Development of a Smart Energy Meter for Electrical Energy Consumption and Power

Amira Haddouk(✉), Asma Tanazafti, and Hfaiedh Mechergui

Department of Electrical Engineering, ENSIT University of Tunis, Tunis, Tunisia
{amira.haddouk,hafiedh.mechergui}@ensit.rnu.tn

Abstract. In this paper, the method of parameters measurement and identification of non linear load, using a Smart Energy Meter (SEM), is proposed. Currently, most loads are non-linear containing harmonics when connected to the electrical network. Most modern electricity meter algorithms take these harmonics into account, but with flaws. The proposed system in this paper replaces the traditional meter. The reading method and the communication module are based on the Node MCU ESP8266 WiFi module, a PIC18F4550 microcontroller and the results (active power P, deformation factor D and the active energy We) are displayed and illustrated by graphs on LabView. An LCD displays the numerical values of power and energy.

Keywords: Non linear load · Distortion Power Ratio (DPR) · Smart Energy Meter (SEM) · Energy consumption · Measurements · Transducers · Uncertainty

1 Introduction

Households are poorly informed about how they use electricity and their environmental impact. Since electricity is invisible, consumers often have trouble understanding when they over-consume [16, 18]. Informational feedback appeared as an instrument responding to this need to identify and understand the foundations of electricity consumption [11, 12, 19, 20].

For example, the electricity bill is a document reflecting a simple transaction (sale of electricity), where the supplier sells kWh to a buyer who does not understand on what basis the said transaction is invoiced, if this is only the electricity he has consumed is not billed at the same price depending on when he called it, consumption being billed in instalments, when subscribers have not taken out a single rate contract where kWh is sold at the same price regardless of the time of day it is consumed. In addition, simply reading the consumption indexes appearing on the electricity bill does not allow the consumer [12, 15, 17] to clearly identify the nature of the changes required or to link the reduction in the consumption of equipment to a change in behavior [5, 8, 11, 16].

Indeed, in [1, 2, 20], it is shown the inadequacy of smart meter to monitor and measure power quality phenomena due to high harmonic content. By the way the actual

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smart energy meter [6, 7, 14] do not deal with the quality of the load in a precise way but they are interested in billing in order to reduce energy consumption and costs.

Thus, a lot of parameters are not analyzed especially the distortion factor which informs us on the degree of nonlinearity of the load [9]. In fact, the consumer does not know about the extra energy consumption because they do not know how to calculate electrical energy that has been used in their house.

As a contribution to solve these issues, can come from the measuring and controlling the Distortion Power Ratio (DPR), to determine the behaviour of the AC electronic equipment Keeping the above issues in mind, we worked on the development of a smart energy meter (SEM) having the ability to measure, process and store the data while remaining in standby to track the fluctuations of the power consumed by the various loads [21]. In fact, this process will allow the customer to have a real idea of his consumption in order to control, if necessary, the excess in electrical energy and this via the identification of the quality factor of the installation and which reflects the behavior of the pollution load.

The performance of the developed SEM was investigated under non-sinusoidal conditions. The SEM is embedded with a PIC18F4550 microcontroller. It is programmed to measure instantaneous and an aggregation of real time total active power consumed; the power due to the first harmonic, the distortion factor, power factor and the consumed energy, then sends it to a PC through the NodeMCU ESP8266. Finally, after processing the collected data, the results are presented using an instrumental LabView platform. This paper proposes a new idea to measure the distortion power ratio DPR easily, in order to improve energy consumption and does not affect the power grid. In fact, by measuring the DPR it is possible to control the current harmonic distortion, and minimize energy consumption by controlling the pollutant load.

The rest of the paper is organized as follows. Section 2 presents the proposed solution for the smart energy meter, Sect. 3 illustrates the approaches and concept design, Sect. 4 introduces the mathematical analysis and Sect. 5 presents the conclusions.

2 Proposed Solution Used for the Smart Energy Meter

In this work, we develop a smart energy meter which measures energy, the active and reactive power and identifies load parameters in order to control energy consumption. The strategy used to measure the total active power is following described.

