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Analysis of the Real Energy Consumption of Energy Saving Lamps

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Abstract: Light emitting diode (LED) and compact fluorescent light (CFL) lamps are widely used because they are associated with low energy consumption and a reduced environmental impact. In the present paper, a study of the real consumption of these devices has been carried out. To do this, the active, reactive, distortion and apparent power and electrical efficiency for various lamps have been measured and calculated. The distortions produced in the network provoke the consumed energy to be in the order of 50–75% higher than that which appears in the commercial characteristics. This situation means that for its operation, it is necessary to generate and distribute an amount of energy much higher than that which is declared as the consumption of these lamps, and so far, this amount of energy is neither quantified nor invoiced. Additionally, groups of lamps have also been studied to check whether, when working together on the same network, there is a compensation phenomenon that reduces the negative effects of individual lamps. We have found that this compensation effect does not occur for the type of devices evaluated.

Keywords: energy saving lamps (CFLs and LED); harmonics; reactive power; THDi; electric efficiency; distortion power; electric bill

1. Introduction

It is evident that in recent years there has been greater awareness regarding the impact that our activity has on the environment. More and more governments are legislating according to environmental criteria, and in that sense, one of the criteria that is considered most important is energy saving. There are many ways to reduce the energy consumed, for example, by improving production processes, manufacturing more energy efficient equipment etc. One of the efforts on which energy saving has focused is based on modifying basic behaviors, which individually may involve a small gesture, but collectively results in a qualitative change. In this regard, the institutions are promoting the replacement of the lamps used for lighting homes, looking for elements that provide a better lighting condition with lower energy consumption

In the DIRECTIVE 2009/125/EC of the European Parliament and of the council of 21 October 2009—published on 31 October 2009—a framework was established for the setting of ecodesign requirements for energy-related products [1] which highlights "Many energy-related products have a significant potential for being improved in order to reduce environmental impacts and to achieve energy savings through better design which also leads to economic savings for businesses and end-users". This sentence reaffirms the need to serve two purposes. On the one hand, to improve products related to the energy sector from an environmental point of view, and on the other, to achieve an economic benefit for both the industry and the end consumer.

The European regulation that applied the framework established by the DIRECTIVE 2005/32/EC of The European Parliament and the council of 6 July 2005, for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council [2] (derogated by 2009/125/EC mentioned above), stated that "Improvements of electricity consumption of products subject to this Regulation should be achieved by applying existing non-proprietary cost effective technologies, which lead to a reduction in the combined expenses for purchasing and operating the equipment".

It is clear that the European Union legislation urged for the replacement of existing bulbs, incandescent in first instance and halogen in the second, with other technologies that enable a lower environmental cost and that result in savings for the domestic consumer. In compliance with these guidelines, the market presence of CFL (compact fluorescent light) and LED (light emitting diode) lamps increased. These products had already been commercialized and used for a long time, with CFLs being the oldest on the market, and LEDs being the most recently introduced. The regulatory change brought about by these guidelines gave an important boost to their use, and the use of CFLs and LEDs is now widespread, mainly in the domestic and commercial sector.

Their proposal as more eco-friendly substitutes is based, fundamentally, on their greater light efficiency with lower nominal consumption than incandescent lamps. This means more efficient lighting for a lower theoretical consumption, which is why they have been called energy saving and high light output lamps. In this sense, there are several papers that mention the characteristics of this type of lamp. Several authors have tried to quantify the energy savings that would occur when this new technology is used. For instance, Ganadran et al. [3] established that by introducing LEDs in the Universiti Tenaga Nasinal (Malasya), the consequential saving would be around 10%. The same conclusion was obtained by Khorasanizadeh et al. [4], however their analysis was completed in homes in Malaysia. They also conclude that the savings are similar when CFLs are used, but they estimate that LED technology had (in 2015 when their study was published) more possibilities for improvement. Houri and Khoury [5] established that the replacement of incandescent lamps with CFLs in Lebanon would imply an 8.3% in consumption reduction, while Islam el al. [6] carried out a similar study in Kazakhstan but expanded it to the commercial/industrial sector and to outdoor lighting, in addition to residential lighting, documenting that energy savings are produced in all three sectors. Limi et al. [7] analyzed the CFL distribution program carried out in Ethiopia, concluding that the savings for the consumer were significant, and that the benefits were most notable in the most disadvantaged sectors of the country.

In summary, it can be concluded that by introducing these types of light, the domestic consumer bill will decrease in relation to the cost of achieving the same quality of lighting using incandescent bulbs.

