Applying FBD-power theory to analysing effective lighting devices' impact on power quality and electric grid efficiency

Aplicación de la Teoría de Potencia FBD al análisis del impacto de los dispositivos eficientes de iluminación sobre la Calidad de la Potencia y la Eficiencia de una red eléctrica

Andrés Pavas[1], Ana María Blanco[2], Estrella Parra[3]

***Abstract*—Currently the impact of high efficient lighting devices such as compact fluorescent lamps (CFL) and light emitting diodes (LED) is an important concern for the electrotechnical community. This paper makes a contribution towards determining the impact of these devices on electric grid power quality and efficiency, proposed by means of applying FBD-power theory to the currents absorbed by CFLs and LEDs. An analysis of the waveform distortion regarding IEEE standard 519 and efficiency detriment quantification are presented.**

***Index terms*—FBD-power theory, CFL, LED, orthogonal decomposition, efficiency, power quality.**

***Resumen*— Actualmente el impacto de los dispositivos de iluminación eficiente tales como Lámparas Compactas Fluorescentes-CFL y Diodos Emisores de Luz-LED representa un interés importante para la comunidad electrotécnica. En este artículo se propone una contribución a la determinación del impacto de tales dispositivos a la calidad de potencia y la eficiencia de una red eléctrica, por medio de la aplicación de la Teoría de Potencia FBD a las corrientes absorbidas por CFL y LED. Se presentan un análisis de la distorsión de la forma de onda con respecto a la norma IEEE 519 y una cuantificación de los detrimentos en la eficiencia.**

***Palabras clave*— Teoría de potencia FBD, CFL, LED, descomposición ortogonal, eficiencia, calidad de potencia.**

1. INTRODUCTION

Nowadays a movement from incandescent devices to newly-developed high-efficiency lighting devices has taken place, where compact fluorescent lamps (CFL) and lighting emitting diodes (LED) have been the most commonly used devices in household installations. This change has been motivated by technical and economic reasons (Blanco, 2010)(Blanco & Parra, 2010). The technical ones mainly concern reducing power consumption and improving lighting efficiency. Reduced power consumption has a direct impact on electrical energy billing and the widespread use of these devices worldwide represent a business opportunity, for producers as well as for lighting device sellers (Pileggi et al, 1993)(Watson et al, 2009).

Despite the technical and economic advantages of CFLs and LEDs, their power electronics-based drivers produce power quality disturbances that may prejudice neighbouring devices and the system where the lamps are connected. Another negative effect should be noted; CFLs and LEDs involve a pretty low power factor which means that they use electric energy inefficiently, although they transform it into light in a more effective manner than incandescent lamps. According to resolution 182544 (19th December 2010) the Colombian government will ban the production, import, sale and use of inefficient incandescent bulbs from the 31st December 2013. Consequently, a residential customer must replace incandescent bulbs with CFLs or LEDs during the next 2 years (Ministerio Minas y Energía, 2010). Widespread use of CFLs and LEDs may have a negative impact on electrical grid efficiency and power quality (Blanco & Parra, 2010)(Koch et al, 2010); Colombia is not an exception.

The use of FBD-power theory has been proposed for analysing these devices' possible impact on an electrical network. This power theory has been used recently to assess responsibilities regarding power quality (Pavas et al, 2008)(Pavas et al, 2009)(Pavas et al, 2010), showing that different phenomena may be assigned to current components, thereby allowing what exists inside the current of a CFL or a LED to be separated and quantified.

This paper presents a current decomposition proposal (Pavas et al, 2010) based on FBD-theory (DIN 40110-1, 1994)(Staudt, 2008). Measurements previously made on efficient lighting devices (Blanco & Parra, 2010) were used to carry out an efficiency and power quality analysis.

2. MEASURMENTS ON CFLS AND LEDS

Seventy-two samples from different manufactures were tested to obtain the CFL and LED electrical signals. The test circuit is shown in Figure 1, where a Fluke 43B power analyzer was used to measure the electrical variables and a Fluke 190B oscilloscope to obtain the lamps' voltage and current signals. Three signal periods were recorded using a 200µs sampling interval.

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[1] Electrical Engineer, Magister and PhD candidate in Electrical Engineering of the National University of Colombia. Professor of the National University of Colombia, Colombia. fapavasm@bt.unal.edu.co

[2] Electrical Engineer and Electric Power Systems Especialist of the National University of Colombia. National University of Colombia, Colombia. eeparral@unal.edu.co

[3] Electrical Engineer and Magister in Electrical Engineering of the National University of Colombia, PhD candidate of the Teknische Universität Dresden - Germany. amblancoc@bt.unal.edu.co

A. Pavas, A. M. Blanco and E. Parra are with the Program of Acquisition and Analysis of Electromagnetic Signals (PAAS-UN) of the National University of Colombia.

