L data analyser was used to verify clock, chip select behaviors and correct bytes where being transmitted [20].

Writing and reading is defined by the most significant bit of the address, 1 to write and 0 to read. Figure 5 shows the request for the energy meter IC to reset by writing 0x0040 to the \textit{MODE} register (0x09). Figure 6 is the reply from the ADE7753 of a successful reset, confirmed by reading the \textit{STATUS} register (0x0C) and acknowledging the reset flag (0x0040). [2]

![Software reset request](image)

Figure 5: Software reset request.

4.2. SD Card and RTCC

Due to the high load that may occur on the SD Card in certain situations, such as: write measured values and read request made over bluetooth to download the last couple hours of data; the card has SPI2 peripheral [3] exclusively dedicated to it. The clock is set at the maximum available internally on the PIC24FJ128GA010 rated at 16 MHz.

During an experiment, the microcontroller was set to continuously write to the SD Card, multiple text files were created and filled with timestamps; every thousand program cycles a new file was created named after the loop number. Files were created successfully and all characters were saved. Furthermore, on Windows file explorer, the file properties specify the correct time and date in \textit{created} and \textit{last modified} variables.

4.3. Bluetooth module - Itead HC-05

A bluetooth communication has been successfully established with a smartphone; the app used to confirm the result was a simple bluetooth serial terminal. All messages sent by the user were immediately acknowledged by the PIC24 thanks to the UART interrupt [3].

Main functionalities are accomplished, but the transmission speed is lacking at a mere 115.2 kHz, due to the UART interface and limited clock fed to the PIC24 peripherals of 16 MHz. To solve this situation, either the UART has access to a higher clock source or changing the bluetooth module for one with a SPI interface would be preferable. Although the latest comes with the caveat of having to share and manage one SPI peripheral with two devices, since both are already in use for the SD Card (SPI2) and the energy meter IC (SPI1) [3].

4.4. Calibration

The PCB design is finalized as depicted in Figure 7.

For calibration purposes, a resistive load is applied to the PCB mains output. Two Alcor HS100 220 Ω aluminium housed power resistor [21] were connected in series, for a total of a 440 Ω load.

For a voltage RMS of 230 V\textsubscript{RMS}, the expected current RMS is,
\[ I_{\text{output}} = \frac{V_{\text{RMS}}}{R} = \frac{230}{220 \times 2} = 0.523 \text{ A}. \]  

From Equation (16), the resulting power consumption per resistor is given by,

\[ P_{220} = (0.523)^2 \times 220 = 60.18 \text{ W}, \]  

which is in the range of the 100 W rated power dissipation capabilities of these resistors. [21]

The calibration values for the voltage channel are given by

\[ V/LSB = \frac{V_{\text{RMS multi-meter}}}{V_{\text{RMS reg}}} = 2.11 \times 10^{-4}, \]  

\[ A/LSB = \frac{I_{\text{RMS multi-meter}}}{I_{\text{RMS reg}}} = 1.85 \times 10^{-5}. \]  

Active and apparent power are equal when current and voltage waves are in sync. For the same test setup it is expected a null reactive power. The expected active and apparent power in this situation from (2) and (5) are given by

\[ P = S = V_{\text{RMS}} \times I_{\text{RMS}} = 132.23 \text{ W(VA)}, \]  

where \( V_{\text{RMS}} \) and \( I_{\text{RMS}} \) were measured with the multi-meter.

The following constants between register values and energy were obtained with accumulation mode set to five line cycles \((n)\) [2] and are calculated from

\[ \text{Wh/LSB} = \frac{P \times \left(\frac{n \times \text{period}}{3600}\right)}{\text{LAenergy}_{\text{reg}}} = 1.41 \times 10^{-4}, \]  

\[ \text{VAh/LSB} = \frac{S \times \left(\frac{n \times \text{period}}{3600}\right)}{\text{LVenergy}_{\text{reg}}} = 1.6 \times 10^{-4}. \]  

Where the line cycle period is calculated in seconds by the IC and is available through \textit{PERIOD} register. [2]

