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Evaluation of the Performance of a Voltage and Current Measuring Device

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Abstract

New technologies offered in the market try to make a better use of electric energy, but it is always necessary to obtain energy consumption data in order to make plans oriented to its rational and efficient use. This article presents the design and implementation of a prototype capable of indirectly taking measurements of RMS voltage and current values from a residential-type electric installation. The objective is to monitor and present the values of these parameters to a subscribed user in real time. The prototype is based on an Arduino embedded system that is in charge of handling voltage and current data given by two sensors which are especially adapted to generate analog impulses. Hence, the Arduino system is synchronized with an LCD touchscreen that serves as an interface to visualize the variables measured in real time. In particular, the measuring device has an accuracy error lower than 1.34% in voltage and 1.5% in current, compared to a reference instrument used in experimental testing that defines the optimal operation of the prototype.

Keywords: Arduino, Current, Electric Energy, Electric Measuring Device, Sensor, Voltage

INTRODUCTION

Currently, technological advances have extended worldwide hence the electric sector has also been permeated by their impact in the scientific and technological development [1]. This growth has led to an increase in energy consumption so supervision plans have been made to mitigate its indiscriminate use [2]. Additionally, the residential user depends on the electric energy bill issued by its supplier, to know the cost in pesos of his energy consumption during the month. If this user has no knowledge on how energy consumption is collected every month, he cannot know with certainty if the payment for the service is in accordance to the energy and gas regulation commission in Colombia (CREG in Spanish) [3].

One way to supervise energy consumption and guarantee its correct billing is to monitor several electric parameters in the network and show them in a understandable way. Hence, this document focuses on the development of an easy-to-use prototype measuring device of electric parameters for a residential user, where variables can be seen in real time such as effective voltage (V_{RMS}) and effective current (I_{RMS}).

The prototype uses voltage and current sensors connected directly to the main electric network. The output signal of the sensors is directed towards an array of elements that perform an electric conditioning operation, allowing the detection of these signals through a mega 2560 Arduino sheet [4], which manages the data and indirectly measures the RMS values of voltage and current.

According to the previous statement, this article is structured as follows. Section 2 describes the methodology used by defining the design criteria of the prototype. In Section, the results obtained from the tests performed on the prototype are described. Finally, section 4 includes the conclusions on the overall work.

METHODOLOGY

The proposed solution is described in Figure 1. The prototype measuring device for electric parameters needs to acquire instantaneous voltage and current data for indirectly measure the RMS values present in the network. Hence, sensors were employed to offer galvanic isolation (voltage and current transformers) due to its constructive qualities which assure that no perturbation exists from the measured circuit to the measuring circuit and vice versa.

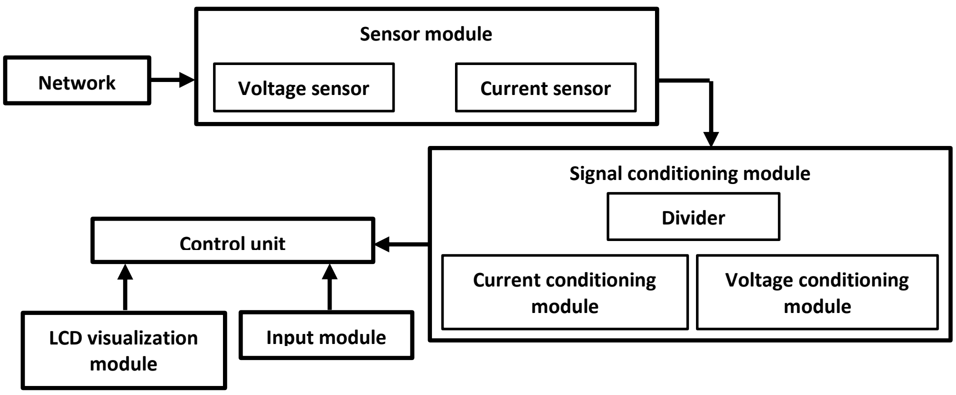

Figure 1. Diagram block of the system

The analog signals acquired by the transformers are digitalized in order to be processed by an embedded logic-based processing unit responsible of making indirect calculations of all the electric parameters. The Arduino module is chosen for the development of the project since it has all the physical and programming characteristics necessary for the creation of the measuring device. The final model includes an interface that shows the RMS value of the voltage and current present in the network.