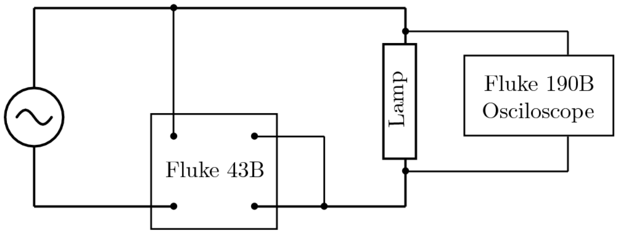

Figure 1. Testing circuit for individual CFLs and LEDs.

According to the standards (IEC 60696, 2001)(IEC 62612, 2009) and regarding the Universidad Nacional de Colombia's available instrumentation and laboratory facilities , the following procedure was used to measure and record the electrical parameters and the CFL and LED signals.

1. Compact fluorescent lamps were aged for a period of 100 h of normal operation before the measurements. LEDs did not require any aging prior to testing;
2. Each bulb had a 15 minute stabilisation period for CFLs and 30 minutes for LEDs before taking measurements;
3. The test voltage was stabilised within 0.5% during; stabilisation periods; this tolerance was reduced to 0.2 % when measurements were taken;
4. Supply voltage total harmonic content did not exceed 3.0 %. Harmonic content was defined as the rms summation of the individual harmonic components (100.0%);
5. Tests were carried out at rated frequency (60 Hz) and rated voltage (120V); and
6. Lamps were operated in free air in a vertical base-up position.

Table 1 gives a measurement summary for two selected samples, where voltage and current were effective values. Figure 2 displays the voltage and current waveforms. The results for the full set of bulbs were similar to the results shown below.

Table 1. Measurement values for 2 samples

Symbol	Nominal Power [W]	Measurement Values				
		Voltage [V]	Current [mA]	Power [W]	PF [-]	THDi [%]
CFL-005	15	120	186	14.06	0.63	94.3
LED-123	5.5	120.1	67.98	5.06	0.62	111.5

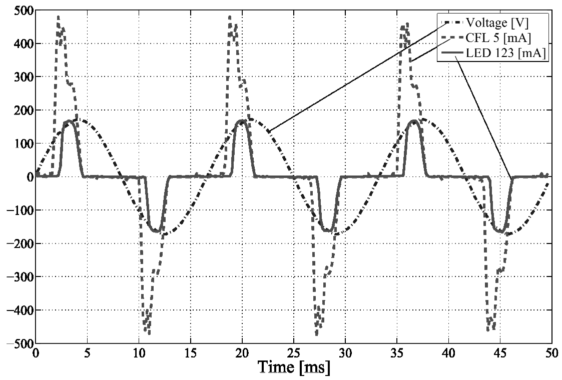

Figure 2. Voltage and current waveforms measured for CFL-5 and LED-123.

3. CURRENT DECOMPOSITION

For a single-phase circuit feeding one load or more, voltage *u* at the point of common coupling (PCC) (IEEE 519, 1992) was taken as reference. Active power absorbed by or delivered to any element composing the circuit, whose current was *i*, could be calculated according to (1):

$$P = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T uidt = \langle u, i\rangle \qquad (1)$$

The notation $\langle u,i\rangle$ was used to represent voltage and current inner product. By definition, the rms effective value of any signal can be evaluated following (2), for example for the voltage:

$$\begin{aligned} U^2 &= \langle u,u\rangle \\ U &= \sqrt{\langle u,u\rangle} \end{aligned} \qquad (2)$$

The apparent power was defined according to (3):

$$S = UI \qquad (3)$$

The equivalent active conductance was defined as follows:

$$G = \frac{P}{U^2} \qquad (4)$$

The active current i_a and non-active current i_x components could be extracted from (4):

$$i_a = Gu \qquad i_x = i - i_a \qquad (5)$$

A displaced voltage was proposed in (Pavas et al, 2009) and (Pavas et al, 2010) to take phase displacement disturbances into account (6).