However, not all research shows positive data for CFLs and LEDs. Several authors have analyzed the behavior of these lamps and have established that their use presents some drawbacks that should not be neglected. As early as 1995, Dwyer et al. [8] evaluated the impact of the harmonics generated by the CFL in distribution systems, concluding that under certain conditions they generate large distortions in voltages, even after taking into account these distortions can be partially canceled when several lamps are used. Koch et al. [9] conducted a simulation to evaluate the effect of the use of CFLs on the voltages and currents of the network, evaluating both the harmonics generated and the resonance conditions. On the other hand, Gil-de-Castro et al. [10] analyzed the light intensity variation and the harmonic emission of LED lamps, finding that there was a relationship between the level of harmonics generated and the sensitivity of the lamps to voltage fluctuations. Another problem that worries researchers, is the flicker of LED and CFL lamps [11,12]. Wilkings et al. [13] in 2010 already proposed technical solutions to reduce this phenomenon and reduce the problems it can generate—including health effects.

Despite these studies and many others in the same direction [14–21], the prevalent belief is that these types of lamp represent, as mentioned above, significant energy savings, and this is a factor that can help in the reducing environmental impacts.

In this paper, it has been evaluated whether the global energy saving is real or not. The starting hypothesis for the present study is based on analyzing the energy cost not only from the point of view of the final consumer, which, as we have already mentioned, is highly contrasted, but in the system as a whole. CFL and LED lamps marketed in Spain from different manufacturers and characteristics have been evaluated, analyzing the harmonics generated and the distortions introduced into the distribution system. The reactive and distortion powers consumed have been evaluated concluding that these are by no means insignificant. The presence of capacitive reactive power and distortion in the network cause higher currents and an increase in the consumption of the apparent power S (VA) that must be supplied by power plants and considered in distribution and in the design of transformation stations.

Additionally, taking into account that in Spain the consumption of electrical energy that is destined for lighting installations is of the order of 10–20% of the global consumption, and that an estimated 25–50% of this is consumed by domestic sources and the rest by public lighting and administrative buildings [22], the extensive use of CFL and LED lamps assumes an energy and economic cost that, so far, has not been considered in terms of the billing to the final consumer (as in many other countries). This cost has been found to be very significant within the overall energy bill.

2. Materials and Methods

For the study of CFL and LED lamps, twelve lamps of different commercial brands and with different characteristics were used. Of these twelve lamps, five were LEDs and seven were CFLs from eight different manufacturers and with different consumption and light efficiencies. Table 1 shows the main characteristics of the lamps used. The power value that is included in the table is the value that the manufacturer declares that the lamp consumes. All of them operate in a voltage range of 230–240 V, with a frequency of 50 Hz. The CFL lamps have an integrated ballast, while the others incorporate a buck LED driver.

Table 1. Summary of the main characteristics of the evaluated light emitting diode (LED) and compact fluorescent light (CFL) lamps.

Key	Type	Brand	P (W)	Light Efficiency (lm/w)	Luminous Flux (lm)	Color (K)	Cost (€)
L1	LED/E27	Lexman	12	88	1055	3000	15.99
L2	LED/E27	H2V	9	89	806	3000	21.45
L3	LED/E27	Mega	6	100	600	2700	12.45
L4	LED/E27	Adeo	6	67	400	3000	28.95
L5	LED/E27	Philips	11	96	1055	6000	10.99
C1	CFL/E27	Lexman	23	61	1398	6500	6.95
C2	CFL/E27	Lexman	22	58	1279	6500	6.45
C3	CFL/E27	Lexman	15	53	800	4000	5.95
C4	CFL/E27	Xavax	15	53	798	2700	13.33
C5	CFL/E27	Osram	14	55	770	2700	4.25
C6	CFL/E27	Froiz	11	55	600	2700	3.95
C7	CFL/E27	Froiz	9	50	450	2700	3.45

Each lamp was assigned with a key to facilitate identification throughout the study. The power consumptions declared by the manufacturers ranged from 23 W to 6 W, and the light efficiency ranged between 100 lm/W and 50 lm/W. The chosen lamps cover a wide range of market prices, representative of what an average final consumer can purchase for their home. Market prices have also been included in Table 1. With this choice, an attempt has been made to evaluate a representative range of the lamps available on the market and most common in domestic use.

Once the study lamps had been selected, an analysis of the real power consumption associated with their operation was carried out. For this, the harmonics generated and the distortion rate of each of the lamps were measured. The power factor was also determined as a measure of the electrical efficiency of the loads.

