

Harmonic Pollution Caused by Non-Linear Load: Analysis and Identification

K. Khelifi, A. Haddouk, M. Hlaili, H. Mechergui

Abstract—The present paper provides a detailed analysis of prior methods and approaches for non-linear load identification in residential buildings. The main goal of this analysis is to decipher the distorted signals and to estimate the harmonics influence on power systems. We have performed an analytical study of non-linear loads behavior in the residential environment. Simulations have been performed in order to evaluate the distorted rate of the current and follow his behavior. To complete this work, an instrumental platform has been realized to carry out practical tests on single-phase non-linear loads which illustrate the current consumption of some domestic appliances supplied with single-phase sinusoidal voltage. These non-linear loads have been processed and tracked in order to limit their influence on the power grid and to reduce the Joule effect losses. As a result, the study has allowed to identify responsible circuits of harmonic pollution.

Keywords—Distortion rate, harmonic analysis, harmonic pollution, non-linear load, power factor.

I. INTRODUCTION

THE electrical energy demand is usually represented by two main physical quantities which are the power demand and the electrical energy consumed by all connected network devices.

The use of non-linear loads is increasing day by day such as computers, low consumption lamps, electronic power supplies, inverters, etc. The harmonic currents generated by these devices have a significant impact on electrical distribution systems [1].

The study of the non-sinusoidal regime is often associated with the harmonics current and voltage magnitudes characterization. However, it is insufficient because this study requires specific tools and synthetic parameters to characterize the global efficiency energy process.

In the present work, we focus on the non-linearity of household loads and the influence that they may have on the electricity grid behavior. Our main objective is to recognize and identify them in order to promote their management while helping to conserve electrical energy and save it from the dangers of harmonic pollution.

Our attitude is based on a causal analysis proposed approach of the harmonic pollution aspect in order to sign the

load attitude [2]. This will be acquired by spectral analyzes and extraction of all the parameters relating to the load: various powers, rate of distortion, etc.

II. HARMONIC POLLUTION: CAUSES AND EFFECTS

The energy sources are characterized by the maximum capacity of production according to the power, the energy cost, and the environmental profiles (CO₂ emission). The higher demand for electricity consumption in residential buildings can largely be explained by the multiplication of electrical appliances linked to technological progress [3].

Nowadays, the abundant presence of harmonics caused by most of these devices which are qualified as non-linear loads pollutes the networks. In addition to that, it records incidences on the quality of the current and consequently becomes source of frequent electric malfunctions or disjunctions. On the other hand, harmonic currents generated in the public network also in the internal networks cause necessarily disturbances which have a lot of repercussions like a bad power factor or additional Joule effect losses which lead to a waste of electrical energy [4].

It is noted that the main responsible of this pollution is the consumers and not the power plants or the distribution networks because of their generation of polluted currents coming from the domestic appliances used.

III. PRIOR METHODS AND APPROACHES FOR LOADS IDENTIFICATION

In general, old and recent experiments have shown that the implemented methods are related to the choice of the equipment used. Indeed, it is demonstrated since there is always the performance concern in terms of precision and computing time. Different calculation and identification methods for analysis characterization of non-linear loads exist in the literature such as Fourier transform method that ensures the transition from temporal to spectral representation by associating to the signal a series of sinusoids frequencies, amplitudes or phases through this integral function form:

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-2\pi jft} dt \quad (1)$$

We note that the most important information is often hidden in the frequency spectrum while being independent of time factor. This method exhibits some disadvantages that it is sensitive to noise. It is affected by the instant at which the disturbances occur and hence introduce error in the calculated duration of disturbance [5]. Moreover, there is also wavelet (Wave Transform technique) which allows analyzing the

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signal with a good resolution and it is defined as a projection on what is called a base of wavelet functions according to the following equation:

$$g(a, b) = \int_{-\infty}^{+\infty} x(t)\psi_{a,b}^*(t)dt = \langle x(t)\psi_{a,b}(t) \rangle \quad (2)$$

where:

$$\psi_{a,b} = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad (3)$$

$\psi_{a,b}(t)$ represents the function resulting by translation and expansion of another function called mother wavelet. The wavelet coefficients (Ψ) and the parameters (a,b) represent the scale factor and the translation factor.

The wavelet sine identification method is applicable for non-stationary transient signals but remains doubts to specify what kind of load has just switched. It exists several other alternatives as the experimental modeling by exponential damped used in the Prony method. This method transforms the nonlinear problem into another linear one by tracking the coefficients and zeros of a polynomial:

$$y(n) = y((n-1)\Delta t) = \sum_{i=1}^M R_i z_i^{n-1} = \sum_{i=1}^M R_i e^{s_i(n-1)\Delta t} \quad (4)$$

where $n = 1, \dots, L = 2M$. M is an unknown root. R_i are the residues, and z_i, s_i are the complex poles.