$$u_d = u(t - T/4) \qquad U_d = U \qquad (6)$$

The inner product of u_d and i_x produces the quantity *displaced* power Q_d (7), as it has been named in (Pavas et al, 2010), that led to calculating displaced susceptance B_d:

$$Q_d = \langle u_d, i_x\rangle \qquad B_d = Q_d / U^2 \qquad (7)$$

From (7) and (5), the non-active current component i_x could be split into two components, the displaced current component i_{Qd} and the rest, named distorted current component i_D (8).

$$i_{Qd} = B_d u_d \qquad i_D = i_x - i_{Qd} \qquad (8)$$

A brief description of each current component is listed:

- Active current i_a contained the whole active power delivered to or absorbed by the circuit; it has the same waveform as reference voltage *u*;
- Non-active current was related to all non-active power related phenomena; it could not hold the same waveform as reference voltage *u* and did not transport any active power. This component was orthogonal to the total current *i* and to the active current i_a, i.e. $\langle i_x, i\rangle = 0$ and $\langle i_x, i_a\rangle = 0$;
- Only in sinusoidal conditions, displaced power Q_d has the same value as Reactive Power (IEEE 1459, 2010), representing a reciprocating power component mainly produced by the presence of inductive and capacitive elements. Displaced current i_d represented a current

containing all information about phase displacement; it held the same waveform as reference voltage but a quarter period delayed. For non-sinusoidal conditions, displaced power and current component were components having the same waveform as the reference voltage but could not be interpreted as reactive power; and

- Distorted current component i_D did not transport any active power (if there were any); it did not have the same waveform of the voltage, therefore being distorted.

The previous set of current components was orthogonal decomposition so that the current and the rms effective values of its components could be calculated as:

$$
\begin{aligned}
i &= i_a + i_x = i_a + i_{Qd} + i_D \\
I^2 &= I_a^2 + I_x^2 = I_a^2 + I_{Qd}^2 + I_D^2
\end{aligned}
\tag{9}
$$

Multiplying (9) by the squared rms effective value of voltage, the apparent power could be split into components (10).

$$
\begin{aligned}
U^2 I^2 &= (UI_a)^2 + (UI_{Qd})^2 + (UI_D)^2 \\
S^2 &= P^2 + Q_x^2 = P^2 + Q_d^2 + Q_D^2
\end{aligned}
\tag{10}
$$

4. RESULTS

The current decomposition method described in the previous section was applied to the measurements. For instance, the current decomposition of signals shown in Figure 2 is shown in Figures 3 and 4. Harmonic spectra for each current component are presented in Figures 5 and 6.

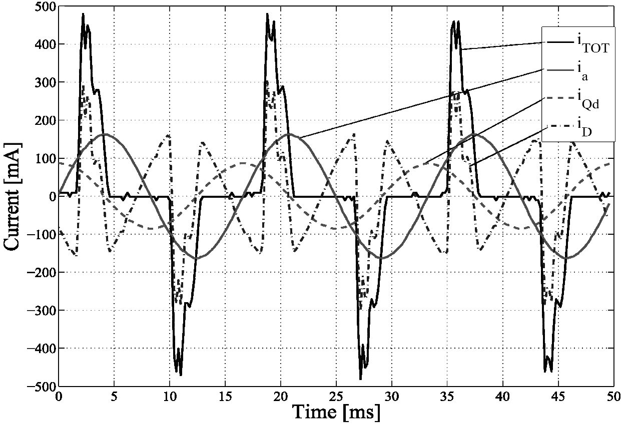

Figure 3. Current decomposition of CFL current.

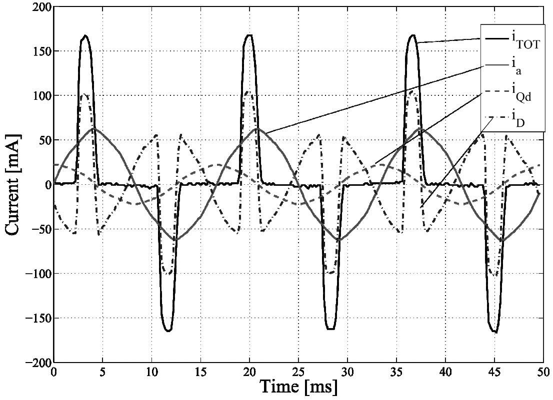

Figure 4. Current decomposition of LED current.

Active and displaced current components have the same voltage waveform and voltage distortion was less than 3.0% meaning that these current components had less than 3.0 % distortion.

The Table 2 shows each current's normalised values divided by their corresponding rms value. Component I_a/I represents the power factor, having the same value reported in Table I. Components I_{Qd}/I and I_D/I show how much current was non-active regarding displaced and distorted power, respectively. It can be seen from the results that the distorted power had a greater amount compared to displaced power.