Sensor Module

The sensor module detects the analog voltage and current signals in the electric network through the use of two transformers. By using them, both voltage and current are reduced to more appropriate values which is not enough; hence, the output from both elements includes a resistive array that converts the incoming variables into adequate equivalents which are conditioned in a subsequent module.

Voltage sensor: This sensor is based on a voltage transformer (TR_1) constituted by a silicon steel core and copper wire with 1200 coils in its primary section and 64 coils in its secondary section. Additionally, there is a resistive divider that turns the voltage supplied by TR_1 into an adequate voltage range.

The voltage transformer takes the network's alternate signal in the input and induces a voltage which is proportional to the transformation rate in the output terminals. Due to its constructive characteristics, TR_1 behaves as a voltage reducer so it can generate 6.43 V in the secondary section when there are 120 V in the primary section. The behavior of TR_1 is described by equation (1).

$$\frac{Vp}{Vs} = a1 = 18.66 \quad (1)$$

120 V is the voltage (Vp) in the primary section and 6.43 V is the voltage (Vs) in secondary section (Vs) so the transformation rate ($a1$) is equal to 18.66.

Since the resulting voltage in the secondary section is greater than the maximum voltage allowed by the Arduino system, it is necessary to adequate this variable into a lower range of values. Hence, the voltage (Vs) in the secondary section is distributed through two resistances: 100 kΩ (R_1) and 10 kΩ (R_2). The output voltage over resistance R_2 is described in equation (2):

$$V_{R2} = Vs.\frac{R_2}{R_1 + R_2} = 0.5\,[V] \quad (2)$$

Using equation (2), a voltage value of 0.5 [V] is obtained in R_2 which is directed towards the conditioning module for its subsequent conditioning and reading in the Arduino device.

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

The operation of this sensor lies in connecting the primary section of the transformer (TR_2) to line of the network circuit with the purpose of inducing an equivalent current in the secondary section. Due to the constructive characteristics of the Arduino system, it does not have the capacity to detect currents so the signal induced in the secondary section of TR_2 goes through a burden resistance hence generating a certain voltage (V_{R5}) which is proportional to the current in the network but with a lower magnitude.

The calculation of the burden resistance takes the characteristics of the TR_2 transformer described in the datasheet offered by the manufacturer. Knowing that the current transformer (TR_2) has a transformation rate (a_2) of 2000:1 and a maximum input current of 100 [A], the burden resistance is calculated with equation (3).

$$R_{Burden} = R_5 = \frac{V_{max} - 2,5}{I_{sec} * \sqrt{2}} = \frac{5 - 2.5}{0.05 * \sqrt{2}} = 35.35\,\Omega \approx 33\,\Omega \quad (3)$$

Where I_{sec} corresponds to the maximum current induced in the secondary section of TR2 calculated with the transformation rate given by the manufacturer and expressed in terms of the effective current; it is therefore multiplied by a factor equal to $\sqrt{2}$ to obtain the maximum peak current seen in this side of the transformer: V_{max} corresponds to the maximum voltage supported by the Arduino system which is 5 [V] and finally, 2.5 V is the conditioning voltage described in the following section. The value calculated for the burden resistance is close to commercially available value which is 33 Ω.

Signal Conditioning Module

The conditioning of the signal is presented when the signals generated by the voltage sensor (V_{R2}) and the current sensor (V_{R5}) need to be processed in Arduino. These signals are sinusoidal so they have some reading inconvenients since embedded systems are designed to work with voltages that have a negative cycle. Hence, it is necessary to condition the Arduino input which has a range of 0 to 5 [V].