The time series of the model (4) satisfies a recurrence equation with a polynomial having roots and complex poles z_i to be determined [6]. This method is well known for its extreme sensitivity to noise and numerical results. On the same principle, we also mention the Matrix Pencil method intended to estimate the best M roots and to find the s_i poles corresponding to the R_i residues according to (5) [7]:

$$y(t) = \sum_{i=1}^M R_i e^{s_i t} \quad (5)$$

This method achieves good performances and resolutions. It also allows advanced automation of treatment but has the disadvantage of the needs to implement the Matrix Pencil algorithm through a predestined processor and conditioning matrices [8]. These analysis methods ensure the identification and the behavior of the non-linear loads but each one of them presents its insufficiencies. In the present work, we chose to use the harmonic analysis of the signal to identify the degree of non-linearity load.

IV. HARMONIC ANALYSIS AND POWERS FOR LOAD IDENTIFICATION

A. Case of a Purely Sinusoidal Alternating Voltage Supplying a Non-Linear Dipole

Under sinusoidal voltage of 50 Hz frequency, only one sinusoidal current having the same frequency brings the active power necessarily developed. Except that, most times, the devices do not call this form of current but rather another one deformed and having in this case harmonics. Thus, these harmonics unfortunately contribute to unnecessarily increase

the effective intensity of the current:

$$v(t) = V\sqrt{2} \sin \omega t \quad (6)$$

$$i(t) = \sum_{n=1}^{\infty} I_n \sqrt{2} \sin(n\omega t + \varphi_n)$$

$$I = \sqrt{I_f^2 + I_3^2 + I_5^2 + \dots + I_n^2} \quad (7)$$

where, $I_f = I_1$, the fundamental current (first rank harmonic), I , RMS is the current value (sum of harmonic currents + the fundamental), and I_n is the harmonic current.

The current harmonics (rank ≥ 2) have no role regarding the active and reactive power:

$$P = VI_1 \cos(\varphi_1) \quad (8)$$

$$Q = VI_1 \sin(\varphi_1)$$

where V is the RMS voltage value and φ_1 is the phase difference between the voltage and current fundamental.

The active and reactive powers are not modified but the apparent power increases since it includes an additional term D called the deformed power which depends directly on the presence of current harmonics of rank ≥ 2 :

$$S = VI = V\sqrt{I_1^2 + \sum_{n=2}^{\infty} I_n^2} = \sqrt{P^2 + Q^2 + D^2} \quad (9)$$

$$D = V\sqrt{\sum_{n=2}^{\infty} I_n^2} \quad (10)$$

Current harmonics which crosses through the electrical system impedances causes voltage drops and can also cause an RMS voltage or current value increase.

The total harmonic distortion (THD) of an alternating signal is the ratio between the harmonics root mean square value and the fundamental current one:

$$\text{THD} = \frac{\text{Harmonics RMS value}}{\text{Fundamental RMS value}}$$

The calculation of this rate is one of the solutions intended to detect the presence of distorted currents.

The harmonic pollution produced by an installation has also the effect of reducing its power factor (PF) or Displacement Power Factor (DPF). It is remained that, in the presence of non-linear loads, we no longer speak of $\cos\varphi$ but rather of the power factor [9]:

- In a no harmonic environment: $PF = \cos\varphi$ also called DPF,
- In a harmonic environment: $PF \neq \cos\varphi$.

So, we define the power factor:

$$PF = \frac{P}{S} = \frac{VI_f \cos\varphi_1}{VI} = \frac{I_f}{I} \cos\varphi_1 = \frac{1}{I_f} \cos\varphi_1 = \frac{1}{\sqrt{1 + \frac{\sum_{n=2}^{\infty} I_n^2}{I_f^2}}} \cos\varphi_1 \quad (11)$$

when S increases, P remains constant, the power factor decreases.

The quantity $\frac{\sqrt{\sum_{n=2}^{\infty} I_{hn}^2}}{I_f}$ is called harmonic distortion rate:

$$THD_I(\%) = 100 \times \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_f} \quad (12)$$

$$THD_V(\%) = 100 \times \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_f} \quad (13)$$

We deduce that $PF = f(THD)$:

$$PF = \frac{\cos \varphi_1}{\sqrt{1 + \left(\frac{THD(\%)}{100}\right)^2}} \quad (14)$$

If the $\cos \varphi$ is fixed and the THD is varied, we obtain the curve represented by Fig. 1.

