3rd International Conference on Green Energy and Environmental Engineering (GEEE-2016)
Proceedings of Engineering & Technology (PET)
pp. 68-75

Developing a Novel Method: Calculating the Deformation Factor to Control Energy Consumption

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***Abstract*— This paper focuses on the design and implementation of a single phase intelligent energy meter (IEM) with monitoring energy consumption by calculating the deformation factor (D). The energy meter was designed using PIC16F877 metering chip and the measurement values are displayed on the LCD screen. Then a MAX232 IC is interfaced between the Microcontroller and the PC.**

***Keywords*— Deformation factor (D), Intelligent Electrical Energy Meter (IEEM), energy consumption.**

I. INTRODUCTION

Energy is an essential input to all aspects of human life. It is employed for all levels of human activities. However, increased electrical energy consumption and its rising cost per kWh informed the consumers of the need for effective energy utilization and monitoring. Low electrical energy consuming appliances such as Compact Fluorescent Lamps (CFL), Light Emitting Diodes (LED), etc, are being used for domestic and industrial illumination nowadays to reduce energy consumption costs. However, whether appliances possess low or high consumption capacity, it is necessary to monitor the quantity of energy consumed at any particular time. This is achieved by an electrical energy metering system. Therefore, metering could be defined as the process of effectively determining and monitoring power consumption.

The objective of this work is to design and implement a single phase intelligent electrical Energy Meter (IEEM) capable of measuring instantaneous and an aggregation of real time total active power consumed; the power due to the first harmonic, the deformation factor and the consumed energy, power factor, which can be monitored.

Furthermore, the calculation of deformation factor can inform us about the degree of non-linearity of the load. Moreover, the reduction of these losses requires the use of capacitors to provide reactive compensation of electrical energy.

II. PROPOSED WORK

During the last years there is a growing interest in the Electric Power Quality. This can be explained partly by the widespread use of non-linear fast switching electronic equipment in the industrial environment and office buildings. These devices are sensitive to distortions in their supply-voltage, but they are also an important contributor to the deterioration of the quality, since they often cause highly distorted currents in the net.

Harmonic problem will not only causes equipment heat, vibration and so on, thereby affecting the normal production and life, resulting in additional waste of energy; but also the way of electric energy metering under the current harmonic influence has caused a greater impact on electricity companies. It is necessary to analyze this situation involved in social and economic benefits and to further explore rational energy measurement method [1].

In the deregulated electricity markets, power and energy measurements are at the base of all electrical commercial transactions. In this context, the calibration and traceability of energy and power meters are key features, both in sinusoidal and non sinusoidal conditions. In real cases, the meters have to operate also in the presence of harmonics, because of the proliferation of nonlinear and/or time-variant loads.

Indeed, in the paper [2]-[8], we have shown the inadequacy of analog devices to monitor and measure power due to higher harmonics of the fundamental.

Electronic energy meters are designed on base of the principle of time-division, so the electronic energy meter has smaller errors with frequency changed. The approximate model is:

$$P = P_f + \sum_{h=2}^{\infty} P_h \qquad (1)$$

Where, P_f is the fundamental power, P_h is the harmonic power.

In general the P is called as full energy. We can be seen that electronic energy meter has wide bands, can be a more accurate measurement on the fundamental power and harmonic power, but because of the equal treatment on its

ISSN: 2356-5608

harmonic power and fundamental power, measurement error will increase.
In other words the load needs to consume more of the active power, some of which converted into harmonic power and injected into the System. The harmonics pollute the power grid and affect the performance of neighboring linear or non-linear load.
We can note that when the harmonic level is relatively low, these errors can be ignored, but if not, the electronic energy meter cannot meet the requirements.
In addition, Electronic energy meters are sensitive to the measurement of the power developed by the first harmonic.

To reflect the actual power generated by all the harmonics, we propose a smart meter based on a µ-controller connected to a PC via an RS 232 port.
Through this last, we will carry out the analysis and the energy management consumed by a nonlinear load.

