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Technological Proposal for Measuring Electric Parameters in Households

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Summary

One way to supervise energy consumption, as well as guaranteeing the correct billing and delivering of the electric service is to monitor several electric parameters in the network and present them in a intelligible way. This article shows the design and implementation of a prototype capable of indirectly measuring electric variables present in a residential installation, with the purpose of monitoring and showing the value of each parameter to a subscribed user while storing the energy consumption data from up to 30 days so they can be visualized in a interface. The prototype is based on an Arduino embedded system, which is in charge of handling data for voltage, current, energy and power. Additionally, the Arduino system is synchronized in real time with a clock, an external memory crucial for validation and an LCD touchscreen that serves as an interface for the analysis of data acquired and the display of variables in real time. In particular, the measuring device has pressure error lower than 1.72% when compared to the reference instrument used in experimental testing which reveals the optimal operation of the prototype.

Keywords: Arduino, Electric Energy, Electric Parameters, Electric Measuring Device, Sensor.

INTRODUCTION

Currently, technological breakthrough have extended worldwide, which is why the electric sector is no exception to this reality since it has also seen significant impact in the scientific and technological development on a global scale [1]. This breakthrough has led to an increase in energy consumption; hence, plans have been focused on mitigating its indiscriminate use along with a supervision of such consumption [2]. The residential user depends on the electric energy bill emitted by the corresponding supplier, to know the value in pesos of its energy consumption over a month's period. Therefore, if the user has no knowledge on the billing process of monthly energy, he will not know for certain if the payment of this service obeys to the regulations of the Commission of Energy and Gas Regulation in Colombia (CREG) [3].

One method to supervise energy consumption, as well as guaranteeing correct billing, consists on monitoring several electric parameters of the network and showing them in an intelligible manner. Hence, this document focuses on the development of a prototype for measuring electric parameters which can be easily used by a residential subscriber. Variables must be shown in real time such as Effective Voltage (V_{rms}), effective current (I_{rms}), active power (P), reactive power (Q), apparent power (S), power factor (PF) and energy (kWh).

The prototype uses voltage and current sensors directly connected to the main electric network. The output signal from the sensors is directed to an array of elements that perform electric conditioning that enables the detection of these signals through an Arduino Mega 2560 [3]. The latter manages the data in order to indirectly measure the mentioned electric variables and take the result of these calculations to an interface that includes an LCD touchscreen and an external card for data storage.

According to the previous statements, this article is structured as follows. Section II describes the work related to the topic of this document. Section III details the methodology used, defining the design criteria of the prototype. Section IV shows the results obtained through testing the prototype. Finally, section V includes a set of conclusions on the overall work.

RELATED WORK

This project seeks to establish a design and information basis, supported in a series of concepts which are openly accepted, which contribute to moving forward on the set goals. It is necessary to perform an overview on the current state of the technologies used, as well as the concepts that this project is built upon. Mainly, this project stems from controlling electric energy consumption through the information registered in the electric measuring device based on Arduino technology.

Alternate power measuring devices require sampling voltage and current simultaneously to obtain real power, reactive power and apparent power. It is common that both measurements are taken in physical proximity to one another and are fed to a single device that measures power. This setting is not the only way to acquire data since previous work have shown that the measuring process in which the channels for detection of voltage and current are decoupled in individual locations works the same way as a conventional measurement as seen in [4].

Smart measuring devices are a technology compatible with many applications in electric networks. Hence, its development involves modern control systems such as Arduino or Raspberry, which are used in electric measurement projects that involve an interaction based on reading values from a registry, in a sampling interval given by the Arduino device. The estimated data is sent to a Raspberry in charge of executing logical commands that turn them into values of active power, reactive power and apparent power [5].

Measuring electric energy must always highly accurate since errors in the measurements can lead to a substantial loss of income for energy suppliers as well as an overload of the end users. One of the factors that affect the accuracy in energy measurements is the phase shift introduced by the current transformer causing an important measurement error. Hence, in [6] algorithms have been employed in microcontroller capable of calculating the energy measurements through mathematical models that reduce the phase shift and boast accuracy without altering the system's relation error via software.