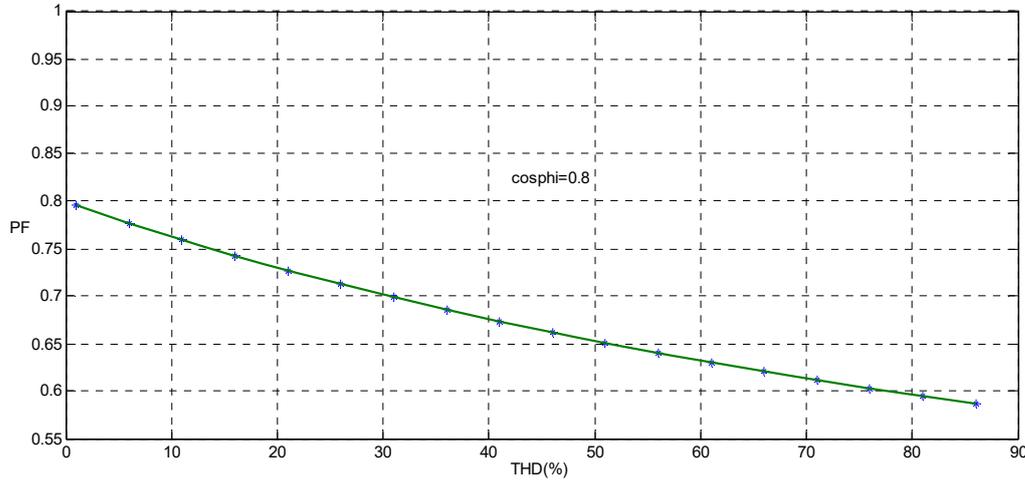


Fig. 1 Representative curve of the PF variation according to the THD

The representation curve of PF based on the THD is nonlinear. We also note that when the THD tends towards 0, the PF in turn tends towards the parameter $\cos \varphi$ until the non-harmonic condition ($PF = \cos \varphi$) is proven.

Moreover, we define the global distortion factor (DF) which represents the ratio between RMS harmonics and RMS total signal value:

$$DF(\%) = 100 \times \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{\sqrt{\sum_{n=1}^{\infty} I_n^2}} \quad (15)$$

In the best case where the waves are purely sinusoidal, we obtain: $I_h = 0$, $THD = 0$ and $PF = \cos \varphi$.

B. Case of a Non-Sinusoidal Alternating Voltage Supplying a Non-Linear Dipole

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

$$v(t) = \sum_{n=1}^{\infty} V_n \sqrt{2} \sin(n\omega t) \text{ and } i(t) = \sum_{n=1}^{\infty} I_n \sqrt{2} \sin(n\omega t + \varphi_n) \quad (16)$$

where n is the harmonic order of both the voltage and current signals.

The RMS values are then expressed as follows:

$$V = \sqrt{\sum_{n=1}^{\infty} V_{hn}^2} \quad (17)$$

$$I = \sqrt{\sum_{n=1}^{\infty} I_{hn}^2}$$

Corresponding total powers are written according to these expressions [10]:

$$P = V_0 I_0 + V_1 I_1 \cos(\varphi_1) + V_2 I_2 \cos(\varphi_2) + \dots + V_n I_n \cos(\varphi_n) \quad (18)$$

$$P = P_t = P_0 + P_1 + \dots + P_n = \sum_n P_n = VI \cos \varphi_n = \sum_{n=1}^{\infty} V_n I_n \cos \varphi_n \quad (19)$$

$$Q = \sum_n Q_n = VI \sin \varphi_n = \sum_{n=1}^{\infty} V_n I_n \sin \varphi_n \quad (20)$$

$$S = VI = \sqrt{S_1 + S_H} = \sqrt{(V_1^2 + \sum_{n=2}^{\infty} V_n^2) \sqrt{(I_1^2 + \sum_{n=2}^{\infty} I_n^2)}} \quad (21)$$

where S_1 ($S_1 = V_1 I_1$) is the fundamental apparent power.

S_H ($S_H = \sum_{n \geq 2}^{\infty} V_n I_n$) is the non-fundamental apparent power corresponded to harmonics in order to measure the overall quantity of harmonic pollution.

The power factor is deduced in:

$$PF = \frac{P}{S} = \frac{\sum_{n=1}^{\infty} V_n I_n \cos \varphi_n}{\sqrt{(V_1^2 + \sum_{n=2}^{\infty} V_n^2) \sqrt{(I_1^2 + \sum_{n=2}^{\infty} I_n^2)}}} \quad (22)$$

The deformed power in a non-linear single-phase voltage and current system is expressed by (23). Its unit is the Distorting Volt Ampere (VAD):

$$D = \sqrt{\sum_{n=2}^{\infty} V_n^2 I_n^2} \quad (23)$$

If we take into account the generality where the voltage harmonic distortion rate is low or inexistent and the current distortion one is high, we can write:

$$P \approx VI_1 \cos(\varphi_1) \quad (24)$$

$$Q \approx VI_1 \sin(\varphi_1) \quad (25)$$

$$D \approx V\sqrt{\sum_{n=2}^{\infty} I_n^2} \quad (26)$$

We note that a low power factor causes voltage drops and energy losses on the network. By improving it (so that it becomes high so close to 1), demand reduction becomes possible and the equipment potentially performances have been improved.

The presence of harmonics has moreover the disadvantage to increase the current RMS value flowing in the electric cables and which will consequently lead to the excess presence of Joule losses [11], [12].