Table 2.Current components according to FBD-power theory normalized with respect to the effective value of total current

Type	I_a/I [pu]	I_{Qd}/I [pu]	I_D/I [pu]
CFL-005	0.6362	0.3338	0.6944
LED-123	0.6254	0.2223	0.7474

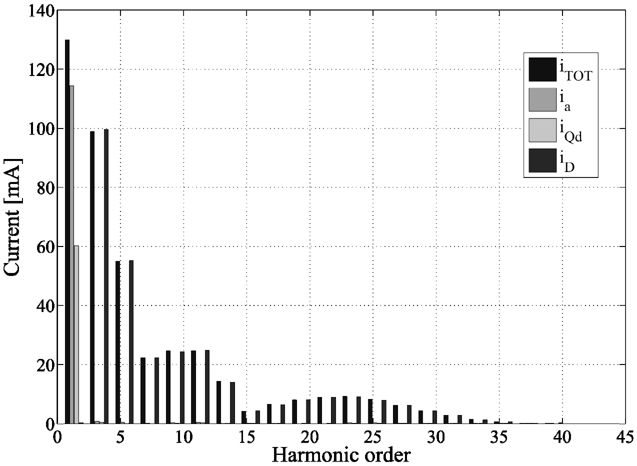

Figure 5. Harmonic components of CFLs current components.

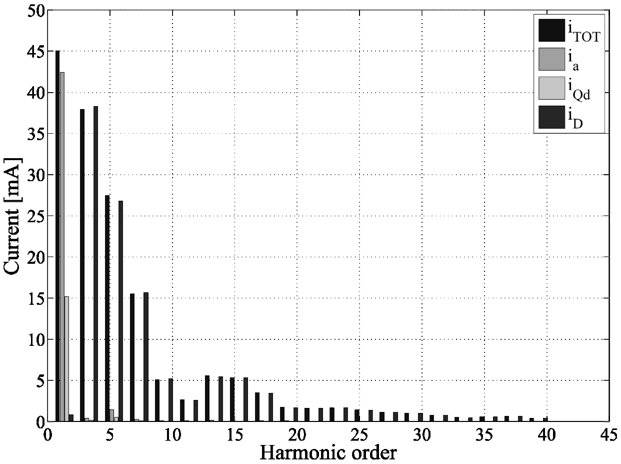

Figure 6. Harmonic components of LEDs current components.

Displaced power has a relationship to reactive power only when perfectly sinusoidal signals are present, otherwise it represents only a current component having the same waveform as the voltage but a quarter of period delayed. The displaced and distorted components do not contribute to power exchange; if they were not present, then the effective current absorbed by lamps would be 36.38% and 37.46% lesser for CFLs and LEDs respectively. Losses in an electrical grid are proportional to the squared value of the rms current value; if there were no non-active components, then losses would have been reduced to 40 % of their value related to the total current. This simple analysis revealed that effective lighting devices use an electric network inefficiently regarding electric energy consumption.

The distorted current component did have a direct relationship with the harmonic distortion listed in Table I. Distorted current components contained all frequency components different to voltage frequency components. If the voltage was slightly distorted, the distorted current would be the time domain representation of the harmonic distorting current components. Therefore, the effective value of the distorted current could be used to calculate a distortion index, which would be equal to total harmonic distortion for non-distorted voltages. The distortion index based on the FDB current components was:

$$DI_{FBD} = \frac{I_D}{\sqrt{I_a^2 + I_{Qd}^2}} \qquad (11)$$

and DFF BD distortion factors are listed in Table 3 for the above described efficient lighting devices.

Table 3. Comparison of THD and distortion index based on FBD power theory

Type	THD [%]	DF_{FBD} [%]
CFL-005	95.85	96.65
LED-123	112.94	112.62

If the comparison of the current components is performed with respect to the active component, the results are as listed in the Table 4. This ratio shows the relative size of displaced and distorted components in comparison to the active one, revealing that the distorted component is higher than the active one.

Table 4. Comparison of THD and distortion index based on FBD power theory

Type	I_{Qd}/I_a [pu]	I_D/I_a [pu]
CFL-005	0.5264	1.0915
LED-123	0.3555	1.1952

5. EFFICIENCY AND POWER QUALITY ANALYSIS

A typical configuration of low voltage network for Bogotá was considered to calculate impedance values range to quantify the losses caused by effective lighting devices. The Figure 7 shows a diagram of typical low voltage network topology and its components.