The idea of a smart electric measuring device has been previously studied due to the goal of reducing energy consumption in households through monitoring tasks. For this reason, the authors in [7] show a current measuring device for homes based on Arduino with a Matlab interface and constituted by current transformers with divided cores, current transducers, circuit rectifiers, the main Arduino board, the additional Wi-Fi Shield board and the base computer. The software portion resided in the Arduino board and in the base computer while the current was measured from two wires in the main supply panel. The authors took samples from the Arduino board and then sent them to the base computer to analyze the packets and carry out the analog-to-digital conversion of data in order to show to the user the current use or estimated apparent and real power.

The monitoring of electric parameters has been executed from a residential electric artifact as seen in [8]. In this case, the authors used an Arduino Due board as a controlling device to create a monophasic power measuring device involving both the current and voltage signals to calculate the instant power with display which was also implemented. The result of their work, derived in the creation of an adequate measuring device to be used in monophasic electric equipment with a maximum current of 13A and an operation accuracy of up to 96.54%.

Energy readings have been obtained through various methods over time; one of them is the SPOT [9] observation tool for scalable power that can measure nodal energy and energy within a dynamic range. SPOT uses a simple architecture that begins by putting a derivation resistance in its input, turning the passing current into voltage. This voltage is proportional to the energy consumption. A differential amplifier and low-pass filter are used to amplify and restrict the bandwidth of the signal, respectively. The authors of SPOT in [9] use voltage-to-frequency converter (VFC) to convert the voltage into a periodic wave with a frequency which is proportional to the input voltage, which is also proportional to the power. Finally, the output pulses of the VFC are added in a counter to determine energy measurements, while a separate counter is used to maintain a time unit so they can be read in the output.

The use of Arduino as a base to create a smart measuring device for energy is a concept that has become frequent over the past years due to its versatility and low cost in the market. Smart measuring devices are digital meters that replace the old analog meters used in households to record the electric use. For example, in [10] a smart meter was created based on Arduino UNO, which takes the signals coming from two sensors especially designed for the Arduino system and registers them in order to measure energy, power and power factor form an electric monophasic installation.

The calibration of a smart meter based on Arduino is crucial to achieve a proper result of the measured parameters. Therefore, the authors in [11] implemented this type of meter over an Arduino Mega 2560, where the voltage and current were simultaneously sampled through sensors. As a consequence, implicit calibration factors were derived in the source code that must be changed according to the chosen sensor. The alteration in these factors added to the use of two ADC converters for voltage and current sampling at the same time led to high accuracy and thereby reducing the time gap between instant voltage and instant current which is a factor contributing to errors in real power.

METHODOLOGY

The proposed solution is described in Figure 1. The prototype of measuring device for electric parameters needs to acquire the voltage and current to get an indirect measure of each parameter. This is why sensors with galvanic isolation (voltage and current transformers) were used due to their constructive qualities that prevent any perturbation of moving from the measured circuit to the measurement circuit and vice versa.

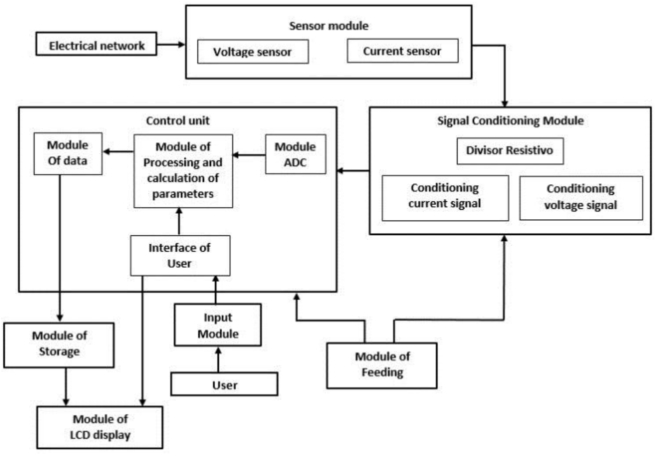

Figure 1. Block Diagram

The analog signals acquired by the transformers, are digitalized in order to be processed by an embedded processing unit responsible of performing the indirect calculations of all the electric parameters. The Arduino module is chosen for the development of the project since it has the physical and programming characteristics necessary to create the meter.