The 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 oscillate over a DC component of 2.5 [V]. Figure 2 shows that there are resistive dividers for the signals (V_{R2}) and (V_{R5}) and the system is fed with a 5 [V] source coming from the Arduino supply module that distributes voltage in the mentioned resistive dividers. The conditioned signals (V_{pADC} and I_{pADC}) are obtained and directed to the analog pins in the Arduino system A_0 and A_1 respectively. Figure 3 shows the waveform without any treatment and the conditioned signal over the DC level.

Control Unit

Once the conditioning process of the signals is over, the reading, calculation, storage and presentation of the electric variables are performed with the Arduino Mega 2560 R3 device. It has a logic code developed in Arduino open source code so it is capable of performing the control and presentation of data through a processing module and a visualization module. Figure 4 shows the flow diagram of the implemented code. The processing module takes the conditioned signals and digitalizes them with an internal ADC converter in the Arduino device. Then, the RMS values of voltage and current are calculated through mathematical equations programmed into the Arduino code.

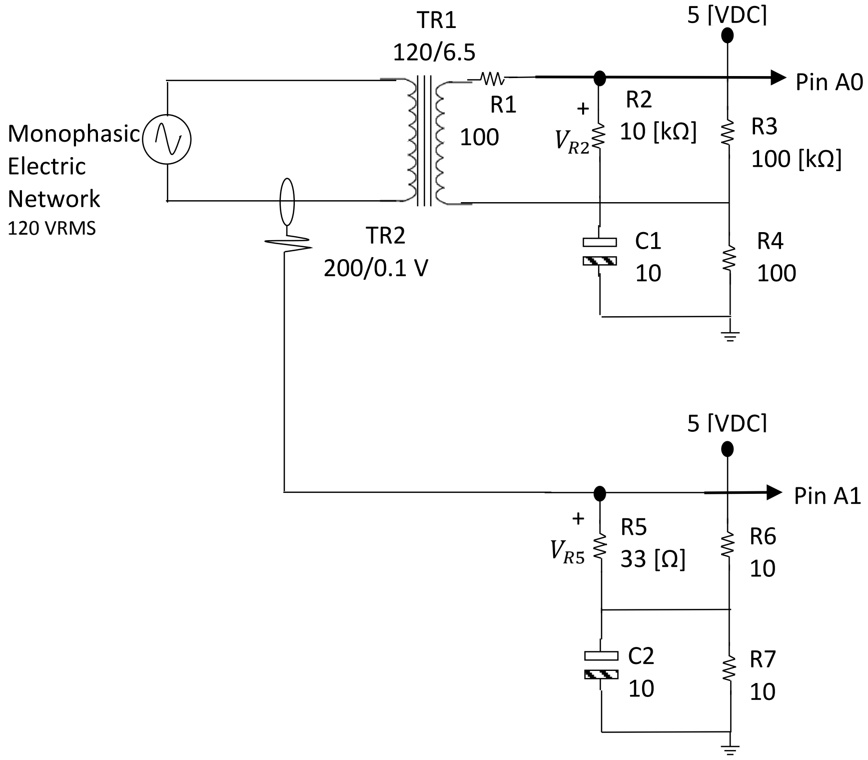

Figure 2. Circuit used to condition the voltage and current signal.