A different load was connected, a fully charged laptop running a benchmark. Since active and apparent power are already calibrated, it is possible to obtain the reactive power based on the calibrated values of active and apparent power (\(\text{LVAenergy}_{\text{reg}}\) and \(\text{LAenergy}_{\text{reg}}\)) from the energy meter IC,

\[ |Q| = \sqrt{S^2 - P^2} = 23.899 \text{ VAR}, \]  

Resulting in a reactive energy conversion defined by

\[ \text{VARh/LSB} = \frac{|Q| \times \left(\frac{n \times \text{period}}{3600}\right)}{\text{LVARenergy}_{\text{reg}}} = 6.363 \times 10^{-4}. \]

4.5. Results

Tests were conducted to prove the functionality of the developed system. Data was logged at a rate of 200 ms intervals. Despite there wasn't always the expected amount of samples, which was nailed down to the energy meter IC itself that sporadically creeps to respond the SPI requests when using a low level of line cycles accumulation, information was correctly saved in the SD Card. Further investigation is required into the limitations in terms acquisition rates but the finalized PCB increased the system stability in terms of voltage supply and signal integrity versus previous prototypes. From the acquired information, RMS voltage, RMS current, apparent, active and reactive power values show expected results.

Figures 8 and 9 show the results of a twenty minutes execution with a constant 440 Ω load with a measured voltage and current of 225 V and 0.512 A, respectively. The results from Figure 9 show an apparent and active power (27) overlap, as well as a near absence of reactive power as expected from a resistive load. These traces of reactive power may be linked to the need for a calibration based on a larger data set and/or the presence of capacitance and noise.

Figures 10 and 11 present the acquired values over a thirty-five minutes run of a laptop in three different states: idling, charging while in sleep mode and running a benchmark. In its turn, Figure 10 shows the RMS voltage and RMS delivered to the laptop charger. The three different load states can be seen on the acquired current values. While idling, the current constantly
Figure 8: Measured RMS voltage and RMS current from a resistive load.

Figure 9: Measured apparent, active and reactive power from a resistive load.

Figure 10: Measured RMS voltage and RMS current from a rated 65 W laptop charger.

Figure 11: Measured apparent, active and reactive power from a rated 65 W laptop charger.

be confirmed as active power in Figure 11.

The energy meter IC response limitations previously mentioned, can be perceived in these tests given that some values mainly in the voltage measurement are off-track from the expected. Nevertheless, the acquired results offer good expectation for further development of this project, although calibration needs further attention.

5. Conclusions

For further insight in electric power consumption, an accurate and feature complete energy metering device is required. The implementation of a system based on an IC designed specifically for the purpose, not only adds an abstraction layer for easier integration but also assures a level of certified accuracy and reliability [2]. This approach only requires signal conditioning which can be accomplished at low cost without a trade-off in size by using a resistive divider and a shunt resistor, with the only concern being power dissipation.

The embedded system has a non-volatile memory (SD Card) access via SPI and a working wireless communication via bluetooth, integrated by UART. Although, with a compromise in data transfer speeds, the asynchronous serial communication and its implementation in the program makes it easily adaptable to a wide range of UART capable bluetooth modules available on the market. As for the data logging, the FAT file system offers compatibility with all devices that include an SD Card reader and the chosen file structure not only improves file access performance for the PIC but also makes it straightforward for the end-user to navigate through the measured information. All files are in Comma-Separated Values (CSV) format making it compatible with spreadsheet programs for advanced information processing. A smartphone APP was successfully developed with the ability to adjust...
acquisition rate, download sections of the acquired data, which is presented in the form of graphs and a constantly updated view of the last measured values. The user can pause the execution and take the SD Card for analysis and later insert it back to resume measurement. The APP is also in charge of adjusting the PIC RTCC automatically upon connection via bluetooth and offers the possibility to fully reset the system and clear the measured data from the SD Card.

The project mostly fulfills the defined goals. An embedded measurement system with data logger functionality and wireless capabilities was fully designed. Furthermore, an APP was developed to complement the system and offer further versatility to view the data.

This work could be improved by focusing on the following aspects:

- Further smartphone APP development could lead to speed improvements when processing the downloaded data;
- Implement a relay and exploit the IC’s capability to detect line anomalies;
- Incorporate a battery and power-path management IC in case of energy fault or the relay being triggered;
- Find a more efficient format to save information and transmit data over bluetooth.

References


