Digital Domestic Meter for the Measurement and Billing of Electricity in Mexico

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Abstract.– This article describes the design, construction and characterization of a digital meter of electric energy based on a microcontroller. The meter carries out the calculation of the demand for the kWh consumption, being based on a staggered rate of domestic type of the Federal Commission of Electricity (C.F.E.) in Mexico. The prototype also presents voltage, current, power and time measurements. The instrument takes voltage and current samples of sinusoidal waves which are converted to digital in real time. The system is based on the microcontroller PIC16F874 of the Microchip technology. All the measured and calculated parameters are visualized in a screen of liquid glass of 2 X 16 characters. There is a menu where the parameters are selected to be shown. As a protection, when the electric power supply fails, the meter stores the energy consumption and the remaining parameters in a EEPROM memory. The prototype was divided in four stages: data acquisition, signal conditioning, signal processing and visualization of results, and together, they are a prototype of a digital meter of electric energy for C.F.E. At the end, a set of tests is presented for its characterization.

Key-Words: - Electric energy measurement, voltage measurement, electricity Billing, Microprocessors, Algorithms.

1 Introduction

The electric energy meters are instruments used to measure the electric energy demand that consumes an electric load, these meters are also called kilowattmeters, because most of them measure the energy in kWh. The measurement of the electric energy has been standardized in kWh, although they can measure at any instant of time, kW per second, minute, day, etc [1]. The energy meters can be analogical or digital. Analogical meters are used actually in Mexico. They have several disadvantages when carrying out the measurement and control. As a possible solution to this problem, in this work the development of a digital meter of electric power of low cost is presented, which uses as the central part of the design a Microchip microcontroller. The instrument, based on the voltage and current measured, carries out the calculation of the electric energy consumption, based on the tariff 1A of the C.F.E. for domestic consumption. This rate is staggered since the cost for kWh is modified according to the consumption, if it is less than 100 kWh the rate has the smallest price, for 100 to 150 kWh, the cost per kWh increases, from 150 kWh and above the price is the highest for this rate. The measurement system is designed specifically to satisfy the requirements of measurement of domestic type electricity in Mexico, under the current legislation. This instrument, presents some advantages when is compared with the analogical meters that C.F.E. uses at the present time, like the fast and efficient reading, secure operation which avoids the illicit that are carried out easily in the analogical meters. Besides measuring electric energy and the payment for the consumption in pesos, it measures RMS voltage, RMS current, active power and the measurement time.

The design includes economic electronic components, easy to find in the market. The structure of the meter is guided toward a simple and efficient system that has the capacity for the energy measurement with a low construction cost. The present design is adapted to the current necessities of electric energy measurement of domestic type in Mexico.

The design has the following stages:

- Data acquisition system.
- Signal conditioning system.
- Signal Processing.
- Visualization and data storage.

In the data acquisition stage, a potential transformer (PT) and a current transformer (CT) are used as voltage and current sensors respectively. The signal conditioning stage uses common electronic components. The signal processing stage is based in a microcontroller of the Microchip technology which belongs to the medium family of the PIC´s.

For the visualization of the measured parameters, the system use a liquid crystal display (LCD).

2 Electronic Energy Meter Structure

In Figure 1, a general block diagram of the proposed meter is presented, which includes the following blocks [1, 2]:

- Sensors.
- Signal Conditioning.
- Signal Processing.
- Visualization of results.
- Parameters selection system.
- Voltage Source.

The voltage and the current measured through the PT and the TC are passed to the conditioning block where they are treated in such a way that they can be processed in the following stage. The microcontroller carry out the calculation of the different parameters base on specially developed algorithms. Latter on, using a selector, the different calculated parameters can be visualized. Another important element is the LCD where the results are presented. The system also has an energy source that feeds to the electronic circuits of the system. On Table 1, the technical characteristics of the meter are presented.

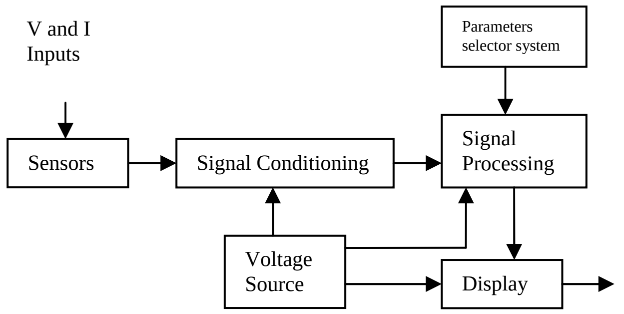

Fig. 1. Block Diagram of the digital meter of electric energy.