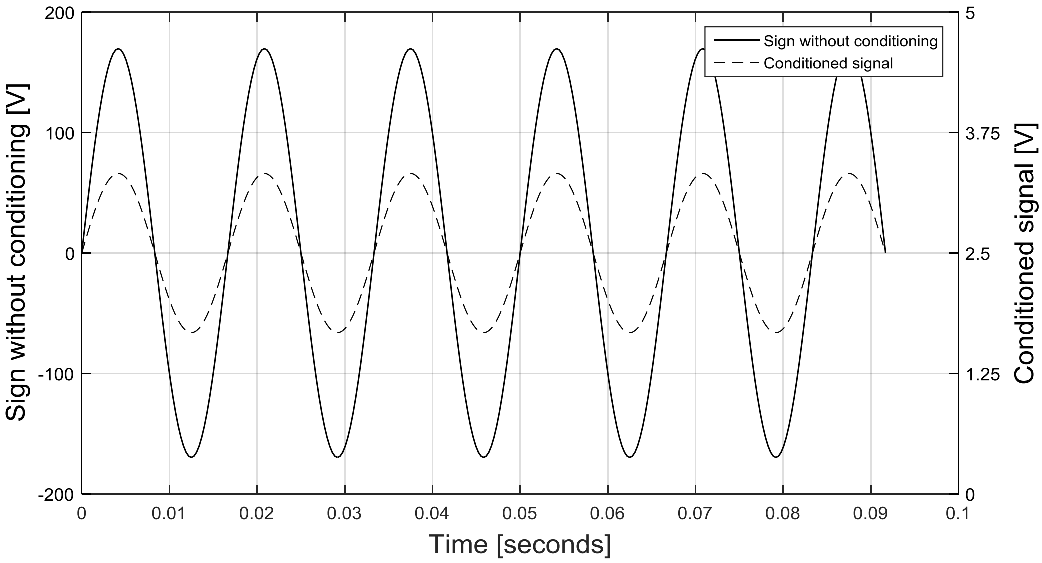

Figure 3. Circuit used to condition the voltage and current signal.