III. ENERGY METER DESIGN

IEM consist of the following modules: a micro-controller unit, a Liquid Crystal Display (LCD), LA-55P current transducer, CYHVS025A voltage transducer and AD734 from Analog Device as shown in Fig. 1 [9].

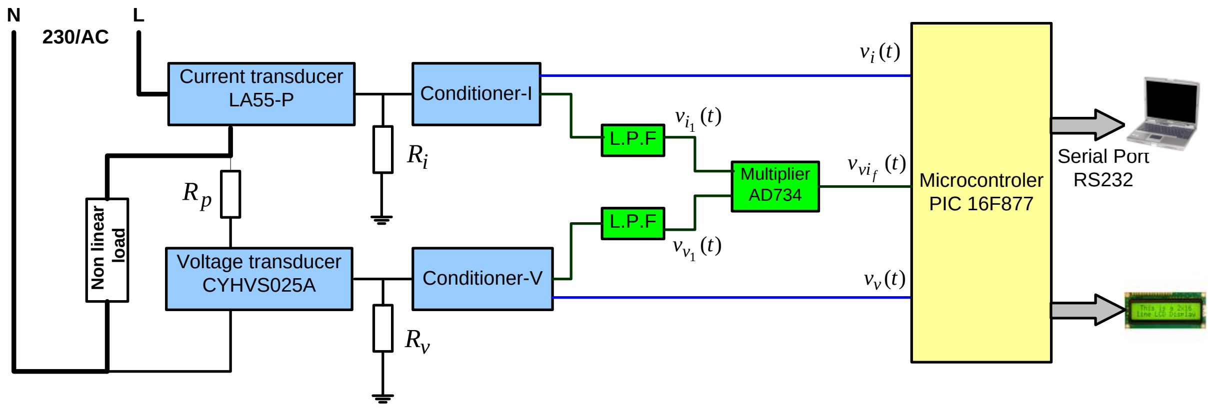


Fig. 1 The block diagram of designed IEM circuit

In the designed Intelligent Electrical Energy meter (IEEM) circuit, the voltage line and the current load are respectively obtained using two Hall Effect transducers. The Hall Effect transducer used to sample the voltage is CYHVS025A [3] from Chenyang. The CYHVS025A is a Hall Effect closed cycle transducer which works with DC or AC signals up to 1000 V (Fig.2). It has galvanic isolation between the primary circuit (high voltage) and the secondary one (electronics) and a theoretical conversion factor of 2500:1000. It needs a power supply ± 15V. It has an excellent precision and an accurate linearity.

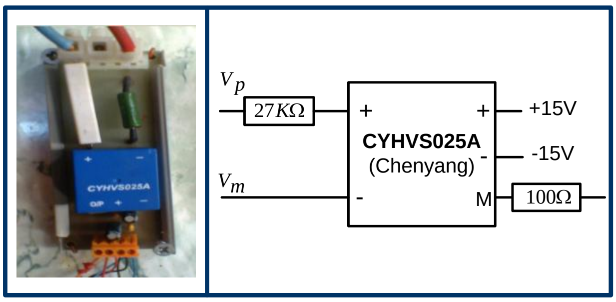


Fig. 2. Voltage Transducer CYHVS025A

The Hall Effect transducer used to sample the current is the LA55-P [4] from LEM USA. The LA55-P is also a Hall Effect closed cycle transducer which works with DC or AC signals up to 50A (Fig. 3). It also has a galvanic isolation between the primary circuit and the secondary one. The power supply is also between ± 12 and ± 15V. It is accurate and linear such as the CYHVS025A.