The final model of the meter includes an interface that shows the real value of the involved electric parameters. This type of display is complemented through a memory card which is capable of storing a variable (monthly energy consumption) during a certain period of time.

Sensor module

The sensor module acquires the analog signals of voltage and current in the electric network through the use of two transformers. The voltage and current are then reduced to more appropriate yet insufficient working values. Therefore, the output from both elements has a resistive array that modifies such variables to a proper equivalent, which is conditioned in a subsequent module.

Voltage sensor: This sensor is based on a voltage transformer (TR_1) constituted by a silicon steel core and a copper wire with 1200 coils in its primary section and 64 in its secondary section; additionally, there is a resistive divider that transforms the voltage supplied by TR_1 into an adequate value range. With 120 V in the primary section (V_p) and 6.43 V in the secondary section (V_s), the transformation relation (a_1) equals to 18.66.

Current sensor: This sensor is based on a window-type current transformer (TR_2), constituted by a ferrite core and 2000 coils in the copper wire as well as a Burden resistance (R_5) of 33 Ω (see equation (1)) located in its output terminals.

$$R_{Burden} = R_5 = \frac{V_{max} - 2,5}{I_{sec} * \sqrt{2}} = \frac{5 - 2.5}{0.05 * \sqrt{2}} = 35.35\,\Omega \approx 33\,\Omega \qquad (1)$$

where I_{sec} corresponds to the maximum induced current in the secondary section of TR_2, calculated through the relation transformation given by the manufacturer in terms of the effective current; therefore, it is multiplied by a factor equal to $\sqrt{2}$ to determine the maximum peak current seen from this side of the transformer. V_{max} corresponds to the maximum voltage supported by the Arduino system equal to 5 V and finally, 2.5 is the conditioning voltage described in section 1.3. The value calculated in the Burden resistance is close to the commercial value of 33 Ω.

Signal conditioning module

Conditioning consists on converting the sinusoidal signals so that the maximum positive peak voltage of the signal is 5 V and the negative peak voltage is 0 V. This means that the input signals of the Arduino must be oscillating over a 2.5 V DC component. There are resistive dividers for signals V_{R2} and V_{R5} and the system is fed with a 5 V source coming from the Arduino supply system. It distributes the voltage in the mentioned resistive dividers to obtain the conditioned signals (V_{pADC} and I_{pADC}) that are directed towards the analog pins of the Arduino named A_0 and A_1 respectively.

Control Unit

Once the conditioning of the signals is finished, the reading, calculation, storage and presentation of the electric variables are carried out with the Arduino Mega 2560 R3. This board has a logic code developed in open Arduino code so it can perform total control through four instructions or basic modules distributed between the ADC module, processing module, data module, user interface (UI) module and supply module.

ADC Module

Due to the technical characteristics of the Arduino, it is necessary to convert from analog to digital the resulting signals of the conditioning module. This requires the *AnalogRead* function which discretizes the signal in pins A_0 and A_1 capable of working with a minimum sampling time of 100 ms.