In the case of non-linear conditions with a non-sinusoidal source supply, voltage and current have the following respective expressions:

$$v(t) = \sum_{j=1}^{\infty} V_j \sqrt{2} \sin(j\omega t) \text{ and } i(t) = \sum_{j=1}^{\infty} I_j \sqrt{2} \sin\left(j\omega t + \phi_j\right) \quad (1)$$

where j is the harmonic order.

From expression (1) we deduce the active power:

$$P = V_1 I_1 \cos\phi_1 + V_2 I_2 \cos\phi_2 + \ldots V_j I_j \cos\phi_j = V_1 I_1 \cos\varphi_1 + \sum_{j=2}^{\infty} V_j I_j \cos\phi_j \quad (2)$$

And

$$Q = Q_1 + Q_2 + \ldots Q_j = \sum_{j=1}^{\infty} V_j I_j \sin \phi_j$$

So the power factor is given as:

$$PF = \frac{P}{S} = \frac{\sum_{j=1}^{\infty} V_j I_j \cos \phi_j}{\sqrt{\left(V_1^2 + \sum_{j=2}^{\infty} V_j^2\right)} \times \sqrt{\left(I_1^2 + \sum_{j=2}^{\infty} I_j^2\right)}} \tag{3}$$

In the case of a non-linear load, the distorting power can be written as:

$$D = \sqrt{\sum_{j=2}^{\infty} V_j^2 \times I_j^2} \tag{4a}$$

We note that D depends on the total harmonic of the current load and voltage network.

In general, the voltage network is sinusoidal and the current load is non linear, so we can write:

$P \approx VI_1 \cos \varphi_1$ and $Q \approx VI_1 \sin \varphi_1$ so the deformed power is:

$$D \approx V \times \sqrt{\sum_{j=2}^{\infty} I_j^2} \tag{4.b}$$

From the Eq. (4.b) we note that more the current is distorted more the Joule losses increase and this will affect the electric cables [13].

3 Approaches and Concept Design

The advantages presented by electronic energy meters are by far those of electromechanical meters. Indeed, modern energy measurement techniques have good reproducibility and are immune to noise. In addition, they take into account the distorting power. They use intelligent systems that deal with algorithms involving digital filtering calculations.

In our work, we have associated, upstream, a PIC18F4550 with a Node MCU ESP8266 module allowing the transfer of data to an instrumental platform managed by LabView. The microcontroller has also been associated with current and voltage Hall effect sensors with their conditioners and an LCD circuit ensuring the display of power and energy.

So we can calculate, V_{RMS}, I_{RMS}, $I_{1\text{-}RMS}$, the total active power consumed and the power due to the first harmonic P_1.

The whole working will be monitored and reported to the user by using a 16x2 LCD display.

An ESP8266 modules comes with a default firmware loaded into it, hence we can program the module using AT commands. These commands have to be sent through a serial communication channel. This channel is established between the PIC and the ESP8266 module by using the USART module in the PIC microcontroller.

The system communicates with an instrumental platform which makes all analysis to control the consumed energy taking into account the signature of the charge (Fig. 1).

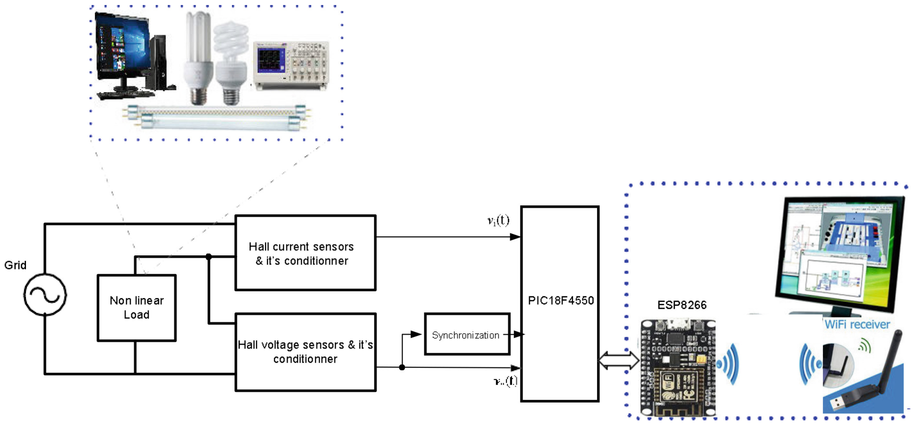


Fig. 1. Block diagram of the proposed SEM.