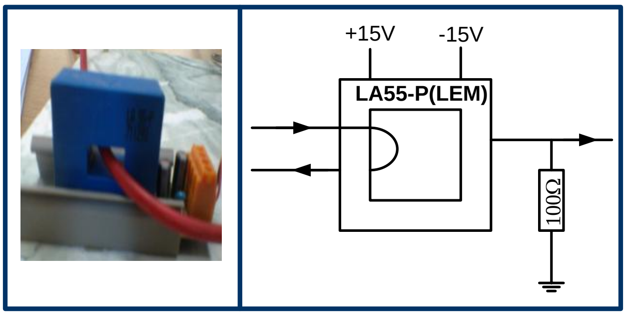


Fig. 3. Current Transducer LA55-P

It is noted that these two sensors to reproduce faithfully all the variations of the voltage and current in their output and also provide galvanic isolation, to protect the experimenter in the laboratory. The two signals (voltage and current) are conditioned by two analog circuits for amplifying the signal at the transducer output.
We use two measurement channels: one to measure the total active power consumed and the other to measure the power due to the first harmonic.

A. Measurement of The Total Power

To measure the total active power, we multiply the outputs of the conditioners. The principle is based on the acquisition

of the current and voltage, and the digital processing of all measured variables.
Let $v(n)$ and $i(n)$ be respectively the digitized waveforms of the analog $v_v(t)$ and $v_i(t)$ during one period T. We calculate, respectively, the effective value of the voltage and the current.

$$V = \frac{1}{k_{VC}} \times \sqrt{\frac{\sum_{n=1}^{N} v_v^2(n)}{N}} \qquad (2)$$

and $$I = \frac{1}{k_{IC}} \times \sqrt{\frac{\sum_{n=1}^{N} v_i^2(n)}{N}} \qquad (3)$$

With:
$v_v(n)$: Voltage sample at a sample instant n.
$v_i(n)$: Image voltage of current $i_{ch}(t)$.
N : is the number of the samples to be acquired during one period of time in 20 ms.
k_{VC} : Scaling factor for voltage
k_{IC} : Scaling factor for current.
The digital measurement of active power is given by:

$$P = \frac{1}{K_p} \frac{\sum_{n=1}^{N} v_v(n) \times v_i(n)}{N} \qquad (4)$$

k_P : Scaling factor for power dependant on the conversion of the transducers, the conditioners, the multiplier and the ADC.
To increase the accuracy of the used method, the measurement operations are performed over a time noted T_m such as:

$$T_m = M.T_s \qquad (5)$$

With: M : integer that is a multiple of the period T_s.
Then, we calculate a rated power P_t , and the expression (4) can be written as follows:

$$P_t = \frac{1}{M} \sum_{k=1}^{K} P_k \qquad (6)$$

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

$$W_e = P_t \times \Delta t \qquad (7)$$

B. Measurement of the Power due to the first harmonic

The signal at the output of the current to conditioner and the signal at the output of voltage conditioner are filtered at the first harmonics; using a 1st order RC low pass filter with a cut-off frequency of approximately 70 Hz was used. A 2.2 kΩ resistor and a 1 µF capacitor were used to implement the filter. Then they are applied to the AD734 analog multiplier of Analog Devices (Fig.4) to extract the power P_1 due to the first harmonic, as:

$$P_1 = \frac{1}{k_P} \frac{1}{M} \left(\sum_{m=1}^{M} \frac{1}{N} \left(\sum_{n=1}^{N} v_{vi_f}(n) \right) \right) = V_1.I_1.\cos\varphi \qquad (8)$$

With:
The multiplier output voltage is:

$$v_{vi\,f}(t) = v_{v_1}(t) v_{i_1}(t) = k_V k_I k_M V_{M_1} \sin(\omega_1 t + \varphi_{v_1}) I_{M_1} \sin(\omega_1 t + \varphi_{i_1})$$

$$v_{vi\,f}(t) = k_P \frac{1}{2} V_{M_1} I_{M_1} \cos\varphi - k_P \frac{1}{2} V_{M_1} I_{M_1} \cos(2\omega_1 t + \varphi_{v_1} + \varphi_{i_1}) \qquad (9)$$