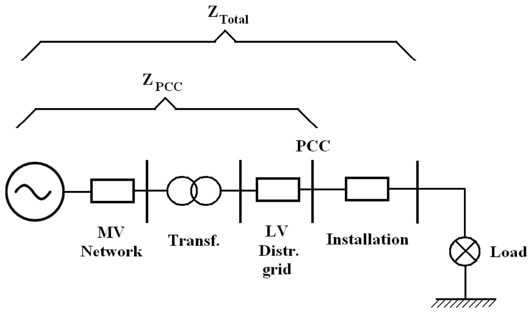

Figure 7. Low voltage network topology.

Equivalent impedance consisted of:

- Medium voltage equivalent impedance. For Bogotá's 11.4kV MV network an average 7.31kA symmetrical short circuit current was taken into account (2.26kA standard deviation). Such symmetrical fault currents are expected at the transformers' MV connection points;
- A 11.4/0.208 kV transformer with rated power from 15 kVA to 2MVA;
- An overhead ACSR section. Swan to Linnet ACSR cables are usually used. At the end of this section the energy measurement device is connected, this point was considered as Point of Common Coupling for power quality purposes. The maximum length was determined according to maximum voltage drop of 2% at the for the conductor's rated current; and
- A section of copper conductor in PVC conduit tubes from the PCC to the lamp's location. Conductors from 6 AWG to 14 AWG were considered. Maximum conductor length was determined considering maximum 3% voltage drop at utilization point for the conductor's rated current.

The minimum and maximum impedance values and resistance values are listed in Table V (all values in mΩ). Impedance values may have been higher because the conductor's rated current was not always used, thus longer conductors were allowed. The values presented in Table V represent a set of minimum values.

The data in Table V represent a range of resistances and short circuit impedance values for assessing losses and power quality effects, respectively.

The mean number of lamps used per residential unit in Bogotá were 8 incandescent lamps (Gonzalez, 2006), four 60W and four 100W lamps. It was expected that each residential unit would use an equivalent of three 60W and two 100W lamps for five hours a day. This information was used for estimating energy losses.

A. *Power and Energy Losses*

Losses were determined according to the expected equivalent usage of lamps. Three cases will be considered and described in the following paragraphs:

- Case 1: Three 60W plus two 100W incandescent lamps. This case represented a reference condition to reassessing the effect of CFL or LED lighting on efficiency;
- Case 2: Three 12W plus two 20W CFL lamps. A 12W

CFL was expected to provide the same luminous flux as a 60W incandescent lamp, a 20W CFL can replace a 100W incandescent lamp;

- Case 3: Six 7W plus six 7W LED lamps. Although LED devices with higher rated power exist, currently 7W LED devices are commercially available in Bogota´, therefore only 7W LEDs were taken into account in this paper. Two 7W LED were expected to produce the same luminous flux as a 60W incandescent lamp and three 7W LED may substitute a 100W incandescent lamp.

The previous cases were designed bearing in mind that lighting devices usage should provide the same luminous flux for the average residential user.

Figure 8 shows device efficiency for each possible resistance. Each lighting device's efficiency was calculated as the ratio of active power absorbed by a lamp to the sum of this power and electric losses in the equivalent feeding network, mainly depending on current rms value. Efficiency was calculated as follows:

$$\eta = \frac{P_{LAMP}}{P_{LAMP} + R_{Eq} I_{LAMP}^2} \qquad (12)$$

It can be observed that the less efficient lighting device is the 100W incandescent lamp, due to its higher rms current in compared to any lighting device considered in this paper. The 60W incandescent lamp and the 20W CFLs had similar efficiency. It is worth noting that the 20W CFLs had a wide range of efficiency, some of them were less efficient than a 60W incandescent bulb. 11W CFLs and 7W LEDs were more efficient, due to their lower rms current values.

The power losses caused by each type of lamp are depicted in Figure 9. The power losses were calculated from Eq. (12), yielding:

$$P_{LOSS} = R_{Eq} I_{LAMP}^2 = P_{LAMP}\left[\frac{1}{\eta} - 1\right] \qquad (13)$$

Power losses caused by incandescent lamps are always higher than the losses of any efficient lighting device. It should be stressed that Figure 9 shows the power losses of each device, but they are not directly comparable because a 7W LED cannot provide the same luminous flux as a 100W incandescent. A suitable comparative analysis can be performed with the power and energy wasted for each Case.