Knowing that normalized monophasic voltage in the Colombian electric network ($V_{network}$) corresponds to 120V over a time period equal to 60 Hz. It is necessary to find a number of data samples in the network that allow the reconstruction of the sensed signals with high reliability without congesting the Arduino Flash memory. For this reason, a total of $N = 56$ data are taken and then the RMS voltage through equation (2).

$$V_{RMS(N=56)} = \sqrt{\frac{\sum_{j=1}^{N} v_{(t)j}^{2}}{N}} = 118.94\,[V] \qquad (2)$$

Where v(t) represents the waveform of sinusoidal voltage, N is the number of data established as 56 and j corresponds to an ascending range of values from 1 to N. The result of equation (4) is compared to the normalized voltage in the monophasic electric network ($V_{network}$) to find the calculation error through equation (3).

$$error = \left(\frac{V_{Red} - V_{RMS(N=56)}}{V_{Red}}\right) * 100 = 0.88108\% \qquad (3)$$

Since the error is lower than 1%, it is stated that the established number of data is a reliable value so $N = 56$ will be kept from this point forward. Having established the number of samples over a time period, the sampling speed required by the Arduino is calculated using the Nyquist criteria through equation (4).

$$T = \left(\frac{P_e}{N}\right) * 2 = 595.23\,uS \qquad (4)$$

Where T is the time that the microprocessor needs to capture one sample, P_C is the period of the signals going through the electric network defined as the inverse of the fundamental frequency defined as 60 Hz and N is the previously chosen number of samples; it is noteworthy that the quotient between

P_C and N is duplicated by a factor of 2 due to the Nyquist criterion.

Therefore, the operation frequency is calculated as the inverse of the time that the microprocessor needs to capture a sample. The operation frequency is described in equation (5).

$$F = \frac{1}{T} \approx 1681\,Hz \tag{5}$$

Where T is the time that the microprocessor needs to capture one sample and F is the value of the real sampling frequency equal to 1681 Hz.

Processing module

The processing module receives the digital signals from the ADC module and uses these values to calculate the electric variables through mathematical equations. All the equations are programmed inside the Arduino code, whilst the first variables found are the RMS values of voltage and current that are used to calculate the apparent power, active power, reactive power, power factor and energy.

RMS Voltage: The RMS voltage is the effective voltage present in the electrical network, this value depends directly on the instant voltage taken from the ADC output in pin A_0 as well as the number of samples over a time period. The calculation of this variable is given by equation (6).

$$V_{rms} = \sqrt{\frac{\sum_{j=1}^{N} V_pADC^2 j}{N}} \tag{6}$$

Where V_{rms} is the effective voltage in the electric network in V, N is the number of selected samples, V_PADC corresponds to the instant voltage in pin A_0 and j is the value that varies from 1 to N.

RMS Current: The RMS current is the effective current value present in the electrical network, this value depends directly on the instant current obtained from dividing the ADC output in pin A_1 in the value of resistance R_5. Finally, equation (7) is applied.

$$I_{rms} = \sqrt{\frac{\sum_{j=1}^{N} I_pADC_j^2}{N}} \tag{7}$$

Where I_{rms} is the effective current in the electric network in A, N is equal to the number of selected samples, I_PADC is the instant current in pin A_1 and j is the value that goes from 1 to N.

Active power: The active power of the system is the power useful to transform electric energy into work; therefore, the actual power consumed by the circuits and, consequently, electric demand is determined by using such power.

The calculation of this power is defined as the sum of the products of instant voltage and current over a time period. Since discrete input values are used, active power is calculated dividing the sum between the number of samples used in the calculation of RMS values. This power is described in the logical code through equation (8).

$$P = \frac{1}{N}\sum_{j=1}^{N}\left(V_pADC_j\ x\ I_pADC_j\right) \tag{8}$$

Where P is the active power present in W, N is the number of selected samples, V_PADC is the instant voltage in pin A_0, I_PADC corresponds to the instant current measured in pin A_1 and j is a value that goes from 1 to N.

Apparent power: This power represents the total occupation of the installations due to the connection of the receiver, since it is the total power consumed by the load; which is the product of the effective voltage and current values. It is defined by equation (9).

$$S = V_{RMS}\ x\ I_{RMS} \tag{9}$$

Where S is apparent power calculated in VA, I_{RMS} and V_{RMS} are calculated before.