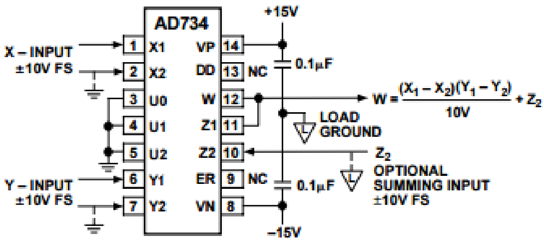


Fig. 4. Basic Multiplier Circuit

C. Calculates Deformation Factor

The network harmonic can be divided into background harmonic and harmonic from the source. Background harmonic appears in the form of voltage source. On one hand, it comes from the harmonic voltage infiltration of higher-level power grid, on the other hand from other harmonic sources influence of the same level of power grid.
The harmonics form the source appears in the form of current source, which is mainly from the nonlinear load [10].
Considering the impact from both the two kind of harmonic, there are three operating mode. Taking a single-phase system as an example, the deformation factor is calculated by the following expression:

$$D = \frac{P_1}{P_t} \qquad (10)$$

1) Operating Mode 1

There is no background harmonic or nonlinear load in electric network.
In this mode, harmonic power is equal to zero.
$v(t)$ and $i(t)$ are given by:

$$v(t) = V_{1m} \sin(\omega t) \qquad (11)$$

$$i(t) = I_{1m} \sin(\omega t + \varphi_1) \qquad (12)$$

Active power is define as:

$$p = \frac{1}{T} \int_0^T v(t).i(t)dt = \frac{1}{T} \int_0^T V_{1m} \sin(\omega t).I_{1m} \sin(\omega t + \varphi)dt$$

$$p = \frac{1}{T}\int_0^T V_1 I_1[\cos\varphi_1 - \cos(2\omega t + \varphi_1)]dt$$

$$p = V_1 I_1 \cos\varphi_1 \tag{13}$$

Where, V_1 and I_1 are respectively the RMS value of voltage and current.

Then the deformation factor is:

$$D = \frac{P_1}{P_t} = 1 \tag{14}$$

2) Operating Mode 2

There is background harmonic and nonlinear load in electric network.

$v(t)$ and $i(t)$ are given by:

$$v(t) = \sum_{h=1}^{\infty} V_{hm} \sin(h\omega t) \tag{15}$$

$$i(t) = \sum_{h=1}^{\infty} I_{hm} \sin(h\omega t + \varphi_h) \tag{16}$$

The active power is defined as:

$$p = \frac{1}{T}\int_0^T v(t).i(t)dt = \frac{1}{T}\int_0^T \sum_{h=1}^{\infty} V_{hm}\sin(h\omega t) I_{hm}\sin(h\omega t + \varphi_h)dt$$

$$p = V_1 I_1 \cos\varphi_1 + V_2 I_2 \cos\varphi_2 + ... + V_n I_n \cos\varphi_n + ...$$

$$p = V_1 I_1 \cos\varphi_1 + \sum_{h=2}^{\infty} P_h \tag{17}$$

Then the deformation factor is:

$$D = \frac{P_1}{P_t} = \frac{P_1}{P_1 + \sum_{h=2}^{\infty} P_h} = \frac{1}{1 + \varepsilon_P} \tag{18}$$

With: $\varepsilon_P = \dfrac{\sum_{h=2}^{\infty} P_h}{P_1}$

It is assumed that ε_P tend to zero, the equation (18) can be written as:

$$D \cong 1 - \varepsilon_P \tag{19}$$

We notice that D depends on the non linearity of the load.

3) Operating Mode 3

The third operating mode is a nonlinear load controlled by a mixed bridge.

The voltage appears across the load once the thyristor is ignited: more the thyristor ignition angle is high; more the voltage obtained at the terminals of the load is low.