It is while understandable that, in non-sinusoidal regime, the additional losses appearance by Joule effect inside drivers also magnetic materials losses are important. They are fundamentally proportional to the square of the RMS current (determined by the amplitudes of the harmonics currents). The conducting wire resistance causes losses which are defined as:

$$P_j = RI^2 = R\sum_{n=1}^{\infty} I_n^2 \quad (27)$$

If resistance increases with frequency and proximity effects are taken into account, the following expression becomes valid:

$$P_{jt} = \sum_{n=1}^{\infty} R_n I_n^2 = R_1 I_1^2 + \sum_{n=2}^{\infty} R_n I_n^2 \quad (28)$$

$$P_{jt} = P_{j1} + P_{jh} = P_{j1}(THD + 1) \quad (29)$$

Harmonic processing allows control of apparent and reactive powers.

To validate and to illustrate the analytical analysis, we simulated a non-linear load.

V. NON-LINEAR LOAD SIMULATION AND SPECTRAL ANALYSIS

A. Spectral Analysis

We proposed to choose the case of non-linear load type-controlled rectifier powered by a sinusoidal voltage.

- Resistive Load in Series with a Thyristor

The system given by Fig. 2 is supplied by a grid voltage given by $v(t) = V\sqrt{2}\sin(\omega t)$ with an RMS value equal to 141.42V and a frequency of 50 Hz.

For a control angle α of the thyristor, the current flowing through this load is represented in Fig. 3 (a) followed by the spectral analysis illustrated in Fig. 3 (b).

Table statement of the Fourier transform (Fig. 3 (c)) provides information on the various components in order to

achieve the signal as:

$$i(t) = I_{dc} + I_1\sqrt{2}\sin(\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_n\sqrt{2}\sin(n\omega t + \varphi_n) \quad (30)$$

where I_{dc} is the continuous component. $I_1 = 0.64A$, the fundamental harmonic and $I = \sqrt{\sum_{n=1}^{\infty} I_n^2} = 0.93A$, total current.

By using (12), we obtain the distortion rate of this current: $THD_i = 65.52\%$

- RL Series Load

Fig. 4 (c) reports the distortion rates list of each harmonic at the multiple frequencies of the fundamental and the corresponding phase shifts.

- RC Parallel Load

Finally, analysis has shown that these loads distorted the current in power lines and produced harmonic pollution which goes up to networks.

B. Simulation Results

Simulations results obtained first highlight the influence of the thyristor in different mounting (resistive, inductive or capacitive): it is the transition to nonlinearity. Indeed, for the resistive load, we obtained a THDi of 65% and a power factor PF equal to 0.6. Moreover, in case of an inductive load, the distortion rate increases slightly (THDi = 51%) and it is clearly shown that it has a consequence on the power factor (PF) which is degraded to 0.5.

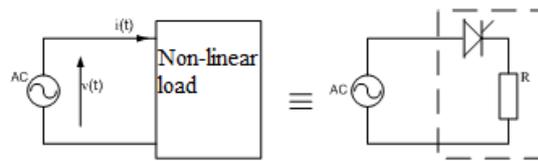
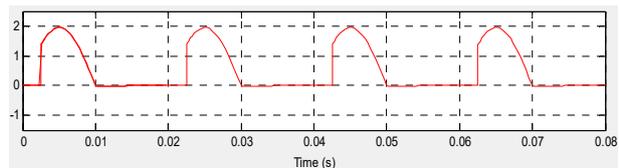
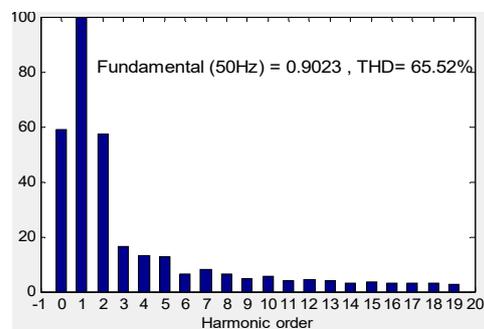


Fig. 2 Non-linear load modeling



(a)

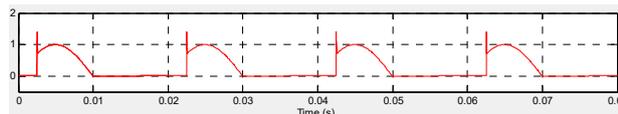


(b)

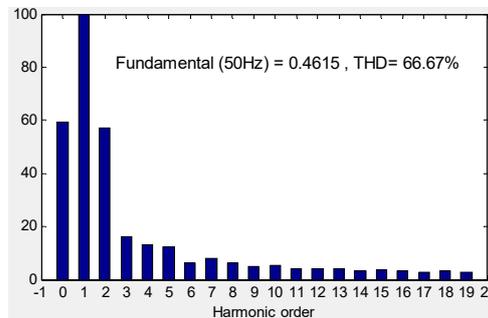
DC component = 0.5334
 Fundamental = 0.9023 peak (0.638 rms)
 THD = 65.52%