Table 1. Design characteristic of the electric energy digital meter.

Concept	Description and range
RMS Voltage Measurement	From 0 up to 255 V, presented in 3 digits in the LCD
RMS Current Measurement	From 0 until 20.0 A. presented in 3 digits in the LCD
Power Measurement	From 0 up to 6.5205 kW Presented in 5 digits in the LCD
Electric energy Measurement	From 0 until 99999.99999 kWh presented in 10 digits.
Time Measurement	From 0 up to 24 hours, restarting every 24 hours again, presented in 6 digits
Billing measurement	From 0 up to 9999.9 pesos, presented in 5 digits
Percentage error in the energy power measurement	0.3122%
Maximum electric power measurement	99999.99999 kWh
Application	For monophasic measurements
Storage	Memory EEPROM
Microcontroller	PIC16F874
Screen LCD	2 x 16 characters

3 Electric Energy Equations

The active power consumed in one period T is defined for [7]:

$$P = \frac{1}{T}\int_0^T p(t)\,dt \tag{1}$$

P is given in watts. Where the instantaneous power p(t) is obtained by the voltage and current product:

$$p(t) = e(t)i(t) \tag{2}$$

The apparent power is defined as the product of the RMS values of voltage and current.

$$S = E_{rms} I_{rms} \tag{3}$$

where the RMS voltage is given by,

$$E_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2(t)dt} \tag{4}$$

and similarly for the current.

3.1 Simplification of equations in sinusoidal conditions

In general, in domestic loads, the total harmonic distortion of the voltage is around of 3% and for the current is around of 17%. This distortion causes an insignificant increment in the RMS value of these two signals. It can be expressed for:

$$E_{rms} = E_1\sqrt{1+THD^2} \tag{5}$$

where E1 is the component at fundamental frequency and THD is the harmonic total distortion of the voltage. The same is valid for current. This distortion is due mainly to the third harmonic in the current and the fifth harmonic in the voltage. This distortion can be considered sinusoidal in domestic loads, not being this way for industrial or commercial loads. Under these conditions, the voltage in domestic loads can be considered sinusoidal in the following way:

$$e(t) = E_m sen(\omega_0 t) \tag{6}$$

and the current:

$$i(t) = I_m sen(\omega_0 t + \phi) \tag{7}$$

where the magnitude and the angle of phase of the current depends on the load. With these considerations, the instantaneous power is represented for:

$$p(t) = \frac{E_m I_m}{2} cos\phi - \frac{E_m I_m}{2} cos\phi \; cos2\omega_0 t + \frac{E_m I_m}{2} sen\phi \; sen2\omega_0 t \tag{8}$$

By means of this decomposition of the instantaneous power, it is observed that it has a constant component and other two cosinusoidal components of double frequency of the source. Solving for the active power:

$$P = \frac{E_m I_m}{2} cos\phi \tag{9}$$

Likewise the values RMS are:

$$E_{rms} = \frac{E_m}{\sqrt{2}}, \qquad I_{rms} = \frac{I_m}{\sqrt{2}} \tag{10}$$

Then, the apparent power is:

$$S = \frac{E_m I_m}{2} \tag{11}$$

3.2 Calculation of the electric energy.

The electric power is the consumption of active power in an interval of time, it is commonly measured in kWh. Equation (12) describes the energy as a function of time and Power.

$$W = \int_{t_0}^{t_1} P dt \tag{12}$$

The energy for conditions of sinusoidal voltage and current is expressed for:

$$W = \int_{t_0}^{t_1} E_{rms} I_{rms} cos\phi \; dt \tag{13}$$

Equation (13) represents the energy calculation for sinusoidal conditions.

3.3 Voltage and current digitalization.

The RMS voltage can be obtained in the way [1],

$$E_{rms} = E(k) \qquad \forall k = 1, 2, 3, ... \tag{14}$$

The sampled voltage and current signals are introduced to a circuit MAV (Mean Absolute Value) which produces an equivalent signal RMS of the input sinusoidal signal. These values are the E(k) and they are introduced into the A/D converter of the microcontroller.

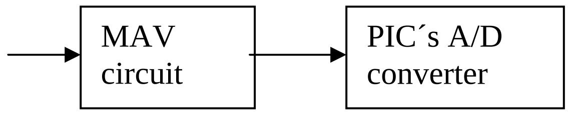

Fig. 2. Voltage and Current Digitalization.