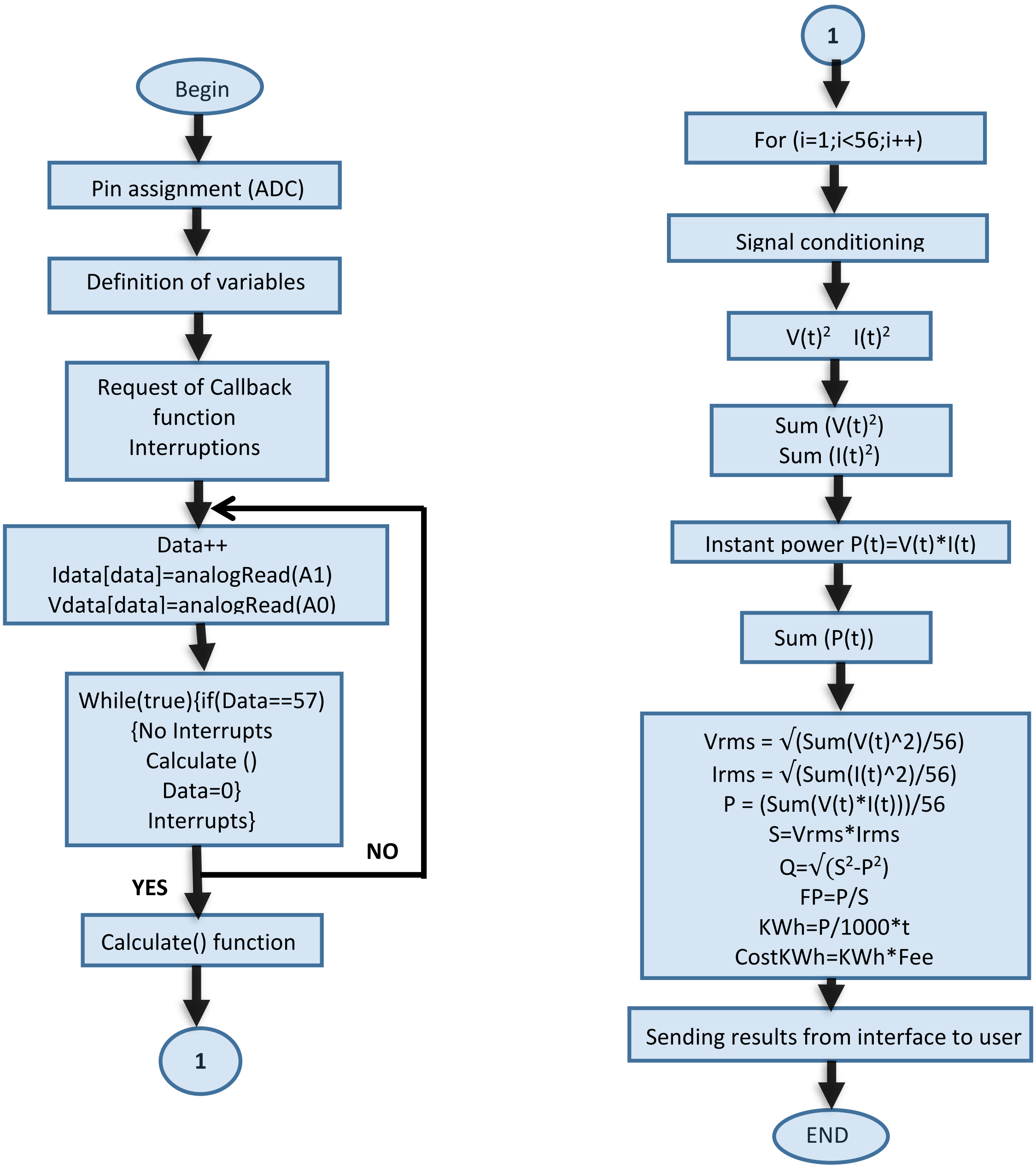

Figure 4. Flow diagram of the control unit

RMS voltage: The RMS voltage is the effective voltage value present in the electric network that depends directly on both the instant voltage taken from the signal registered in pin A_0 of the Arduino and the number of samples in a period of time. The calculation of this variable is given by equation (8):

$$V_{rms} = \sqrt{\frac{\sum_{j=1}^{N} V_p ADC^2 j}{N}} \quad (8)$$

Where V_{rms} es el voltaje eficaz en la red eléctrica en [V], N equivale al número de muestras seleccionadas igual a 56, $V_p ADC$ corresponde al voltaje instantáneo en el pin A0 y j es un valor que varía desde 1 hasta N.

RMS current: The RMS current is the effective value of the current present in the electric network which directly depends on the instant current obtained by dividing the registered signal in the A_1 pin in the value of resistance R_5. Finally, equation (9) is applied.

$$I_{rms} = \sqrt{\frac{\sum_{j=1}^{N} I_p ADC_j^2}{N}} \quad (9)$$

Where I_{rms} is the effective current in the electric network in [A], N is the number of selected samples which is 56, $I_p ADC$ is the instant current in pin A_1 and j goes from 1 to N.

Visualization Module

To visualize data the data from electric variables calculated in the processing module, an LCD TFT touchscreen of 3.2’’ 240*400 set to visualize for each parameter with the respective measuring units.

RESULTS

The results of the work contained in this text are indicated with different tests that verify the correct operation of the implemented prototype. For each test, reference values were obtained for the Fluke 435 network analyzer due to the high reliability of its data presentation.

Calibration Test

It is unavoidable that an algorithm has no rounding or truncating errors. This is why the implemented prototype has a calibration that reduces the implicit error in the code so that the reliability of the equipment is not affected.

This procedure takes the input values of the Arduino system and approximates them to the reference values through a constant calibration that is obtained through interpolation taking as a basis the equations of the straight lines exposed in Figure 5.