Given the power losses, an estimation of the energy losses caused by substituting incandescent lamps can be calculated. According to the most recent available statistics, there are 1.601.428 residential units in Bogotá (DANE, 2005). Determining each residential customer's precise connection impedance is currently impossible. This paper was not aimed at accurately determining the energy losses caused by efficient lighting devices compared to conventional incandescent bulbs. This paper was aimed at highlighting how different the losses are when efficient devices are used, thus a reasonable approximation would suffice.

If the location of a specific residential customer is not specified, or if its network impedance is not available, a reasonable approximation must be used. In this paper it has been supposed that all customers were distributed uniformly throughout all possible network resistance values. The network resistance values are listed in Table V. As explained before, an equivalent lighting energy consumption per residential customer may be extracted from the energy absorbed by three 60W and two100W incandescent lamps during 5 hours, or by the suitable substitutes described in Case 2 and Case 3 Figure 10.

Table 5. Impedance Values

-	MV Network	Trafo	Dist grid	Installation	Total at usage	Total at PCC
Zmin [mOhm]	0.134	1.3	4.2	16.2	19.4	5.6
Rmin [mOhm]	0.115	0.3	2.1	16.2	18.7	2.5
Zmax [mOhm]	0.494	129.8	34.3	432	565.5	161.0
Rmax [mOhm]	0.332	90.8	33.0	432.0	556.1	124.1

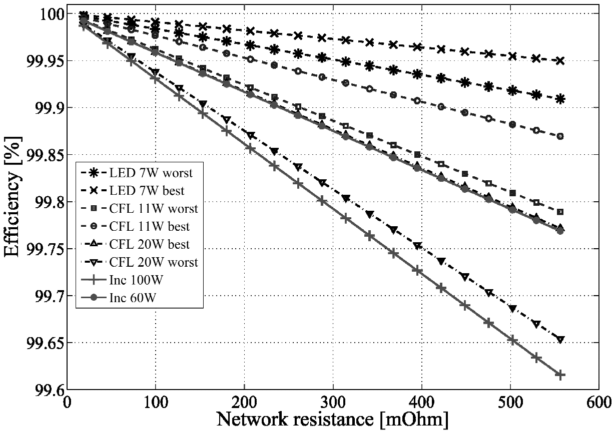

Figure 8. Efficiency of LED (left) and CFL devices (right) for different feeding resistances.

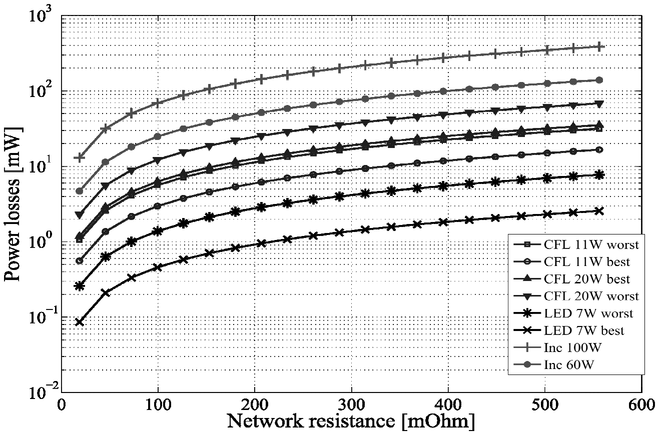

Figure 9. Power losses of LED (left) and CFL devices (right) for different feeding resistances.

Taken into account the power losses presented in Figure 9, the energy losses in Figure 10 and the previous considerations, the monthly minimum and maximum energy losses for each Case are listed on Table VI:

Table 6. Expected energy losses in mwh/month for each case

MWh/month	Case 1 Incandescent	Case 2 CFL	Case 3 LED
Minimum	692.43	57.49	64.85
Maximum	-	127.31	93.26

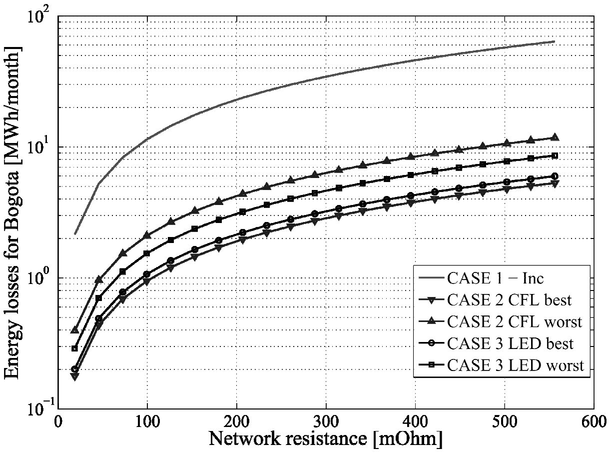

Figure 10. Estimated energy losses for each case in MWh per month

The energy losses using efficient lighting devices became reduced to around a tenth to a fourth part of the energy wasted using incandescent lamps.