Being E_{rms} the output voltaje of a MAV circuit, $E(k)$ is the digital voltage represented in binary numbers converted by the A/D converter, and k is the number of samples that carries out the A/D converter. The equation (15) describes the current sampling, where I_{rms} is the equivalent of the MAV output of the circuit. $I(k)$ is the digital value of the current.

$$I_{rms} = I(k) \qquad \forall k = 1, 2, 3, ... \tag{15}$$

3.4 Active power digitalization

The calculation of the active power is obtained as follows [1,3,6]:

$$P(k_1) = E(k) I(k) \; cos\phi(k_1) \qquad \forall k, k_1 = 1, 2, 3, ... \tag{16}$$

Where $P(k_1)$ is the active power represented in digital form by a binary number. The angle $ø(k_1)$ is the angle between the current and the voltage; k_1 are the sample taken on each cycle of a sinusoidal wave. It is observed that the number of samples for voltage and current depends on the samples taken by the A/D converter, being different to the samples carried out for the defacement angle, since this is presented 60 times in one second while the A/D converter is much faster in its process since it takes 4000 samples per second, it is not representative for the electric energy calculation, because the samples are carried out each 50 ms.

3.5 Apparent power digitalization

In the same way the apparent power [1,3, 6,7] is given by:

$$S(k) = E(k) I(k) \;\; \forall k = 1, 2, 3, ... \tag{17}$$

where $S(k)$ is the digital apparent power represented in a binary number. Since one watt is

1x10-3 kilowatts, then the factor it is $2.77x10^{-4}$. The equation (18) shows the energy.

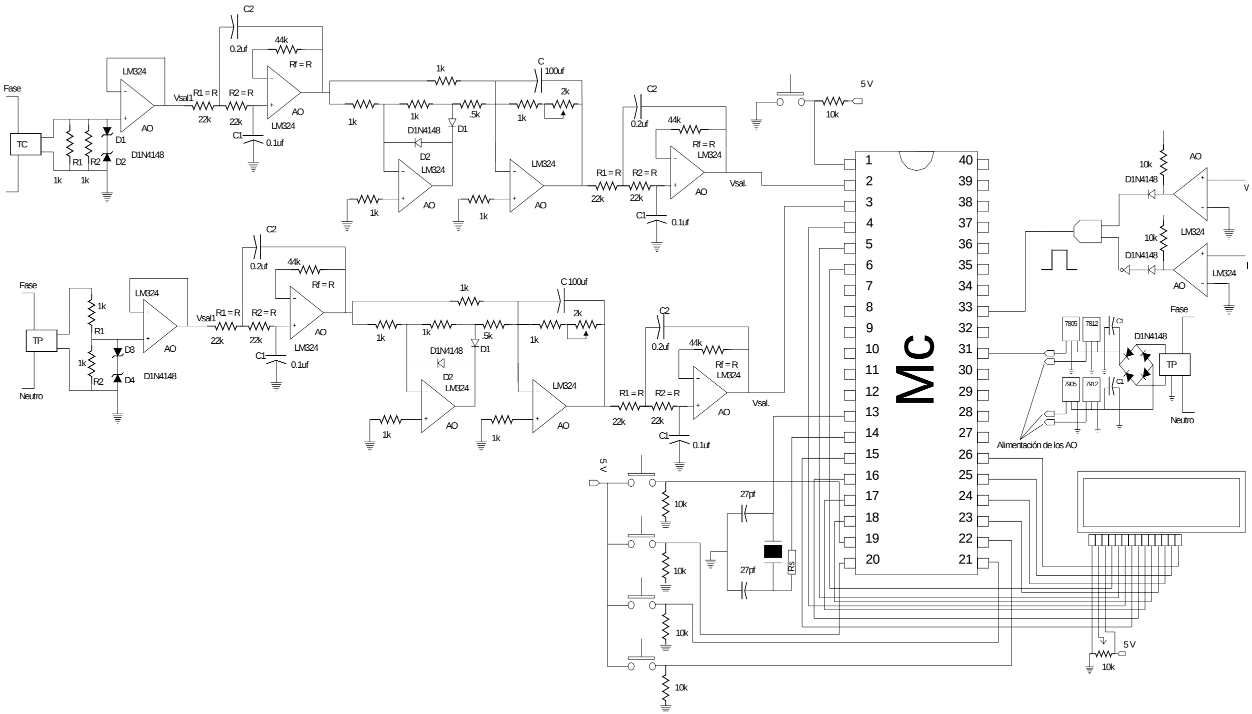

Fig. 3. General schematic diagram of the digital energy meter.