To measure the currents in the lamps, a Fluke 435-II analyzer was used, with a supply voltage of $\overline{V}_1 = 230_{\angle 0^\circ}\,V \mp 2\%$ supplied by an adjustable three-phase source Model DL 1013 T1 from the manufacturer De Lorenzo. In Section 4.2.5 of the UNE-EN-50160 standard, the limit for consider a linear voltage system is a voltage distortion rate (THDv) of 8% [23]. The value of the voltage distortion rate (THDv) associated with the source is less than 2%, which allows us to consider that the power supply system for the evaluated loads is linear. Therefore the feed is considered constant and linear, while the load is non-linear. All measurements were made after the luminaire stabilization time indicated by the manufacturer had elapsed.

For each of the eleven lamps and the four associations evaluated, the current harmonic distortion rate (THDi) and the harmonic spectrum (up to the 50th harmonic) were obtained, as well as the value of the argument and the angle of each harmonic. The distorted current waveform and the phasor diagram were also obtained.

The current consumption, I, can be decomposed into a fundamental frequency current, I_1, made up of an active and a reactive component (I_{1a} and I_{1r}, respectively), and a harmonic or distortion current, I_D, associated with all non-fundamental frequencies, as expressed in Equation (1):

$$i(t) = i_1(t) + i_D(t) = i_{1a}(t) + i_{1r}(t) + \sum_{n \neq 1}^{\infty} i_n(t) \quad (1)$$

Czarnecki [24,25] and Emanuel [26] in the IEEE Standard 1459/2010 establish that each of these currents are associated with physical phenomena present in the electrical system. These phenomena are the useful, the reactive and the distortion energy. The same is established by León in the unified power measurement (UPM) [27]. This author quantifies these phenomena through active power (P), reactive power (Q) and distortion power (D), orthogonal to each other, as are the associated currents. Starting from P, Q and D, the apparent power (S) is determined, which is the real power that must be supplied to the receiver for it to work. The expressions that allow us to calculate these powers are shown in Equations (2)–(5).

$$P = V_1 \cdot I_1 \cdot \cos\varphi_1 = V_1 \cdot I_{1a} \quad (2)$$

$$Q = V_1 \cdot I_1 \cdot \sin\varphi_1 = V_1 \cdot I_{1r} \quad (3)$$

$$D = V_1 \cdot \sqrt{\sum_{n \neq 1}^{\infty} I_n^2} = V_1 \cdot I_D \quad (4)$$

$$S = V_1 \cdot \sqrt{I_{1a}^2 + I_{1r}^2 + I_D^2} = \sqrt{P^2 + Q^2 + D^2} \quad (5)$$

Despite the fact that the measurements carried out with the Fluke analyzer present the complete harmonic spectrum, in view of the results obtained it has been considered that from the 9th harmonic the values can be negligible, so the previous equations have been applied using the current harmonics 3rd, 5th, 7th and 9th.

From the apparent power previously calculated, the efficiency of the receiver, ε, is determined by the relationship between P and S, shown in Equation (6), and that in non-linear systems, like these, it does not coincide with the $\cos\varphi$ [27].

$$\varepsilon = \frac{P}{S} \quad (6)$$

This value gives us an idea of the real power that must be supplied to the receiver for it to work. Only if $\varepsilon = 1$ would the power supplied coincide with the active power, which is the consumption that is actually billed for domestic consumers (for example, in Spain those consumers with consumption

P <15 kW are considered as such). When the efficiency value is less than one, a part of the energy that is consumed is not counted in the billing, but it must be generated and distributed to the consumer. For example, if the value of ε was 0.5, the receiver would have to be supplied with twice the power it uses for it to work. The part that is not used is that related to reactive (var) and distortion (VAd) powers, and this energy is not measured for the billing of small consumers.

The current distortion rate has also been calculated for each lamp with the expression shown in Equation (7), as defined by the EN-61000-2-2 standard [28]:

$$THD_I(\%) = \frac{\sqrt{\sum_{n=2}^{40} I_n^2}}{I_1} \quad (7)$$

According to some of the literature [29–31], the distortions generated individually by certain non-linear devices compensate each other, so it is suggested that, despite the fact that the distortions determined individually are significant, when they work jointly, the distortion generated in the distribution system is not. To evaluate whether there is a compensation effect in the case of the lamps, in addition to analyzing the behavior of each one individually, groupings of lamps working on the same network were evaluated. For each grouping, the same parameters as those obtained for the lamps individually were measured.

Groups only of LEDs, only CFLs and two combinations of mixed type have been included. Table 2 shows the type of association, the lamps that constitute it, and the keys with which they will be designated in the document.

Table 2. Evaluated lamp associations.