The previous results confirmed that efficient lighting devices contribute to saving energy; they are more efficient regarding electric energy use. Nevertheless, it is well known (Blanco, 2010)(Pileggi et al, 1993)(Watson et al, 2009) that they produce waveform distortion able to exceed the compatibility levels. Waveform distortion has an impact on power composition. Using FBD power theory provided decomposition into power components, listed in Table VII.

The powers listed in Table VII are the expected power components absorbed by all residential customers in Bogota´ due to equivalent lighting consumption.

The power values listed in Table VII were calculated according to the following assumptions:

- Each residential installed power had a 600 VA to 1600VA rated value. Not only lighting devices were fed, the resting loads are supposed to be linear non-distorting devices.
- It was supposed that, regardless of the rated apparent power, the power factor for Case 1 was 0.9 lagging;
- The incandescent lighting devices absorbed 380W, no reactive, displaced or distorted power was generated by these bulbs; and
- For Case 2 and Case 3, 380W was subtracted and the respective active, displaced and distorted power added to the count.

Case 1 revealed that the expected power necessary to feed the lighting load energy demands was 608.92 MW for incandescent lamps; the corresponding apparent power had values from 961.45 MVA to 2563.9 MVA, as described above.

Table 7. Expected Power Components for Bogotá

CASE		P_{light} [MW]	P_{TOT} [MW]	ΔQ [MVAr]	Q_{TOT} [MVAr]	ΔD [MVA]	S [MVA]	PF [pu]
Case 1	Min	608.92	865.31	-	419.09	-	961.45	0.9000
	Max	608.92	2307.5	-	1117.6	-	2563.9	0.9000
Case 2	Min	107.66	364.05	32.14	451.23	132.86	594.80	0.4558
	Max	139.50	1838.1	75.90	1193.5	213.71	2202.0	0.8135
Case 3	Min	95.32	351.70	13.45	432.54	115.92	596.40	0.5289
	Max	158.74	1857.3	95.60	1215.2	215.22	22298	0.8233

Case 2, power reduction was very clear; the minimum and maximum expected powers consumed by CFLs were 107.66 MW and 139.50 MW, respectively, representing a power reduction of 77.1% to 82.3%. However, two additional power unexpected components appeared, the displaced and the distorted powers. In Case 2, distorted power can be two to four times the displaced power. The required apparent power for Case 2 had values ranging from 594.8 MVA to 2202.0 MVA, the minimum value represented a significant reduction of the necessary installed capacity compared to the corresponding value for Case 1, but the second one revealed that the non-active power components could increase the apparent power to values comparable to the corresponding ones of Case 1. This situation meant that non-active power caused by CFLs can demand from the network a similar rated capacity. A similar analysis could be made for Case 3; slightly higher non-active power components would be expected.

The previous conditions were caused because the CFLs and LEDs used in Colombia for residential units are low power factor loads. Regrettably, the power factor for these lighting devices is not regulated by Colombian rules; a suitable power factor is only demanded for lamps having power rated over 80W. Such lamps are rarely used in residential units.

A. *Power Quality*

Power quality detriment was evaluated according to IEEE 519 standard recommendations (IEEE 519, 1992). In (Blanco,

2010) and (Blanco & Parra, 2010) it has been shown that voltage distortion limits may be exceeded due to efficient lighting devices. In this paper an evaluation of current distortion is presented.

Table V listed the expected short circuit impedances for low voltage residential units are listed. The following assumptions were made to perform a current harmonics assessment:

- Maximum Demand Current I_L could have values from 5A to 15A; and
- Although other devices were able to disturb the current waveform, it was assumed that only the lighting devices cause current distortion. Therefore, the results shall represent a minimum current distortion condition.

The results for the cases proposed in the previous section are shown in Figures 11 and 12. Given that the ratio I_{SC}/I_L would be different for demand current values and for all possible short circuit currents, the minimum and maximum current distortion limits have been displayed in the Figures.