0 Hz (DC):	59.12%	90.0°
50 Hz (Fnd):	100.00%	-8.3°
100 Hz (h2):	57.46%	255.0°
150 Hz (h3):	16.55%	182.5°
200 Hz (h4):	13.02%	191.4°
250 Hz (h5):	12.53%	122.3°
300 Hz (h6):	6.37%	87.6°
350 Hz (h7):	8.15%	54.1°
400 Hz (h8):	6.30%	-5.7°
450 Hz (h9):	4.98%	-31.2°
500 Hz (h10):	5.67%	-81.7°
550 Hz (h11):	4.14%	230.9°
600 Hz (h12):	4.30%	199.0°
650 Hz (h13):	4.16%	145.0°
700 Hz (h14):	3.31%	108.0°
750 Hz (h15):	3.74%	66.5°
800 Hz (h16):	3.29%	15.8°
850 Hz (h17):	3.06%	-19.6°
900 Hz (h18):	3.23%	-67.7°
950 Hz (h19):	2.74%	248.3°

(c)

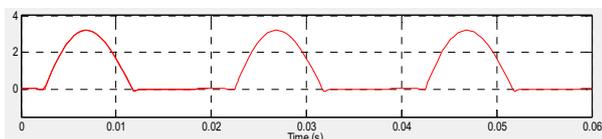


(a)

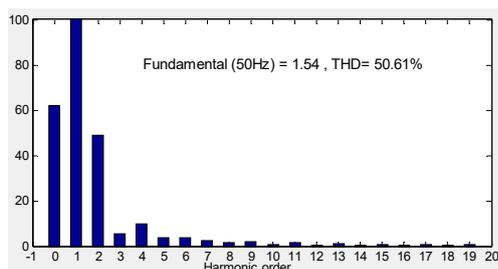


(b)

Fig. 3 Current harmonic analysis (R load): (a) Non-linear load current, (b) Current harmonic spectrum, (c) THDi and Fourier transform list



(a)



(b)

DC component = 0.2736
 Fundamental = 0.4615 peak (0.3264 rms)
 THD = 66.67%

0 Hz (DC):	59.28%	90.0°
50 Hz (Fnd):	100.00%	-7.5°
100 Hz (h2):	57.20%	254.7°
150 Hz (h3):	16.23%	182.8°
200 Hz (h4):	13.12%	191.3°
250 Hz (h5):	12.36%	122.0°
300 Hz (h6):	6.32%	88.9°
350 Hz (h7):	8.11%	53.9°
400 Hz (h8):	6.14%	-5.2°
450 Hz (h9):	4.97%	-30.3°
500 Hz (h10):	5.57%	-81.6°
550 Hz (h11):	4.04%	232.0°
600 Hz (h12):	4.25%	199.5°
650 Hz (h13):	4.05%	145.7°
700 Hz (h14):	3.27%	108.7°
750 Hz (h15):	3.64%	66.1°
800 Hz (h16):	3.13%	16.3°
850 Hz (h17):	2.95%	-18.8°
900 Hz (h18):	3.09%	-67.3°
950 Hz (h19):	2.63%	248.9°

(c)

Fig. 5 Current harmonic analysis (RC load): (a) Non-linear load current, (b) Current harmonic spectrum, (c) THDi and Fourier transform list

DC component = 0.9531
 Fundamental = 1.54 peak (1.089 rms)
 THD = 50.61%

0 Hz (DC):	61.89%	90.0°
50 Hz (Fnd):	100.00%	-35.1°
100 Hz (h2):	48.94%	199.6°
150 Hz (h3):	5.57%	90.8°
200 Hz (h4):	9.61%	119.2°
250 Hz (h5):	3.48%	2.8°
300 Hz (h6):	3.66%	40.0°
350 Hz (h7):	2.46%	-80.1°
400 Hz (h8):	1.61%	-38.0°
450 Hz (h9):	1.79%	199.6°
500 Hz (h10):	0.75%	244.0°
550 Hz (h11):	1.40%	118.6°
600 Hz (h12):	0.23%	176.6°
650 Hz (h13):	1.01%	39.4°
700 Hz (h14):	0.09%	131.7°
750 Hz (h15):	0.83%	-39.7°
800 Hz (h16):	0.13%	165.0°
850 Hz (h17):	0.61%	238.8°
900 Hz (h18):	0.20%	91.7°
950 Hz (h19):	0.44%	158.1°

(c)

Fig. 4 Current harmonic analysis (RL load): (a) Non-linear load current, (b) Current harmonic spectrum, (c) THDi and Fourier transform list

The current spectral harmonic representations given by Figs. 3 (c)-5(c) show the existence of odd and even harmonics up to order 20 because of the presence of the DC component.

Concerning the powers, current distortion has an instant effect observed as to the increase of the transited powers. This results in an apparent power S greater than the active power P when it should be as low as possible in order to require the minimum power supply current: according to Table I, we note $S = 131.6$ VA and 219.4 VA for the respective active powers $P = 88.87$ W and 126.1 W.