Key	Type	Goup	Lamps
G-L	Only LED	4 LED	L1, L2, L4, L5
G-C	Only CFL	4 CFL	C2, C3, C4, C5
G-M-1	Mixed	2 LED+2 CFL	L1, L5, C2, C3
G-M-2	Mixed	2 LED+6 CFL	L1, L5, C1, C2, C3, C4, C5, C6

For the calculation of the powers associated with the groups, the result of the phasor sum of the currents for each of the devices within each group has been taken.

3. Results and Discussion

Figure 1 shows the harmonic spectrum, waveform and phasor diagram for the L3 LED lamp and the C7 CFL as an example of the results obtained for the individual lamps.

Harmonic spectra are represented up to the 50th harmonic. In the examples shown in Figure 1 it can be seen that the current distortion rate (THDi) measured is 127% for the LED lamp and 108% for the CFL (Figure 1a,d). Both values are very high, which implies that the distortions that are generated in the network are very significant. It can also be seen that for the higher harmonics, the values gradually decrease until they become negligible.

Figure 1b,e shows the voltage and current waveform for L3 and C7. In both cases, an absolutely distorted current waveform is obtained.

Finally, Figure 1c,f shows the phasor diagrams of the two lamps shown as an example. In both cases, it can be seen how the load shows a capacitive character. The measured currents present 32° and 27° (for L3 and C7, respectively) ahead of the voltage.

The behavior presented in Figure 1 for two of the lamps analyzed is extensible for the rest of the lamps evaluated. Table 3 shows the values obtained in the measurements for the twelve lamps. The experimentally obtained values for THDi, active power (P), reactive power (Q), distortion power (D) and apparent power (S) are summarized.

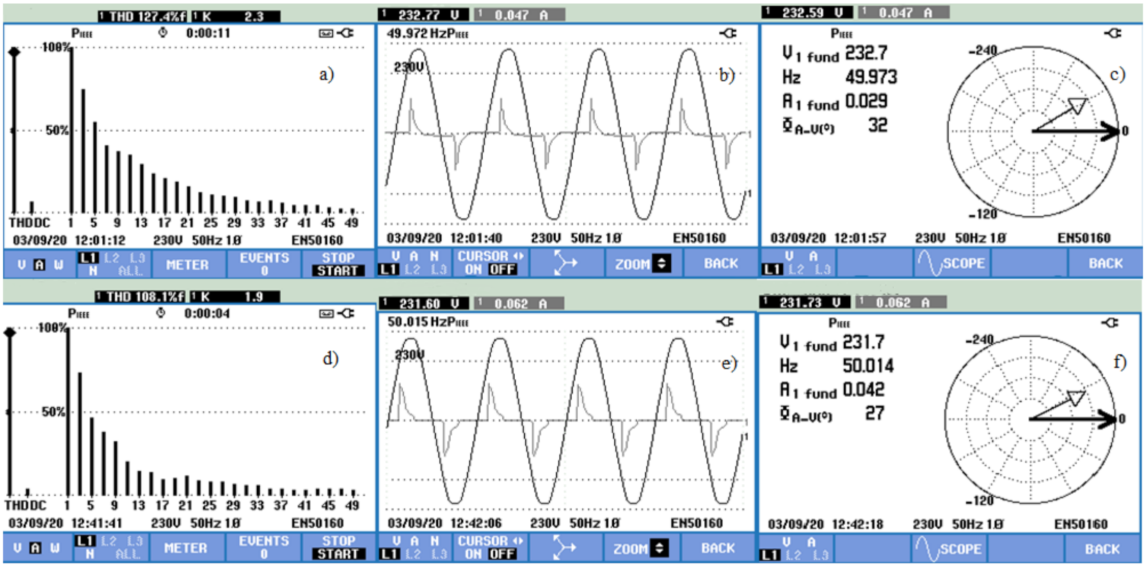

Figure 1. Measurements obtained for individual lamps: Harmonic spectrum (**a**), waveform (**b**) and phasor diagram (**c**) of the L3 lamp. Harmonic spectrum (**d**), waveform (**e**) and phasor diagram (**f**) of the C7 lamp.

Table 3. Values measured with the Fluke analyzer on the twelve lamps.