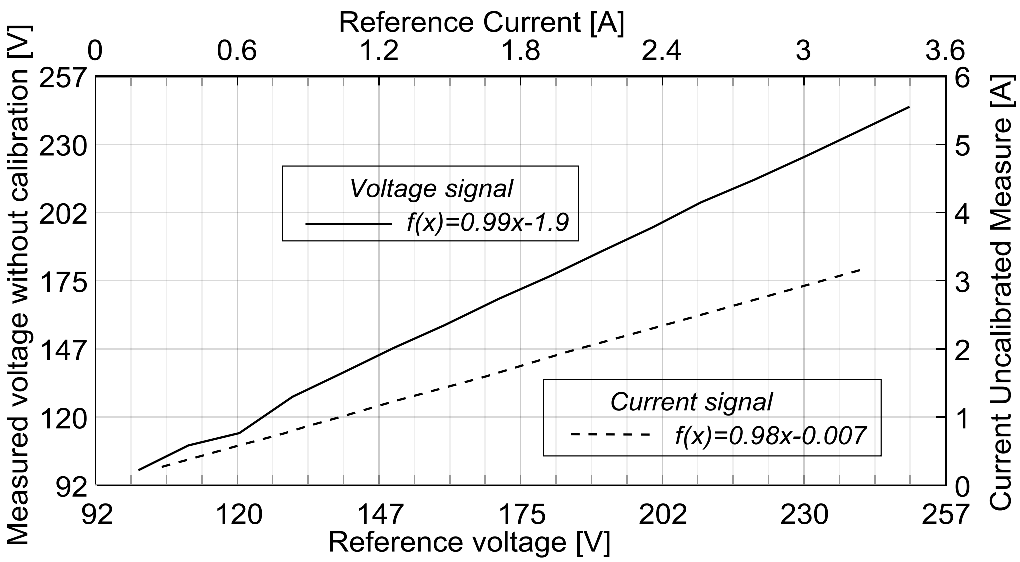

Figura 5. Signal measured VS Reference signals

Results of the Voltage Calibration

The value of the calibrated voltage signal is defined by equation (15).

$$V_{pcal} = C_{calA0} \times V_p ADC \quad (15)$$

Where C_{calA0} is the constant for voltage calibration with a value of 1.01112 and calculated by inverting the slope of the voltage signal in Figure 5. $V_p ADC$ is the value of the instant voltage in pin A_0 of the Arduino and $V_{pcal}$is the newly calibrated instant voltage.

The calculation of the RMS voltage affects the instant voltage when there is a variation; after calibration, the new RMS voltage is given by equation (16).

$$V_{RMS} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(C_{calA0} \times V_p ADC\right)^2} \quad (16)$$

The result of the new measurement of RMS voltage is presented in Figure 6. In this chart, the percentage error can be observed, depending on the similarity between the measured voltage and the reference voltage which vary between 100 and 250 [V]. The results show that the average error is 0.93% while the maximum registered error is 1.34% for a voltage value of 130.3 [V].

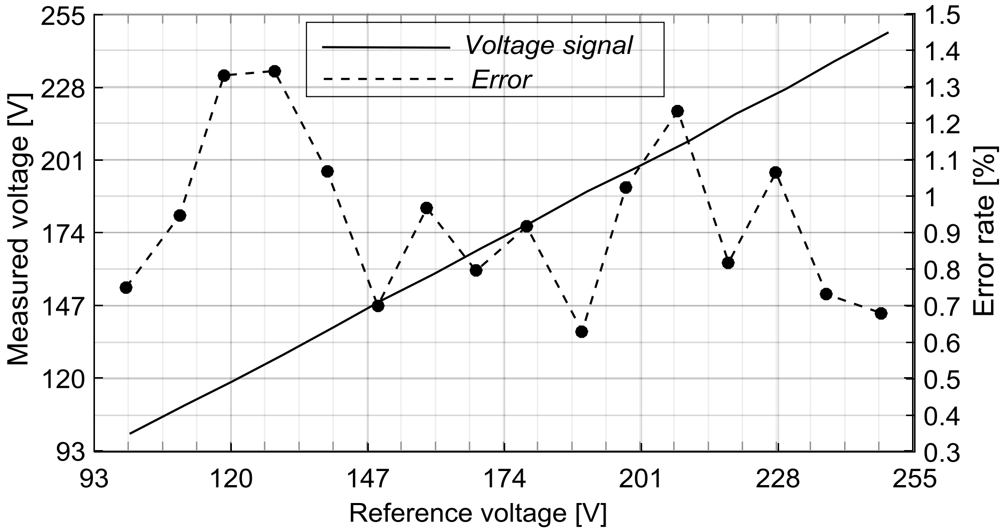

Figura 6. Voltaje medido vs Voltaje de referencia y Porcentaje de Error

Voltage Resolution

A parameter of great importance is the resolution of the RMS voltage which is calculated through the resolution of the internal ADC converter in the Arduino. Knowing that this converter is 10-bit (1024 different values) with an analog reference of 5 [V], it is concluded that the minimum increase of the measurable voltage (ADC_{bme}) with this converter is 0-0049 [V]. With the previous information, the voltage resolution of the prototype is calculated from the voltage within the network with equation (17).

$$Res_V = ADC_{bme} \times \left(\frac{R1 + R2}{R2}\right) \times a1 \qquad (17)$$

Where R_1, R_2 and a_1 are the values described in section 2.1.1 and ADC_{bme} is the resolution voltage seen by the Arduino system. The result of this equation indicates that the resolution of the measuring device (Res_V) seen from the voltage standpoint in the network is equal to 1.0061 [V].