Reactive power: This power is required by the coils and capacitors to generate magnetic and electric fields, but it is not transformed into effective work but fluctuates through the network between the generator and the receivers. Currently, electricity companies in the country keep track of the reactive power consumed by the user and if they exceed certain values, a reactive-related penalty is included in the electric bill.

For this work, the calculation of reactive power in the logical code through equation (10).

$$Q = \sqrt{S^2 - P^2} \tag{10}$$

Where Q is the reactive power value in VAR, S is the apparent power and P is the active power.

Power factor

The power factor is the relation between active power and apparent power. The closer this value is to 1, the higher the energy efficiency. The power factor is given by equation (11).

$$FP = \frac{P}{S} \tag{11}$$

Where FP is the power factor of the property, S is the apparent power and P is the active power.

Electric energy

Electric energy is a variable that emerges when a voltage is present between two points connected through a conductor that allows the circulation of current between them. For this work, an energy measurement is performed when it is active; its calculation comes from the product between the active power and the consumption time in hours. The previous statement is expressed in the logical code by equation (12).

$$E = P\ x\ t \tag{12}$$

Where E represents the consumed energy in kWh, P is the active power and t is the energy consumption time in hours.

Data module

This module is in charge of executing the basic commands, that serve to store the calculated variables in the processing module in an external environment. These commands are executed using the SD Library in charge of saving the energy consumed over the past 30 days. As a first measure, the variable *day* which has the function to store consumption data for 24 hours, to then copy them into a variable named *month* linked to an external SD card. Once the daily consumption data is transferred to *month* the code automatically reestablishes the variable *day* to begin the process once again; this step is performed with the purpose of avoiding saturation of the Arduino and keep a record of the variation of electric energy consumption for one month, as well as its cost.

User interface

The user interface is the communication channel between the user and the prototype, including a physical point installed specially to transmit the information of the prototype and vice versa. It encompasses both a display module and an input module.

Display module

In order to display the data from the electric variables calculated in the processing module, the function *Serial.print* is included in the logic code which is adjusted to transmit the data of the variables into a LCD-TFT 3.2 inch touchscreen (240 x 400) set to display each parameter with their respective measurement units.

The communication screen-Arduino through *Serial.print* create a half-duplex data transmission mode so the user is capable of interacting with the screen to obtain a better presentation of the electric variables through a menu. Additionally, this user has the possibility to define the price in kW/h within his region to determine the monthly cost of energy consumption of the property.

Input module

The input of data by the user into the meter is programmed in Arduino which allows the display of touchscreen keyboard. This keyboard has some alphanumeric characters, which can enter data with a direct touch on the surface. This emulates a conventional keyboard input process.

Storage module

It is necessary to store the captured data from the energy consumed by the user over the last 30 days in an external memory; then, the cover of the device was installed as a module where a micro SD card can be inserted to store the registry of the values in a text file with *txt* format.

This module allows the communication from the device to the memory through a SPI, requiring a supply of 3.3 V in the inputs.

Supply module

The correct operation of the device implies having a supply module that energizes the Arduino board, sends the supply voltage to the conditioning module and feeds the storage module.

This supply module has foremost an adapter that can transform AC voltage of the electric network into a 12 V DC voltage required to boot the Arduino system, activating the 3.3 V and 5 V sources included in the embedded system's board. The voltage in these sources is directed to the conditioning and storage modules respectively.

RESULTS

The results of the work discussed in this article were obtained based on different tests that seek to confirm the correct operation of the implemented prototype. Each test takes reference values obtained from the red Fluke 435 network analyzer due to the high reliability in data presentation.

Calibration test

It is unavoidable that an algorithm has rounding or truncating errors, which is why the implemented prototype must have a calibration that reduces the error implicit in the code in order to not affect the equipment's reliability.

This procedure takes the input values from the Arduino system and approximates the reference values through a calibration constant that is obtained from the interpolation principle, taking as basis the equations on the straight lines exposed in Figure 2.