Lamp	THDi (%)	P (W)	Q (Var)	D (VAd)	S (VA)
L1	104.54	12.2	−3	15.6	21.4
L2	149.06	9.5	−3	15	18
L3	126.65	5.8	−3.6	8.6	11
L4	124.04	6.1	−4.1	9.2	11.7
L5	137.96	10.7	−4	15.9	19.6
C1	112.32	21.2	−8.9	27.1	35.1
C2	120.85	21.8	−10	29.2	37.8
C3	107.86	14.8	−7.5	17.9	24.4
C4	119.82	13.4	−6.4	17.9	23.3
C5	106.05	15.3	−8	18.4	25.2
C6	105.35	10.8	−5.6	12.9	17.7
C7	106.01	8.9	−4.6	10.7	14.7

To calculate the powers and the distortion rate according to Equations (2)–(5) highlighted in the Materials and Methods section, the values from the third to the ninth harmonic have been taken, which are the ones that have been shown to be most important within the spectrum. Table 4 shows the value of the fundamental current and each of these harmonics for the twelve lamps, and Table 5 shows the values of THDi P, Q, D, S and ε calculated according to the mentioned expressions.

Comparing the values shown in Table 3 (measured) and Table 5 (calculated), it can be seen how they are very similar. The differences may be mainly due to the fact that for the calculations according to the theories defined by [24–27] only the first harmonic currents have been taken, while the Fluke analyzer uses the entire spectrum up to the 50th harmonic.

Table 4. Measured values for the fundamental current and the 3rd, 5th, 7th and 9th harmonic currents for the twelve lamps.

Lamp	I_1 (A)	I_3 (A)	I_5 (A)	I_7 (A)	I_9 (A)
L1	$0.062_{\angle 34^\circ}$	$0.044_{\angle -91^\circ}$	$0.028_{\angle 166^\circ}$	$0.023_{\angle 76^\circ}$	$0.019_{\angle -27^\circ}$
L2	$0.044_{\angle 18^\circ}$	$0.037_{\angle -126^\circ}$	$0.029_{\angle 95^\circ}$	$0.021_{\angle -36^\circ}$	$0.017_{\angle -155^\circ}$
L3	$0.029_{\angle 32^\circ}$	$0.022_{\angle -122^\circ}$	$0.016_{\angle 105^\circ}$	$0.012_{\angle -18^\circ}$	$0.011_{\angle -134^\circ}$
L4	$0.032_{\angle 34^\circ}$	$0.023_{\angle -108^\circ}$	$0.017_{\angle 131^\circ}$	$0.013_{\angle 22^\circ}$	$0.013_{\angle -91^\circ}$
L5	$0.049_{\angle 21^\circ}$	$0.04_{\angle -117^\circ}$	$0.029_{\angle 115^\circ}$	$0.022_{\angle 1^\circ}$	$0.021_{\angle -113^\circ}$
C1	$0.101_{\angle 25^\circ}$	$0.08_{\angle -101^\circ}$	$0.053_{\angle 147^\circ}$	$0.042_{\angle 48^\circ}$	$0.039_{\angle -60^\circ}$
C2	$0.102_{\angle 25^\circ}$	$0.078_{\angle -103^\circ}$	$0.051_{\angle 145^\circ}$	$0.042_{\angle 48^\circ}$	$0.038_{\angle -62^\circ}$
C3	$0.069_{\angle 27^\circ}$	$0.052_{\angle -97^\circ}$	$0.033_{\angle 156^\circ}$	$0.027_{\angle 61^\circ}$	$0.024_{\angle -46^\circ}$
C4	$0.068_{\angle 26^\circ}$	$0.05_{\angle -100^\circ}$	$0.031_{\angle 54^\circ}$	$0.026_{\angle 58^\circ}$	$0.023_{\angle -50^\circ}$
C5	$0.074_{\angle 28^\circ}$	$0.053_{\angle -94^\circ}$	$0.033_{\angle 164^\circ}$	$0.027_{\angle 76^\circ}$	$0.022_{\angle -42^\circ}$
C6	$0.054_{\angle 28^\circ}$	$0.037_{\angle -93^\circ}$	$0.023_{\angle 162^\circ}$	$0.019_{\angle 75^\circ}$	$0.016_{\angle -27^\circ}$
C7	$0.043_{\angle 28^\circ}$	$0.032_{\angle -93^\circ}$	$0.02_{\angle 164^\circ}$	$0.016_{\angle 76^\circ}$	$0.014_{\angle -29^\circ}$

Table 5. Calculated values for the twelve lamps.