3.6 Equation for the electric power registration

The electric power registration is carried out each second and expressed in kWh. The equivalent is obtained in kilowatts/hours, one hour has 3600 s and the representation of the digital measurement of electric energy is:

$$W(k_1) = \frac{1}{c} \sum_{k=1}^{k=c} E(k) I(k)\ Cos\phi(k_1)$$

$$\forall k, k_1 = 1, 2, 3, ... \qquad (18)$$

Where the constant c is the number of energy samples. The system consists of four main modules which are interconnected, they are:

- Voltage and current transducers.
- Signal Conditioning.
- Signal processing.
- Data visualization.

Figure 3 presents the schematic diagram of all the modules interconnected between them which form the digital meter of electric energy.

4 Prototype Development

4.1 Voltage and current transducers Module.

The module uses a voltage transformer and a current transformer like sensors. The potential transformer that is used as voltage sensor is a PT from 127 Vrms to 6 Vrms. As current transformer the CS2106 Coilcraft was used, it is a transformer of reduced size, capable of sensing currents until 20 amperes with a totally linear response. Their sensitivity is of 0.1 volts for ampere, but this can be changed varying the polarization resistance. The transformer can work with alternating current from 60 up to 400 Hz. The isolation level is of 2500 volts.

4.2 Signal Conditioning Module.

The circuits of signal conditioning includes a voltage divider, voltage follower, the Butterworth filter of second order and a precision rectifier.

The tension divider is formed by two resistances one of a fixed value of 1 K and the other one is a variable resistance of 10 K to vary the input signal and prototype calibration; the voltage follower is formed by an Amp Op LM324 that is used to couple the data acquisition stage. In the output of the Amp Op, 2 diodes zenner are connected to regulate any over-voltage in the input, the limit is five volts.

The precision rectifier is used to obtain the RMS value of the input sinusoidal waves; because they have to be conditioned to the microcontroller can process them like values rms. The second order filter Butterworth is used to filter the MAV input and output signals to maintain them in frequencies of 60 Hz; it was built based on an Amp. Op. LM324.

4.3 Signal Processing Module.

This module is based on the PIC16F874 microchip microcontroller and uses an oscillator of 4 Mhz. The module has a selector, it is employed to select the parameters that are wanted to visualize, the selector switch is connected to the port C of the microcontroller, and it receives 5 volts signals like high states of selection.

The design of the prototype consists of 23 routines in assembler language and they have several subroutines. Some of the routines of this design are: visualization, algorithm of the A/D converter, sum of 48 bits, menu algorithm, algorithms for the calculus of electric energy and billing according to the domestic Mexican tariff. All these routines were programmed in the software MPLAB of the Microchip Technology, and they were assembled to the microcontroller PIC16F874, by means of the interface PICSTART-BONUS of the same technology.

4.4 Output Visualization Module.

The LCD that integrates this module has 2x16 characters of 5x7 pixels for character. It can display voltage, current, power, energy, time and the cost of the energy consumption at a certain time. The microcontroller B port sends the 5 volts signals, with a maximum current of 50 ma, to control and send data to the LCD screen.

5 Proves and Results

In this section four tests are presented that were carried out on the electric energy digital meter. The device was characterized using a variable load and a fixed load. The measurements are compared with theoretical calculated energy.

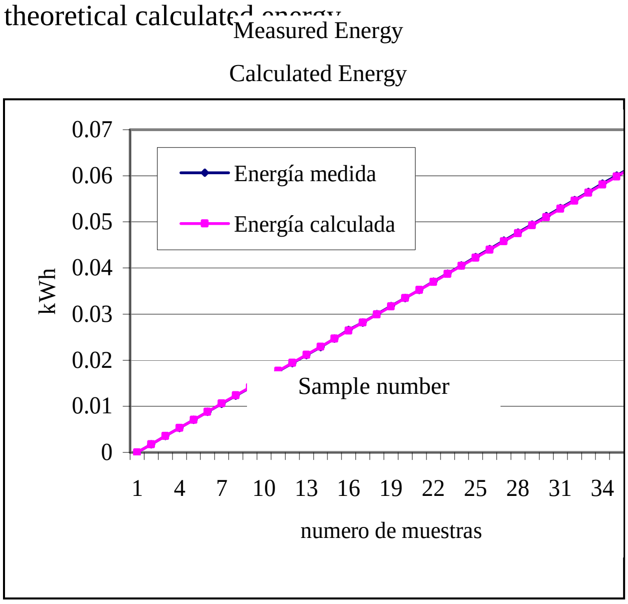

Fig. 4. Comparison of energy measured and calculated for a 1.5 A fix load, sampled each 5 s.