Regarding to the grid, the current harmonics flowing through the load are circulated at the same time in the voltage source. Therefore, these harmonic currents will cause a slight deterioration of the voltage waveform at the load point connection to the network.

VI. PRACTICAL TESTS FOR SINGLE-PHASE LOADS

To validate the proposed theory, some experimental tests

are carried out which illustrate the current consumption of some domestic appliances supplied with single-phase sinusoidal voltage.

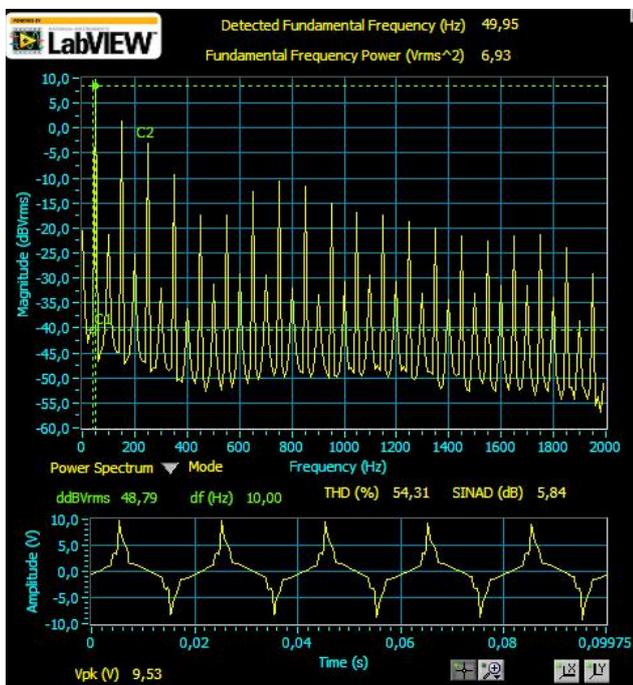
The experimental test bench designed is represented by the structure in Fig. 9. Acquisition results are obtained using the NI ELVIS model. Figs. 6-8 show waveforms of current and voltage signals in real time. Parts (a) of these figures illustrate the behavior of the currents consumed as well as the frequency spectral analysis of each non-linear load: lamp, computer, and oscilloscope. The current deformation given by Fig. 6 (b) is very noticeable, but even more important with rather similar shapes for the computer and the oscilloscope shown

respectively in Figs. 8 (b) and 7 (b).

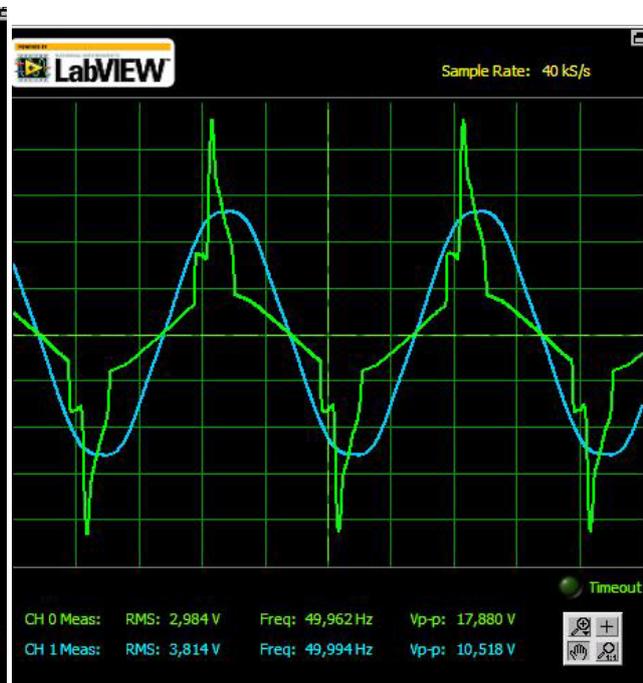
We first notice the abundant consumption of deformed currents staffed with harmonics coming from the computer and the oscilloscope. Indeed and according to Table II, their respective harmonic distortion rates are 127.65% and 148.72%. On the other hand, the compact fluorescent lamp has the lowest level of THDi (54.31%) but still remains important enough to record the presence of harmonic pollution because it is a highly non-linear device. These non-linear loads must be processed and tracked in order to limit their influence on the power grid, the power factor, the Joule effect losses and many other previously considered effects.