Results of the Current Calibration

The current calibration is similarly applied to the signal voltage. Hence, it is defined by the equation (18).

$$I_{pcal} = C_{calA1} \times I_pADC \qquad (18)$$

Where C_{calA1} is the constant current calibration with a value of 1.02733 calculated by inverting the slope of the current signal in Figure 5. I_pADC is the instant current value in pin A_1 of the Arduino and I_{pcal} is the newly calibrated instant current.

Similarly, to the effective voltage, the RMS current is directly affected by the inclusion of the calibration constant. This change is described by equation (19).

$$I_{RMS} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(C_{calA1} \times I_pADC\right)^2} \qquad (19)$$

The new current values due to the constant calibration are shown in Figure 7 as well as the potential error in comparison to the current given by the reference instrument. In this chart, there is an average error of 0.76% for a range of values between 0.28 [A] and 3.6 [A] while the maximum error registered is 1.5% for a current of 1.575 [A].

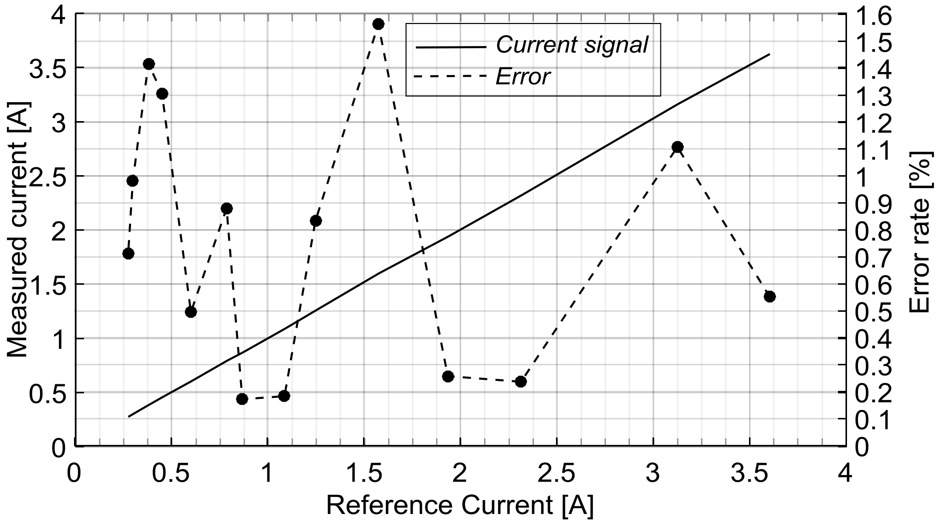

Figure 7. Measured current VS Reference current and percentage of error

Current Resolution

As in the case for voltage, the current resolution is calculated from the resolution of the internal ADC converter in the Arduino. The (ADC_{bme}) factor is presented this time for the calculation of the measuring device's resolution seen from the RMS current in the network. This resolution is given by equation (20).

$$Res_I = \frac{a_2 \times ADC_{bme}}{R5} \quad (20)$$

Where R_5 and $a2$ are the values described in section 2.1.2 and ADC_{bme} is the resolution voltage seen by the Arduino system. The result of this equation shows that the resolution of the measuring device (Res_I) from the current standpoint in the network is 0.030 [A].

CONCLUSIONS

A measuring device was implemented for electric parameters capable of measuring the values of RMS voltage and current with a maximum error of 1.34% and 1.5% respectively. All the data calculated in real time show that the methods established for the calculation of the electric variables are adequate. Therefore, it can be stated that the measuring device satisfyingly complies with the main desired characteristics making it possible to efficiently measure the energy consumption.

Something to consider is the disadvantage of not having the capacity of bidirectional communication. However, the implemented code is open source so future work consists in establishing this type of communication and even the capacity to control the load.

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