Lamp	THDi (%)	P (W)	Q (Var)	D (VAd)	S (VA)	ε
L1	96.91	11.89	−8.02	13.89	19.97	0.60
L2	123.23	9.73	−3.16	12.61	16.24	0.60
L3	109.32	5.72	−3.58	7.38	10.00	0.57
L4	106.25	6.17	−4.16	7.90	10.85	0.57
L5	118.40	10.65	−4.09	13.51	17.69	0.60
C1	110.67	21.27	−9.92	25.98	35.01	0.61
C2	100.92	21.59	−10.07	25.47	34.87	0.62
C3	103.48	14.21	−7.24	16.50	22.95	0.62
C4	100.45	14.34	−7.00	16.03	22.62	0.63
C5	96.61	15.37	−8.17	16.82	24.21	0.64
C6	82.87	11.08	−5.89	11.65	17.12	0.65
C7	100.73	8.78	−4.67	10.01	14.11	0.62

According to Section 7.4.2 of the UNE-EN IEC 61000-3-2 standard [32], the limits for the harmonic current emissions for equipment with a rated power greater than or equal to 5 W and less than or equal to 25 W are established. These devices must meet one of the following criteria:

- The harmonic currents shall not exceed the limits established in the standard (3.4 mA/W for the third harmonic, 1.9 for the fifth, 1.0 for the seventh and 0.5 for the ninth).
- The third and fifth harmonic currents, expressed as a percentage of the fundamental current, shall not exceed the values of 86% and 61%, respectively.
- The THD shall not exceed 70%, and the harmonic currents, expressed as a percentage of the fundamental current, shall not exceed the values stablished in the standard (35%, 25%, 30% and 20% for the third, fifth, seventh and ninth, respectively).

Table 6 shows the values of the harmonic currents, expressed as a percentage of the fundamental current for comparison with the limit values defined in the standard.

Of the three criteria established in the standard, only the second is met, while the first and third are notoriously breached. As established in the regulations, the lamps are within the norm, but it is evident that, from an energy point of view, their operation is not as efficient as would be desirable.

Table 6. Harmonic currents expressed as a percentage of the fundamental current.

Lamp	I_1/I_3 (%)	I_1/I_5 (%)	I_1/I_7 (%)	I_1/I_9 (%)
L1	70.97	45.16	37.10	30.65
L2	84.09	65.91	47.73	38.64
L3	75.86	55.17	41.38	37.93
L4	71.88	53.13	40.63	40.63
L5	81.63	59.18	44.90	42.86
C1	79.21	52.48	41.58	38.61
C2	76.47	50.00	41.18	37.25
C3	75.36	47.83	39.13	34.78
C4	73.53	45.59	38.24	33.82
C5	71.62	44.59	36.49	29.73
C6	68.52	42.59	35.19	29.63
C7	74.42	46.51	37.21	32.56

Evaluating the efficacy determined for each receiver (Table 5), it can be observed how the highest efficiency is presented for the C6 lamp (CFL), and the worst for the L3 and L4 (both LEDs). In any case, all of them are in a very narrow range of values, between 0.57 and 0.65, as can be seen in Figure 2. According to what was explained in Section 2, if the value of ε is 0.57, for every 1 VA of apparent power, 0.57 W of active power used. In other words, to obtain 100 W it is necessary to have 175 VA. That is, 75% of the energy is wasted, and in the most favorable case, the wasted energy is 54%. If this behavior found for each lamp is extrapolated to the amount of lamps of this type that are used in a country, it is clear that the supply companies must generate and distribute a much higher amount of energy than is used, so the overall system is not very efficient. Although there are other kinds of considerations to take into account for the implementation of these devices (mercury emissions, for instance), from an energy point of view they do not represent a good solution. This problem could be aggravated if, as is discussed, the cost of the poor efficiency of these lamps begins to be passed on to the end consumer, since one of the advantages of this type of lamps is, precisely, the savings they represent for the home user. If a change in legislation is proposed in the future, it is possible that the measurement of reactive and distortion power consumption for small consumers may be considered. If this happened, their consumption would be included in the bill, and the advantage of the low cost of these lamps would disappear.