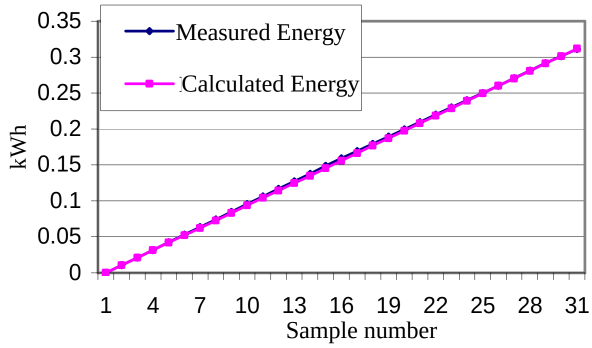

Fig. 5. Comparison of energy measured calculated for a 10 A fix load, sampled each 30 s.

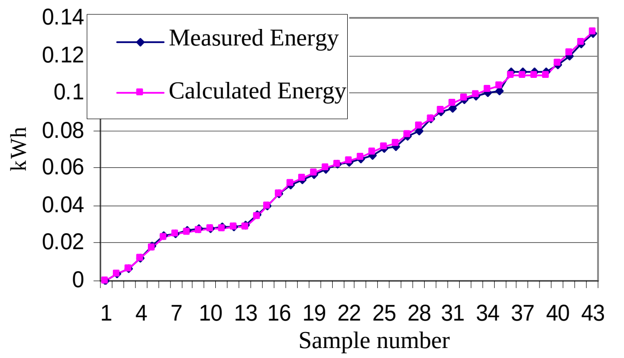

Fig. 6. Comparison of energy measured and calculated for a variable load, sampled each 10 s.

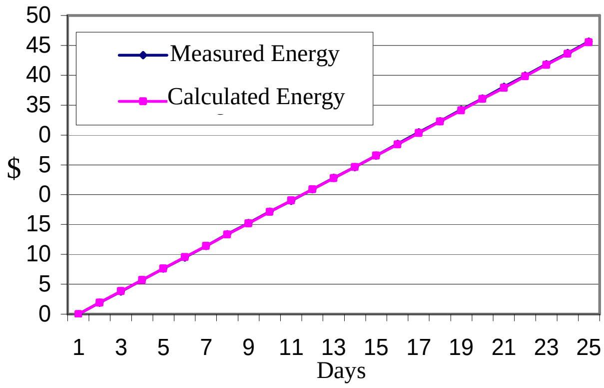

Fig. 7. Comparison of energy measured and calculated for a 15 A fix load, sampled every hour.

Figure 4 shows the comparison of the measured energy with the calculated energy with a fix load of 5 A. Very few variations are observed, the maximum variations percentage is 2.3%. In the Figure 5, a 10 A fix load was analyzed in intervals of 30 s, not significant variations are appreciated. Figure 6 shows the meter response with a variable load, causing important changes of power. It is observed that when the power is near to zero the

energy it is not increased, then the energy is an horizontal line through the time, and it doesn't increase on the vertical axis. If the consumption is near to 2 kW then is increased quickly on the vertical axis. Figure 7 shows the energy cost versus days. This test was carried out for a fix load that consumes 15 A with an interval of 24 hours, taking samples every hour. The graph on Figure 7 shows the measured energy that arrived until a little more than 40 kWh. The payment is calculated t for this consumption with the rate of 0.455 pesos for kWh that corresponds to consumptions smaller than 100 kWh.
Figure 8 presents the prototype of the electric power meter.

Fig. 8. Electric power meter Prototype.

6 Conclusions

The digital meters of electric energy presented is a good option for the measurement of electric parameters. They have the capacity to store data and communicate with different electronic systems. The advance of electronic device technology contributes to the simplicity in the design and accuracy during measurements. These devices are designed more sophisticated and more economic each day, obtaining better electric parameters measurement. However, this work has presented the prototype of a digital electric power meter using a microcontroller. In accordance with the obtained results, the digital energy meter is a device with the appropriate conversion speed and precision for the calculation of the domestic electric energy, as well as to determine and visualize the cost of the electric power consumption based on a staggered rate. The prototype do not use very sophisticated electronic components, besides low cost, which leads to an economic design as a result. Another of the characteristics of the design is that the meter can register additional parameters. In fact, the prototype can display more parameters; voltage, current and active power and they are stored inside the memory of the meter.

7 References

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