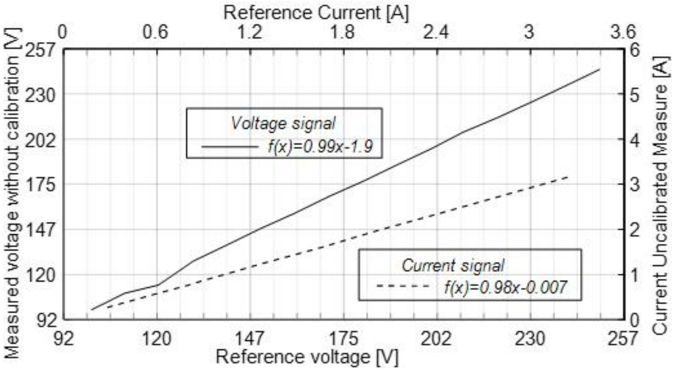

Figure 2. Measured signals vs Reference signals

Calibration results for Active Power

Since there is only one ADC converter it is impossible to sample two signals simultaneously, which generates a delay in the phase angle between voltage and current. For this reason, the phase calibration method described in [13]-[14] is applied through equation (13).

$$V_{pADC}[\theta_{CAL}] = V_{pADC}[Ant] + \theta_{CAL} \times \{V_{pADC}[Act] - V_{pADC}[Ant]\} \qquad (13)$$

Where $V_{P}ADC$ [Prev] is the instant voltage previously calibrated (before the reading), θ_{CAL} is a calibration constant chosen by trial and error equal to 1.5, $V_{P}ADC$ [Act] is the instant voltage calibrated of the current reading and $V_{P}ADC$ $[\theta_{CAL}]$ is the newly calibrated active power given by equation (14). [15]-[16].

$$P_{cal} = \frac{1}{N}\sum_{j=1}^{N}\left(V_{pADC}[\theta_{CAL}] \times I_{pcal}\right) \qquad (14)$$

Where P_{CAL} is the calibrated active power, N is the number of selected samples, $V_{P}ADC[\theta_{CAL}]$ is the calibrated instant voltage without phase error, I_{PCAL} is the calibrated and j is a value that goes from 1 to N.

The result of the new active power measurement is shown in Figure 3 where the power varies between 147 W and 923 W with a mean error of 1.01% compared to the reference active power. The maximum error recorded is 1.68% with 250 W of power.

Due to the method of calculating the calibrated active power, there is no constant resolution since the product between the values of instant voltage and current that vary depending on the electric network and load respectively. The resolution will also vary depending on the load and electric network where the measurements are carried out.

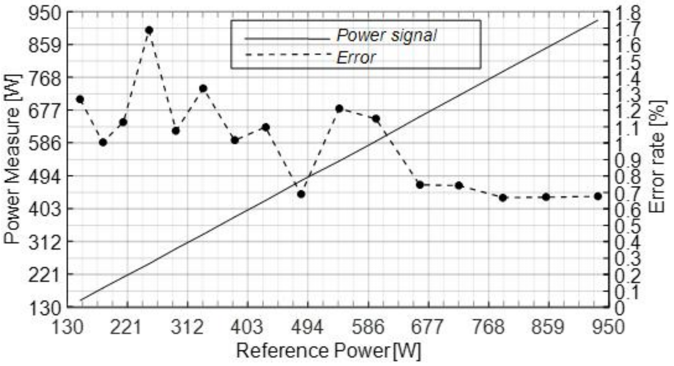

Figure 3. Measured power VS Reference power and Percentage error

Measurement of Apparent Power, Reactive Power and Power Factor.

Since the apparent power (S), reactive power (Q) and power factor (PF) are obtained from previously calibrated variables, there is no need to calibrate once again; therefore, the calculations of S, Q and PF are established through equations (9), (10) and (11) respectively.

The results obtained by measuring these parameters are shown in tables 1, 2 and 3 where the measured data is compared to the reference instrument, as well as the percentage error of each measurement.