The effective value measured across the load is:

$$V_{eff}^2 = \frac{1}{T}\int_0^T v(t)^2 dt = \frac{1}{\pi} V_m^2 \int_\alpha^\pi \sin^2(\omega t)dt$$

$$V_{eff}^2 = \frac{1}{\pi} V_m^2 \int_\alpha^\pi \frac{1 - \cos(2\omega t)}{2} dt$$

$$V_{eff}^2 = V^2\left[1 - \frac{\alpha}{\pi} + \frac{1}{2\pi}\sin(2\alpha)\right] \tag{20}$$

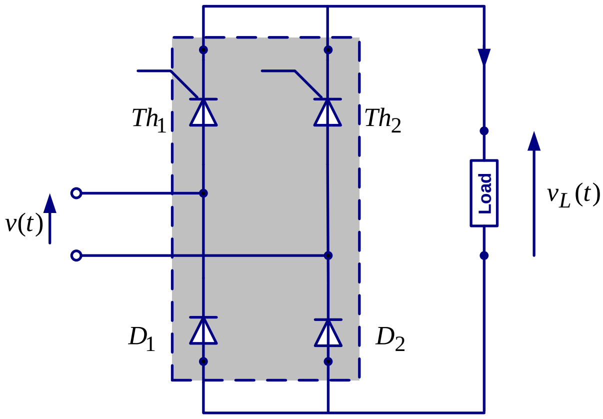


Fig. 5. Mixed bridge: Non Linear Load

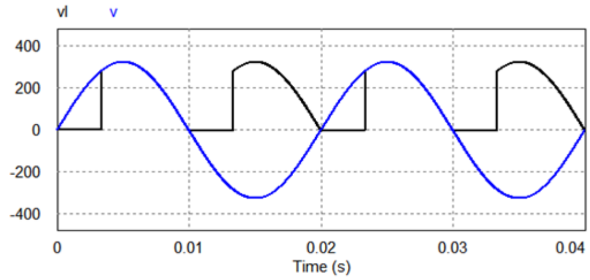


Fig. 6. Rectified voltage: Flow on R

The calculated total active power is given by:

$$P_t = \frac{V_{eff}^2}{R} = \frac{V^2}{R}\left[1 - \frac{\alpha}{\pi} + \frac{1}{2\pi}\sin(2\alpha)\right] \tag{21}$$

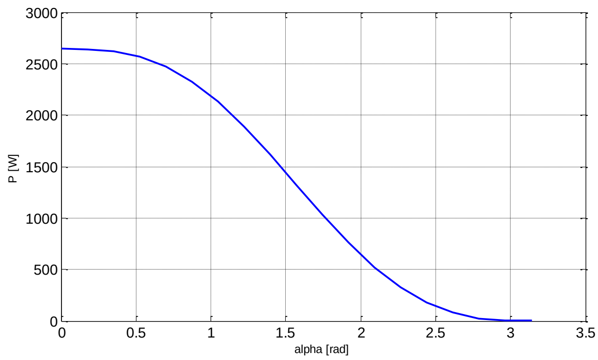


Fig. 7. The shape of the curve of the power according the angle α

- For $\alpha = 0°$, the power is maximum.

- For $\alpha = 180°$, the power is minimum.

The deformation factor is:

$$D = \frac{P_\alpha}{P_{\max}} = \frac{\frac{V^2}{R}\left(1 - \frac{\alpha}{\pi} + \frac{1}{2\pi}\sin(2\alpha)\right)}{\frac{V^2}{R}} \tag{22}$$

With: $P_{\max} = \frac{V^2}{R}$

- When $\alpha = 0$, the deformation factor equal 1.
- When $\alpha = \frac{\pi}{2}$, the deformation factor equal $1/2$.
- When $\alpha = \pi$, the deformation factor equal 0.

From the analysis to calculate the deformation factor, we notice that this last informs us about the non linearity of load.