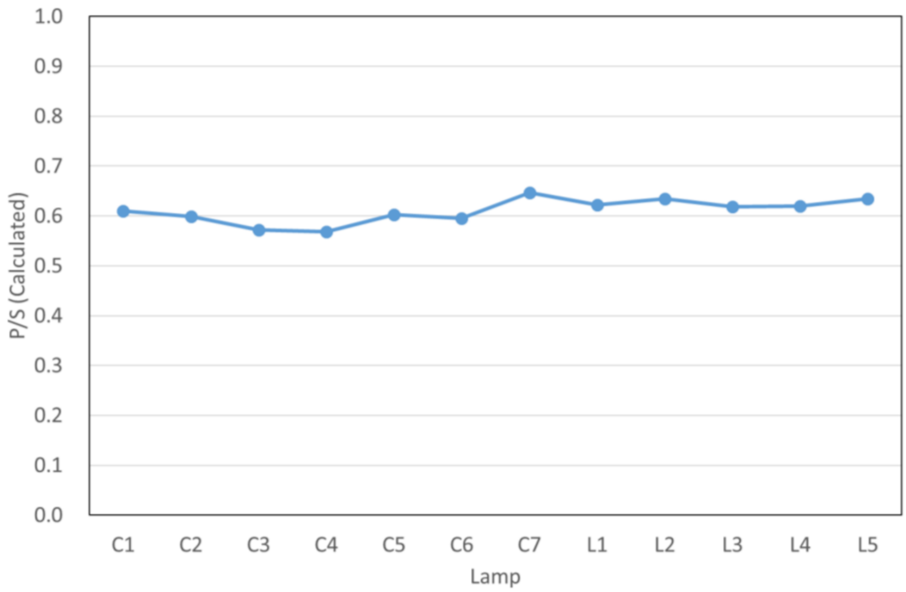

Figure 2. Energy efficiency value calculated of each receiver.

Figure 3 shows the measurements made for one of the groups made with the different lamps. These measurements are intended to evaluate whether the compensation phenomenon that can be assumed to occur between loads working on the same network occurs in these systems. Tables 7 and 8 show the measured and calculated values, respectively, for the four proposed groupings.

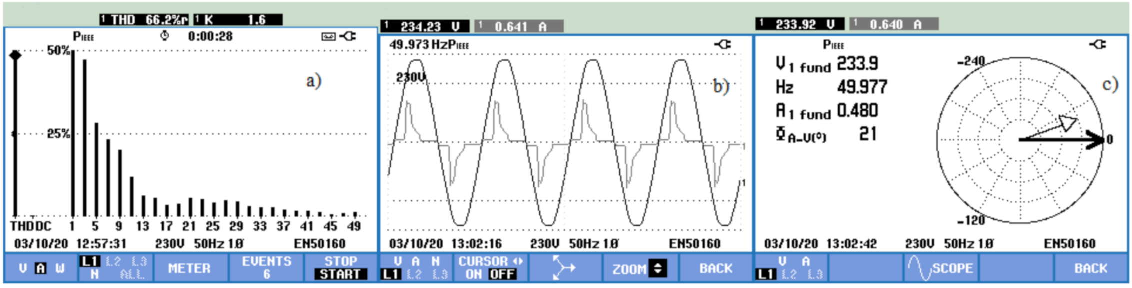

Figure 3. Measurements obtained for the G-M-2 grouping: Harmonic spectrum (**a**), waveform (**b**) and phasor diagram (**c**).

Table 7. Values measured with the Fluke parsed in the four groups.

Lamp	THDi (%)	P (W)	Q (Var)	D (VAd)	S (VA)
G-L	104.16	38.3	−19.5	44.9	62.1
G-C	53.32	62.1	−29.2	79.2	104.9
G-M-1	104.78	59.5	−30	70.2	96.8
G-M-2	64.97	104.2	−40.9	98.9	149.4

Table 8. Calculated values for the four groups.

Lamp	THDi (%)	P (W)	Q (Var)	D (VAd)	S (VA)	ε
G-L	97.44	38.28	−18.67	41.50	59.46	0.64
G-C	104.78	63.42	−30.93	73.93	102.20	0.62
G-M-1	100.91	59.33	−28.94	66.61	93.78	0.63
G-M-2	84.10	104.32	−42.15	94.62	147.01	0.71

Looking at the efficiency value, ε, for the four groupings, it can be seen that in all cases the value is still quite bad, which indicates that the system is still inefficient from an energy point of view. In comparison with the results obtained for the individual lamps, the efficiency values of the of the associations is slightly higher, but the improvement is not significant enough to confirm that—contrary to the results published by Mansoor et al. [33] who evaluated the harmonic compensation between different devices— the distorting effect of the lamps are compensated. The overall effect on the system continues to be that of introducing distortions and requiring an excess of energy that is not used in its operation, in this case, representing between 40% and 60%.

This conclusion is reinforced by seeing the comparison in the phase angle obtained for the third to ninth harmonics of the twelve individual bulbs, which is shown in Figure 4. It can be seen that the phase angles presented by the different lamps for each of the harmonics considered are very similar to each other, represented in the same quadrant of the figure. This implies that when groups of lamps work on the same network simultaneously, they do not compensate for each other. In Figure 5, the phase angles of the harmonics obtained for the four groups are shown. It can be seen that for the third harmonic, regardless of whether the group of associated lamps consists of all LEDs, CFls or mixed, the phase angle obtained is between 240° and 270°. For the fifth harmonic, the angle obtained moves between 120° and 150°, between 15° and 60° for the seventh and between 260° and 310° for the ninth.