TABLE I
POWER MEASUREMENT AND CURRENT DISTORTION RATE (NON-LINEAR LOADS SIMULATIONS)

Upstream loads with the thyristor	P (W)	Q (VR)	S (VA)	PF	D (VAD)	THDi (%)
R	88.87	14.34	131.6	0.6	95.95	65
<i>Serial RL</i>	126.1	88.82	219.4	0.5	156	51
<i>Parallel RC</i>	45.38	6.35	67.12	0.6	49.09	67



(a)



(b)

Fig. 6 Real time acquisition of current/voltage signals and spectral analysis: case of a non-linear load (compact fluorescent lamp 25 W)

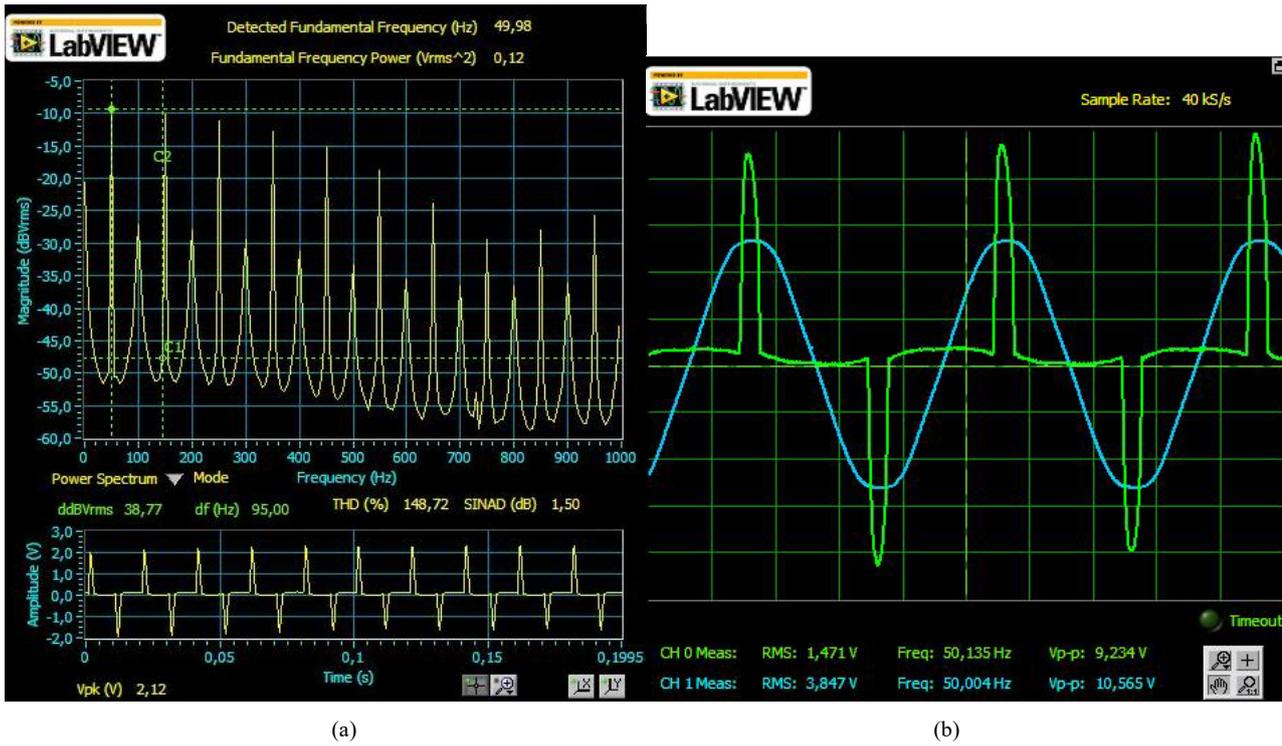


Fig. 7 Real time acquisition of current/voltage signals and spectral analysis: case of a non-linear load (oscilloscope)