D. Microcontroller

The microcontroller (PIC) used was the 40-pin PIC16F877 [6] from Microchip controlled by an external 10 MHz oscillator clock. It is a low voltage microcontroller (2.5 V) with 10-bit analog inputs. PICs have been mostly preferred control devices because of their low cost, consuming less energy and having small volume in design [7].
The 3 analog inputs available were used to measure the rms current, the rms voltage, total active power and power due to the first harmonic.
The PIC is programmed to calculate the total active power for linear or non linear load, the apparent power, the power factor, the power due to the first harmonic, the deformation factor, the energy and to display it on the screen of the LCD. The IEM interfaced to communicate with a PC via a serial port RS232.
The designed IEM experimental setup is given in Fig.8

Fig. 8. The designed IEM experimental setup

The flow chart of the IEM written in Hex programme is depicted in Fig.9.

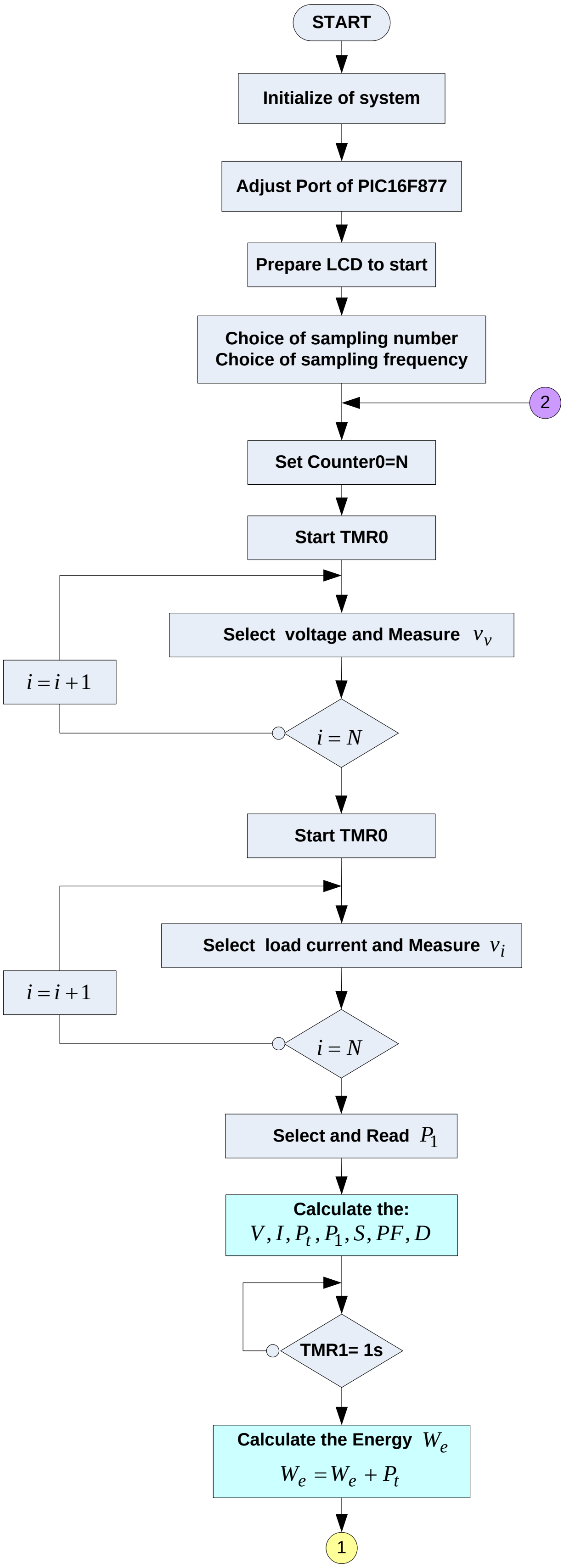
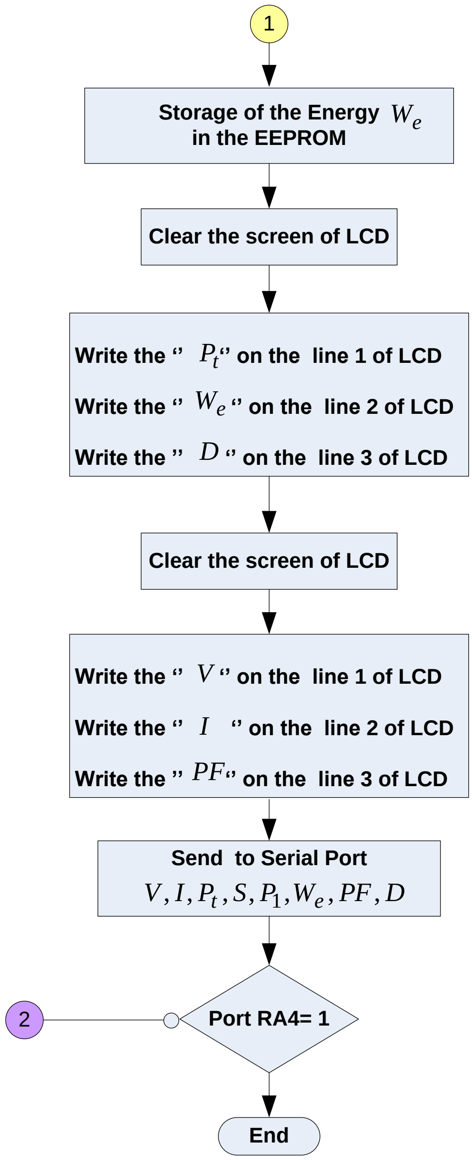