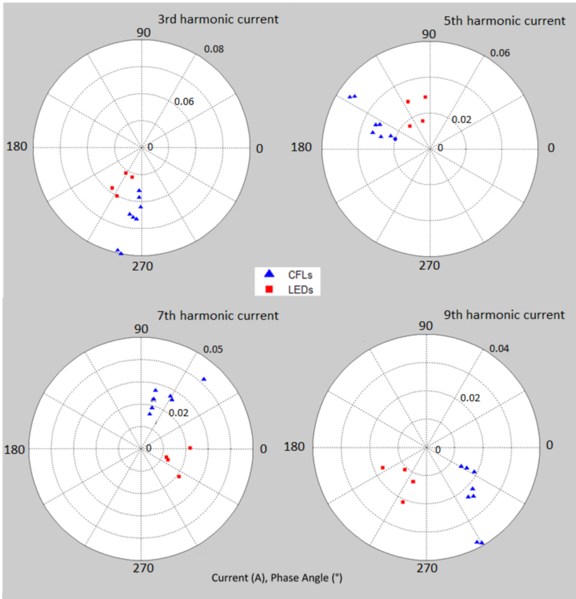

Figure 4. Phase angles of 3rd, 5th, 7th and 9th harmonic currents of LED and CFL lamps.

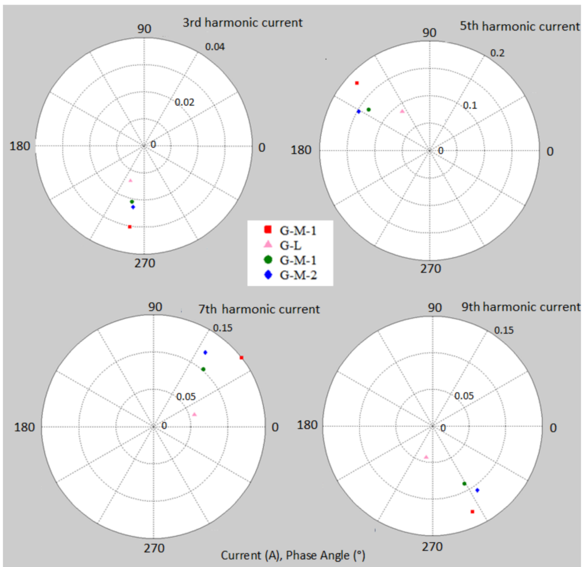

Figure 5. Phase angles of 3rd, 5th, 7th, and 9th harmonic currents of lamp groups.

Da Silva et al. state in the conclusions of their work published in 2019 [34], that the distortions that are generated in the network because of the operation of several lamps, have a considerable effect on the electricity bill. Based on the findings of this paper, the statement is the same, but the fundamental difference with Da Silva is that our conclusions are drawn from a linear voltage system. In addition, they analyzed the loads individually, and in this case it is found that the conclusions can also be applied to load associations, and that there is no compensation for the distortion phenomena that are generated.

The best solution to minimize the problem mentioned would be the incorporation of notch or absorption filters in the loads. In this way, excess consumption would be significantly reduced and the introduction of distortions into the electrical network would be avoided. This solution would have to be incorporated by the manufacturer, and since it would entail an extra cost, it is unlikely that this will occur unless there is legislation that regulates it. Another possibility would be to incorporate these filters not to the lamps individually, but to the residential community. In this case, only the problem of distortions introduced in the electrical network would be improved.

4. Conclusions

In the present work, the distortion phenomena produced by various LED and CFL lamps for domestic use and their effects on the actual consumption of electrical energy have been studied.

It has been determined that the generation of distortions in the currents that occur in these loads is between 80% and 125%, which are unacceptable values. It has also been proven that the actual energy consumption required for their operation is 50–75% higher than declared by the manufacturer. This means that it is necessary to generate and distribute a large amount of energy that is neither used nor invoiced. This excess of energy is due to the reactive power and distortion power that these devices generate. Considering the total amount of energy that is used in lighting residential areas, this amount of wasted energy is not negligible.

To check if there is a compensation effect between loads working on the same network, different load groups have been evaluated. In all cases, it has been found that, although there is a slight improvement, the distortion effect on the currents is still too high, and the energy wasted in this case is still greater than 40%.

It is therefore concluded, that the commitment to LED and CFL lamps as elements with less environmental impact, is not as clear as was estimated. There are additional energy consumption demands that have not been considered, but which, overall, are very significant. One way to improve the response of these lamps would be to incorporate absorption filters into loads or consumer groups, however this is not an ideal solution.

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