Table 1. Comparison of Apparent Power measurement.

Apparent Power measurement [VA]	Apparent Power referenced [VA]	Percentage Error [%]
528,39	532,80	-0,83
488,99	483,60	1,10
454,77	452,40	0,52
440,50	435,60	1,11
429,04	426,00	0,71
423,79	418,80	1,18
415,10	414,00	0,26
413,69	411,60	0,51
411,18	408,00	0,77
406,29	406,80	-0,13

Table 2. Comparison of Reactive Power measurement.

Reactive Power measurement [VAR]	Reactive Power referenced [VAR]	Percentage Error [%]
11,47	11,67	-1,71
200,06	203,12	-1,52
239,24	239,52	-0,12
252,41	251,05	0,54
258,33	256,42	0,74
260,33	258,64	0,65
262,85	260,42	0,92
264,02	262,22	0,68
264,77	262,42	0,89
265,16	263,59	0,59

Table 3. Comparison of the Power Factor measurement.

Power Factor measurement	Power Factor referenced	Percentage Error [%]
1,00	0,9998	0,0240
0,91	0,9075	0,6002
0,85	0,8483	0,1953
0,82	0,8172	0,2186
0,80	0,7986	-0,0702
0,79	0,7865	0,3156
0,77	0,7774	-0,4367
0,77	0,7708	-0,1052
0,77	0,7657	-0,0941
0,76	0,7617	-0,4842

Through the results shown, the largest percentage error belongs to the reactive power with 2.21% when it reaches 11.42 VAR. In contrast, the lowest percentage error is 0.0240% belonging to a power factor of 1. These data show an average error of 0.52% for the apparent power, 0.0650% for the reactive power and 0.0163% for the power factor.

Measurement of Electric Energy

Once the parameters required to indirectly measure the energy are calibrated, the measurement is then carried out by comparing the results of the prototype with the data delivered by the reference instrument used in all previous tests. The result of the test is shown in Figure 4, where the variation of the active power is shown in terms of the sampling time between 7:30 AM and 9:30 AM of the same day.

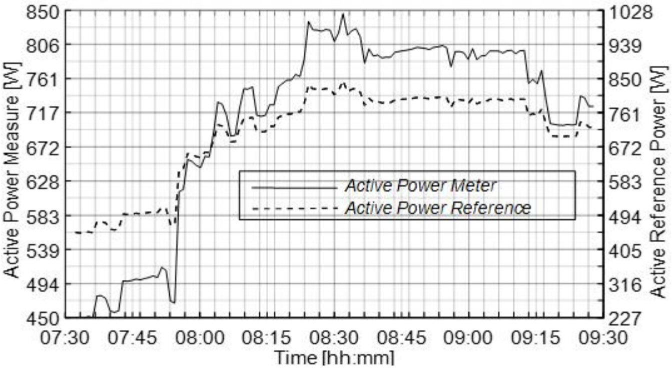

Figure 4. Active Power from the meter VS Reference Active Power in terms of the sampling time.

Once the test is finished, the meter automatically calculates the electric energy defined in equation (12). This result is seen in Table 4 along with the reference energy and percentage error.

Table 4. Comparison of the Electric Energy measurement.

Electric Energy measurement [Kwh]	Electric Energy referenced [Kwh]	Percentage Error [%]
170,387	170,702	0,184

CONCLUSIONES

Through the results obtained, it is concluded that the prototype implemented has a high degree of functionality and precision; whereby it can be taken into account by the operator network to implement a residential parameter meter in commerce that meets with the different quality standards that this one decides. While it is true that this is only a prototype, the code and hardware design is open, this allow an extension and modification depending on the application or need that is required, making it an alternative to conventional residential meters which present less versatility of use.

The calibration performed on the signals produced by the different elements that make up the prototype allows the technical requirements necessary to perform measurements with an error of less than 1.72% to be met, fulfilling the objective of not significantly affecting the measurement made by the prototype.

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