Fig. 9. General Flow Chart of main operation (Cont.)



(Cont.) Fig. 9. General Flow Chart of main operation

IV. Discussion of Results

To validate the operation of the Intelligent Energy meter (IEM), it was tested in our instrumentation laboratory, which is equipped with all kinds of electrical appliances present in a traditional home lighting, refrigerator, electric heating, PCs and air conditioner; during one week. The results are representative of the actual consumption. All the data was transferred to a personal computer for analysis. The energy consumed at the facility will be deducted accurately.

In Fig.10, we show the power consumption during a one week period.

The results of the analysis showed that the nonlinear behavior of the load affects the stability and the pollution of the network voltage and increases consequently the losses. A detailed mathematical analysis showed that the deformation factor can inform us about the degree of the load nonlinearity. Moreover, the reduction of these losses requires the use of capacitors to provide reactive compensation electrical energy.

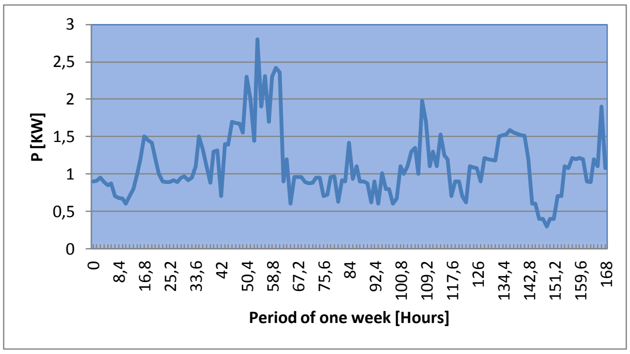


Fig. 10. The Power consumption during a one week period

V. Conclusion

Day after day, the group of consumer of electricity increases prompting the producer of energy to control the quality of their production by an efficient system that takes into accounts the variation of the consumer user.

The advantage of this paper is to make an Intelligent Energy meter (IEM) for measuring billings of electric power consumption loads (linear or nonlinear). This system has the flexibility and the ability to be changed and manipulated according to various environments of combinations of electrical loads. Another point to consider is the digitization of measures.

This Intelligent Energy meter (IEM) measures the total active power, apparent power, power factor, factor of deformation (D) and the energy consumption (W_e). The consumer can control the consumption of fluctuating energy.

In this paper, we developed and implemented Intelligent Energy meter, making use of modern technologies and computer means.

Indeed, the realization of the Intelligent Energy meter helped overcome the constraints of implementation and testing. It can control the power consumed by the same load strongly nonlinear.

In fact, with the development of electronics, we realized a smart meter which allows the control of all parameters of an electrical charge. This smart meter can transmit, via WiFi system information, the energy consumed.

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