4 Mathematical Analyses

In general, to measure the active power, we multiply the outputs of the signal conditioning circuits $v_v(t)$ and $v_i(t)$.

For a non linear load the active power, which is also called real power; in fact the average value of the instantaneous power $p_h(t)$ is given by

$$\begin{aligned} p(t) &= \frac{1}{T}\int_0^T v(t)\cdot i(t)dt \\ &= \frac{1}{T}\left(\int_0^T \sum_{h=1}^{\infty} [V_{hm}\sin(h\omega t)\cdot I_{hm}\sin(h\omega t+\varphi_h)]dt\right) \end{aligned} \tag{5}$$

According to (2) and (5), the total harmonic distortion is defined by (6):

$$THD_P = \frac{\sum_{h=2}^{\infty} P_h}{P_1} \tag{6}$$

We define the distortion power ratio DPR as follow:

$$DPR = \frac{P_1}{P} = \frac{P_1}{P_1 + \sum_{h=2}^{\infty} P_h} \tag{7}$$

It is assumed that THD_P tend to zero, the Eq. (7) can be written as:

$$DPR \cong 1 - THD_P \tag{8}$$

In some cases, the voltage supplying a non-linear load is non-sinusoidal. This leads to a harmonic distortion of current and voltage, which degrades the distorting power D. To determine the various electrical quantities necessary for the measurement of active and reactive power, energy and the deformation factor, then, the current flowing through the load and the voltage across are acquired periodically.

Let $v_v(n)$ and $v_i(n)$ be respectively the digitized waveforms of the analog $v_v(t)$ and $v_i(t)$ during one period T_g, of the power grid. Thus we can write: $v_n = k_v v(nT_e)$ and $i_n = k_v v_i(nT_e)$.

k_v: scaling factor for the voltage

k_i: scaling factor for the current

T_e: sampling period

T_g: grid period.

Having acquired over one period the N samples of $v_{v\text{-}acq}$ and $v_{i\text{-}acq}$, we calculate, respectively, the effective value of the RMS value of the voltage and the current:

$$v_{vacq} = V_{dc} + v_v(t) \text{ and } v_{iacq} = V_{dc} + v_i(t) \tag{9}$$

To extract $v_v(t)$ and $v_i(t)$, it is necessary to read sampled data from each ADC and store it in location in the static Random access memory(SRAM), where it cannot be over written by new data.

To remove the DC offset we need more calculations, so the best solution is to use a digital High-Pass Filter (HPF) of type infinite impulse response (IIR). According to the transfer function of the filter can be written as follows:

$$y[(n)] = 0.996 \times y[n-1] + 0.996 \times x[n] - 0.996 \times x[n-1] \tag{10}$$

This digital filter is simple one and it removes the DC offset.

Then we calculate V_{rms} and I_{rms}.

To increase the accuracy of the used method, the measurement operations are performed over a time noted T_M such as:

$$T_M = M \times T_g \tag{11}$$

where M is the integer that is a multiple of the period T_g. Then, we calculate a rated power P_t, and the expression (11) can be written as follows:

$$P_M = \frac{1}{M}\sum_{j=1}^{M} P_N \tag{12}$$

The consumed energy is then calculated based on the active power value for each frame of one second, that means:

$$\Delta W_e = P_M \times \Delta t(1\,\text{second}) \tag{13}$$

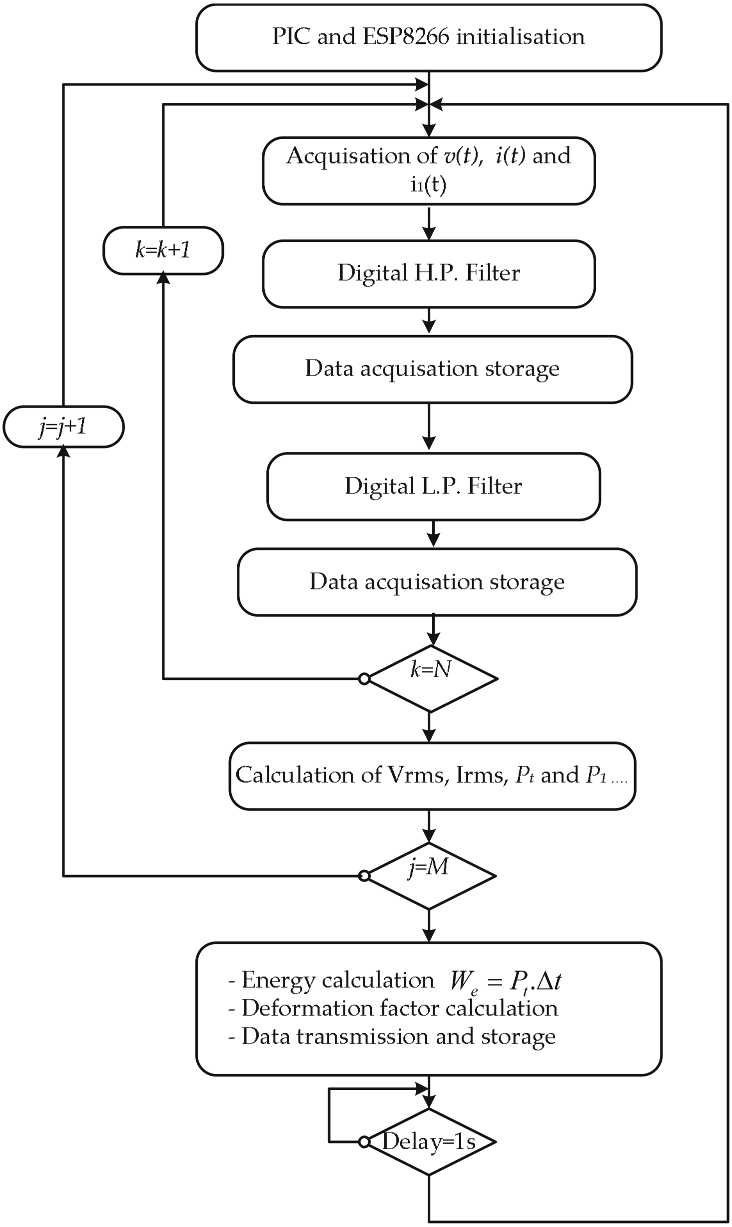


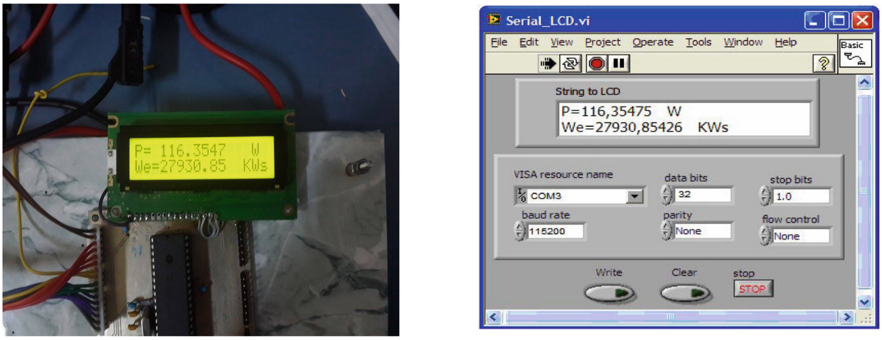
Fig. 2. General flow chart

To calculate the power P1 due to the first harmonic of the current, we use, also, a digital low pass filter, so can write:

$$P_1 = \frac{1}{k_P} \cdot \frac{1}{M}\left(\sum_{j=1}^{M} \frac{1}{N}\left(\sum_{n=1}^{N} v_{v_1}(n) \cdot v_{i_1}(n)\right)\right) \tag{14}$$

Making recourse to Eq. (2) and (14), we determine the behavior of the load. The flow chart of the SEM is depicted in Fig. 2.

Figure 3 presents the implemented hardware of the SEM.



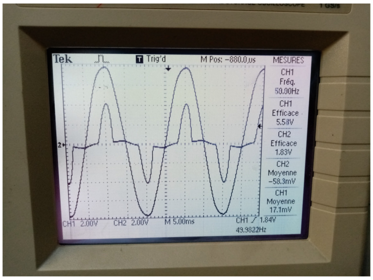
(a) (b)

Fig. 3. Experimental setup: (**a**) Experimental results displayed in LCD; (**b**) Experimental results transmitted and displayed on the Labview.