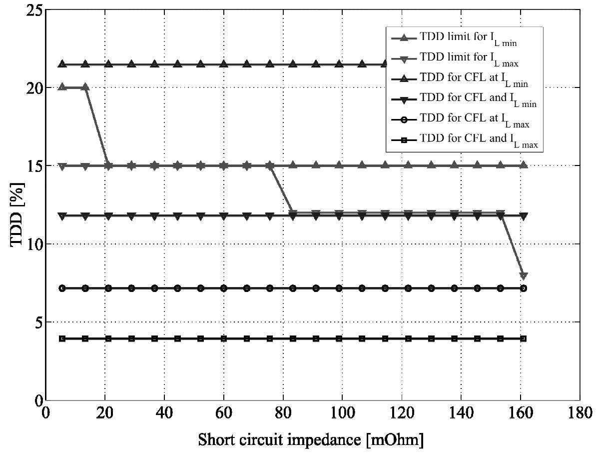

Figure 11. Current distortion limits and expected values for CFLs

It can be seen, that for low demand currents I_L, it was easy to exceed the current distortion limits for both CFLs and LEDs. For higher demand currents I_L, the current distortion was always below the limits. A review of the computed results revealed that a minimal 7A demand current was required to prevent the current distortion above the prescribed limits. For the CFLs, the rms current of all lighting devices together had not to exceed the 5% of demand current I_L for the current distortion limits to be below the limit; a maximum 2% of demand current was necessary for LEDs.

6. DISCUSSION ABOUT THE IMPACT OF CFLS AND LEDS

Efficient lighting devices represent a significant technological advance that allows better lighting conditions which spend a lesser amount of energy. The power consumption reduction has a corresponding energy losses reduction, which also allows the usage of the saved energy in any other applications.

The most CFLs and LEDs distributed in Colombia for residential customers have a very low power factor. The non-active power components caused by efficient lighting devices are the displaced and distorted ones; displaced power components can be compensated by means of a suitable and properly placed capacitor bank.

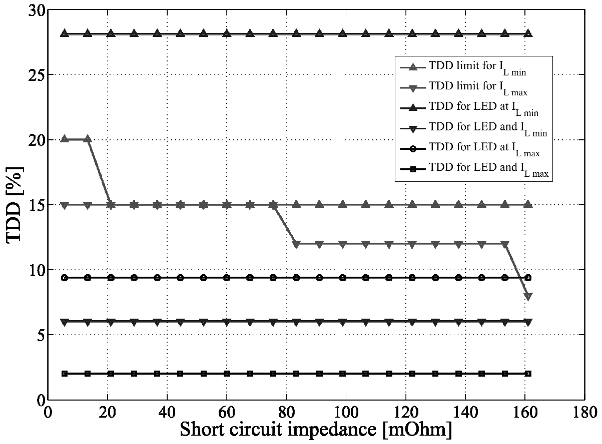

Figure 12. Current distortion limits and expected values for LEDs

The distorted power generated by these devices imposes a new condition on a particular system. Although the waveform distortion is a normal problem in low voltage distribution networks, the mass use of CFLs and LEDs would take the distortion to a higher level not handled before. Distorted power cannot be compensated by capacitor banks; harmonic filters and active compensators are required, thereby increasing a distribution utility's operating and maintenance costs. The most suitable solution is that regulatory policies demand the sale of efficient lighting devices having high power factors, i.e. luminously and electrically-efficient lighting devices.

Power quality is affected by efficient lighting devices mainly because of harmonic distortion. It has been shown (Blanco, 2010) (Koch et al, 2010) (Pileggi et al, 1993) that voltage distortion can be easily exceeded by CFLs and LEDs. It has been shown in this paper that current distortion limits may also be exceeded. However, if efficient lighting devices represent a limited portion of total capacity, their effect on waveform distortion can be controlled. Devices having higher power factors will cause lower distortion, so luminously and electrically efficient lighting devices will have less negative impact on energy efficiency and power quality as well.

7. CONCLUSIONS

Efficient lighting devices' current components have been analysed, providing a new approach to analysing the impact of the widespread use of CFLs and LEDs on electrical networks.

The results revealed that electrical losses related to the presence of high-efficient lighting devices were lower than those related to traditional inefficient lighting devices. Non-active power components appeared to be displaced and distorted components increasing rated power and demanding additional compensation devices in a particular system. It has been shown that a limited amount of efficient lighting devices compared to rated demand current contribute to holding harmonics within distortion limits. Efficient lighting devices must be efficient regarding both luminous source and electrical energy; a minimal impact on power usage and power quality can thus be achieved.

8. ACKNOWLEDGMENT

The authors would like to thank the Universidad Nacional de Colombia and the Research Group on Acquisition and Analysis of Electromagnetic Signals (PAAS-UN) for their support in developing this paper.

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