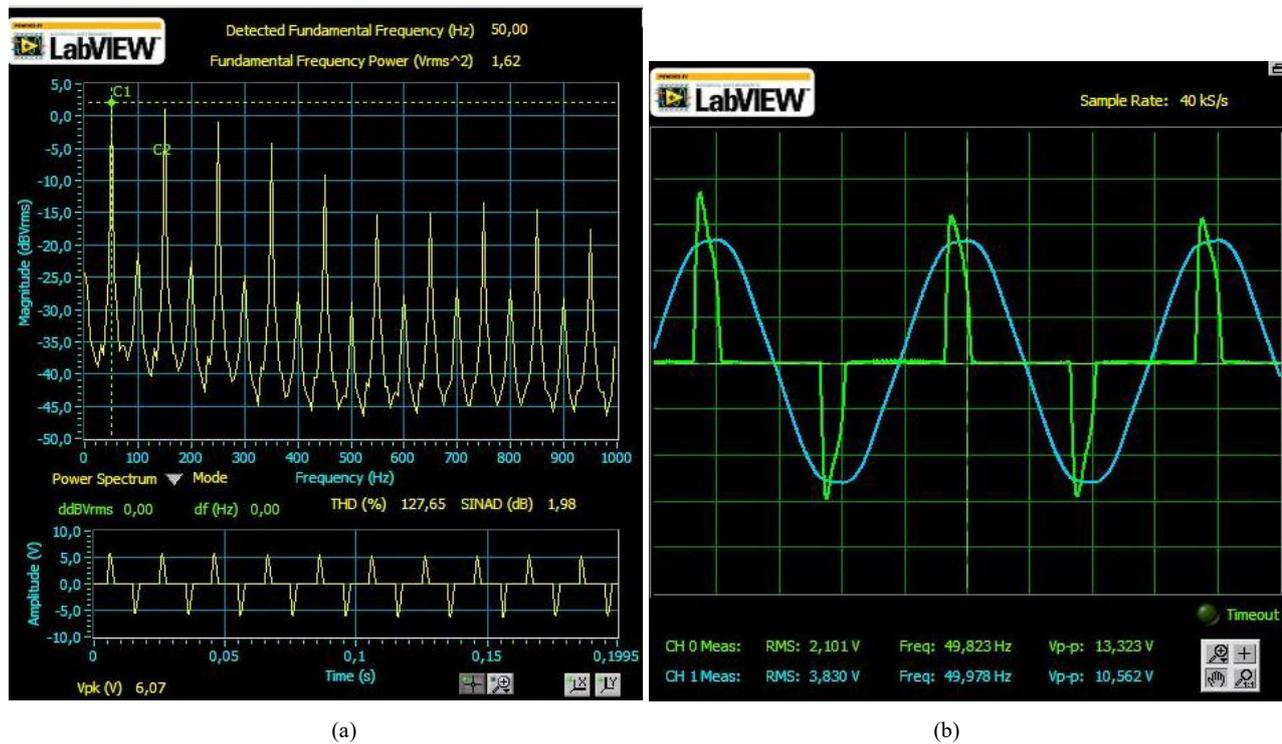


Fig. 8 Real time acquisition of current/voltage signals and spectral analysis: case of a non-linear load (computer)

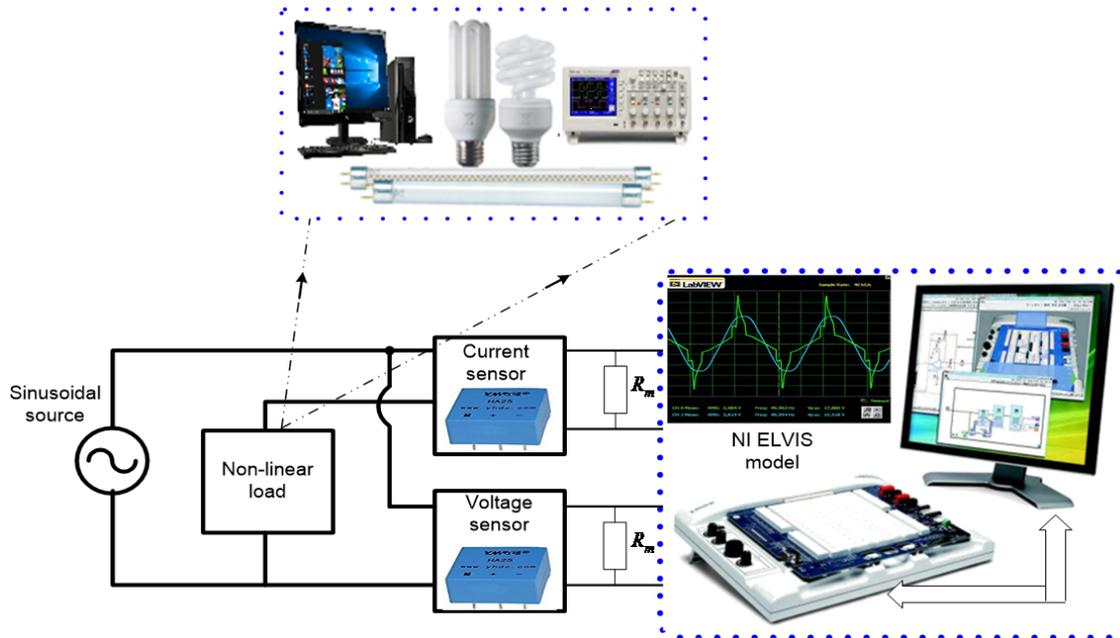


Fig. 9 Instrumental platform for the measurement of the non-linear load current and voltage

TABLE II
THD RESULTS FOR SOME USUAL LOADS

Single phase load	THDi (%)
<i>Compact fluorescent lamp</i>	54.31 %
<i>Computer</i>	127.65 %
<i>Oscilloscope</i>	148.72 %

VII. CONCLUSION

In the present work, harmonic analysis was performed for nonlinear household loads. This analysis made it possible to identify the behavior of these loads as well as their influence on the electrical network and this was illustrated by the THD.

In order to validate the theory that has been presented in this paper, we have performed measurements on these loads. The results show that these ones have a non-linear behavior accentuated until having $THDi \geq 148\%$. This high and considerable distortion rate will be responsible for the injection of harmonic currents in the network and has the consequence of damaging its quality or producing disturbances which then causes long-term electrical malfunctions. Finally, we concluded that smart metering services can give data about the deformed power factor and ensure the power factor monitoring.

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