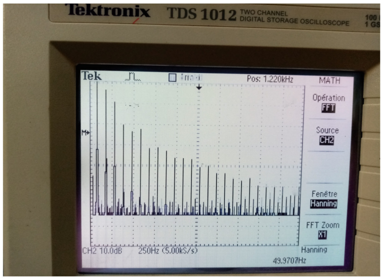
• *Practical identification of the current consumed by a non-linear load (example: power supply model PR-657).*

Experimental tests were carried out on a non-linear load (PR-657 type laboratory power supply). From the spectral analysis, it can be seen that the load current is much distorted, which has an impact on the voltage shape at the contact point at the network connection. The Fig. 4 and Fig. 5 illustrates also the behavior of the currents across the load and the instantaneous power consumed.

The designed energy meter has been tested in our instrumentation laboratory. Indeed, the latter contains electrical appliances similar to those of a dwelling house. We took measurements, during a week, according to the objective presented in this work. Thus, the collected data is processed and analyzed by a LabView platform. The results of the analysis showed that the nonlinear behavior of the load affects the stability and pollution of the network voltage and consequently increases the losses.



(a)



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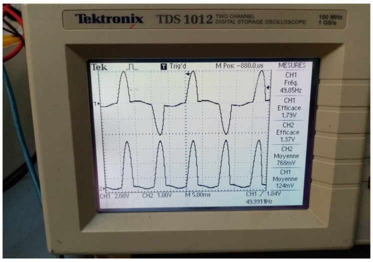
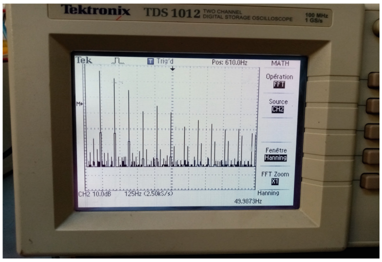


(c)



(d)

Fig. 4. Experimental curves: (a) waveforms of voltage and current; (b) Current harmonic spectrum; (c) Waveforms of current and power p(t) signals; (d) Instantaneous power harmonic spectrum

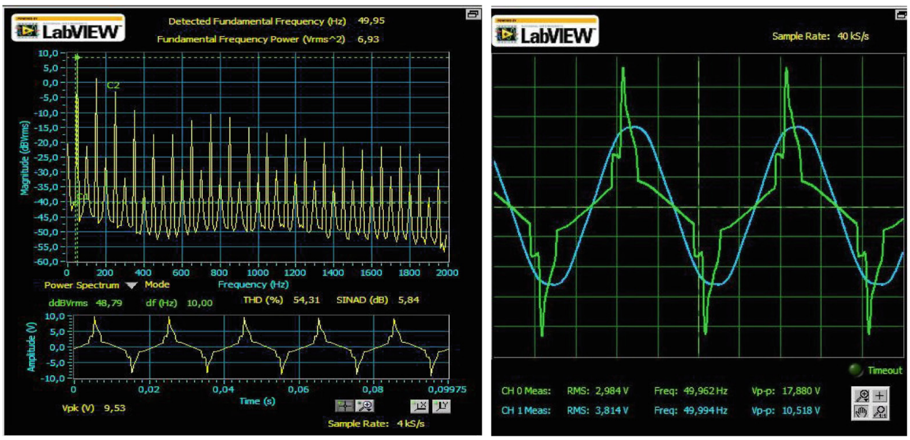


Fig. 5. Real time acquisition of current/voltage signals and spectral analysis: case of a non- linear load (compact fluorescent lamp 25 W)

5 Conclusions

This paper presents the design and implementation of an intelligent energy meter (SEM) that can be used in the home with the possibility of real-time energy measurement and the determination of the deformation factor in order to control the load affecting excessive electrical energy consumption. This system has the flexibility and ability to be modified and manipulated to suit various environments of electrical load combinations. The SEM uses modern digital techniques which are acquisition, digital filter processing and data transmission via WiFi.

A platform managed by LabView allows the processing, calculation, analysis and representation of consumption curves, the purpose of which is to validate the use of the smart energy meter in the housing sector.

The spectral analysis carried out showed that modern electronic devices (using semiconductors) are highly non-linear loads which the SEM carried out can intervene to control the latter so as not to affect the network voltage.

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