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Experimental analysis of power quality indicators of residential LED lamps E27 available in the Brazilian market

Análise experimental de indicadores de qualidade de energia de lâmpadas LED E27 residenciais disponíveis no mercado brasileiro

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Abstract

With advances in energy demand, investments in energy efficiency and power quality are increasingly important. One of the extensively adopted measures is the replacement of fluorescent lamps by LED lamps. This measure contributes to the increase of energy efficiency, but produces a high load of current harmonics, which may cause degradation in power quality indicators of the electric distribution networks, due to the presence of rectification electronic circuits present in such lamps. In this work, several models of LED lamps available in the Brazilian market were tested for harmonic and power factor production, taking as reference the standards Inmetro 389/2014, 143/2015 and 144/2015. Applying the Fast Fourier Transform (FFT) the modules and phases of each harmonic component in the currents were measured. Subsequently, the total harmonic distortion (THD) of the current in each lamp was calculated and the estimated total power factor. The results obtained were compared with the nominal values of the lamps and the circuit of four of the lamps was analyzed. It was verified that only six models out of the twenty-three analyzed had THD below 100% and of the analyzed models, 61% did not meet the nominal technical specifications regarding the power factor, and that Power Factor Correction (PFC) techniques present in some of the models were responsible for adjusting the lamps to the regulation parameters.

Keywords: Fast Fourier transform. LED lamps. Power quality. Total harmonic distortion. Power factor.

Resumo

Com o avanço na demanda por energia, investimentos na eficiência energética e na qualidade da energia se mostram cada vez mais importantes. Uma das medidas extensivamente adotadas é a substituição da iluminação com lâmpadas fluorescentes pela iluminação com lâmpadas LED. Tal medida contribui com o aumento da eficiência energética, porém, produz uma carga elevada de harmônicos de corrente, podendo causar degradação em indicadores de qualidade de energia das redes de distribuição de energia elétrica, devido à presença de circuitos eletrônicos de retificação presente em tais lâmpadas. Neste trabalho, diversos modelos de lâmpadas LED disponíveis no mercado Brasileiro foram testados quanto à geração de distorções harmônicas de corrente e fator de potência, tomando como referência as normas Inmetro 389/2014, 143/2015 e 144/2015. Aplicando-se a Transformada Rápida de Fourier (TRF) os módulos e fases de cada componente harmônica nas correntes foram medidos. Posteriormente, a distorção harmônica total (DHT) da corrente em cada lâmpada foi calculada e o fator de potência total estimado. Os resultados obtidos foram comparados com os valores nominais das lâmpadas e o circuito de quatro das lâmpadas foi analisado. Constatou-se que apenas seis modelos dentre os vinte e três analisados, apresentaram DHT inferior a 100% e dos modelos analisados, 61% não cumprem as especificações técnicas nominais quanto ao fator de potência, e que técnicas de Correção do Fator de Potência (CFP) presentes em alguns dos modelos foram responsáveis por adequar as lâmpadas aos parâmetros da regulamentação.

Palavras-chave: Transformada rápida de Fourier. Lâmpadas de LED. Qualidade de Energia. Distorção harmônica total. Fator de potência.

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Introduction

The lighting market is a great example of the investments that the industry has made in recent years in energy efficiency. In the past, most residential lamps were incandescent lamps, which had very low efficiency, dissipated a lot of energy in the form of heat and had an extremely short life span. Over time, incandescent lamps were replaced by fluorescent lamps, which were about four times more efficient and with a life time up to six times greater than incandescent (LIMA, 2013). However, the pursuit of energy-efficient technologies has encouraged the popularization of LED lamps - light-emitting diodes, which are even more efficient and have a much longer service life compared to other technologies (RYCKAERT *et al*., 2012).

In spite of all the economic advantages of LED lamps, in the criterion of the power quality, there is some compromise due to the appearance of harmonic distortions, which are essentially composed of signals of multiple frequencies or submultiples of the fundamental frequency of 60 Hz (PIRES, 2006; TORRES *et al*., 2003). The resulting effect of the sum of these signals is known as harmonic distortion and causes various undesired effects on the equipment connected to the network (BOLLEN *et al*., 2011).

Among the effects, we can mention the electronic equipment failure (including the equipment that generates the harmonic distortions), reading errors in electricity meters, increasing the amount of circulating reactive power due to the reduction of the power factor, instead requires over-dimensioning of distribution equipment, such as transformers and lead wires; In addition to these effects, there is also a great reduction in the life of transformers and capacitor banks, the first due to overheating and the second to resonate with the inductive components of the network (DUARTE, 2010; EMANUEL *et al*., 1994; RODRIGUES, 2009; VITAL; VITAL, 2015).

As fluorescent lamps are replaced by LED lamps the need to investigate the impact of massive use of such technology grows substantially. Several studies have been carried out to demonstrate the advantages of using LED technology and to compare it with traditional lighting technologies in energy efficiency (MATVOZ; MAKSIĆ, 2012; MONTEIRO *et al*., 2014; RÖNNBERG; WAHLBERG; BOLLEN, 2012). However, there are still few studies that analyze the power quality aspects of LED technology, especially at the national level, under the aegis of the current regulation (SANTOS *et al*., 2016).

About 20% of world energy consumption is due to lighting systems, and at least one study showed that voltage distortion exceeds the standard limit set by the IEC by 8% when 80% of incandescent lamps in the system analyzed were replaced. LED lamps, also featuring power loss, especially on the low voltage side of the distribution transformers, which is marginally reduced in the transmission lines (UDDIN *et al*., 2015).

The objective of this work is to evaluate the harmonic distortions in the electric current of LED lamps available in the national market, taking as reference the current technical regulations published by Inmetro. These technical regulations present no definition for limits of harmonic currents. In this way, the current waveform, total harmonic distortion (DHT), power factor and total power factor are evaluated, and a comparison between certified and non-certified lamps is done. The power factor values are compared to the nominal values, declared by each manufacturer, and compared to the values expressed in the regulations. The harmonic current distortion, however, is calculated only for the purpose of determining the cause of low power factor in some of the models analyzed and serve as a warning to the regulatory institutions of the sector.

Current Regulations

Inmetro Ordinances No. 389, dated August 25, 2014 and Inmetro No. 143, dated March 13, 2015, include as an annex the technical regulation of quality for LED lamps with integrated device, including minimum requirements for performance, safety and electromagnetic compatibility for this technology. These regulations, among other specifications, define limits to the power factor. It is defined that the power factor should be greater than or equal to 0.70 for LED lamps with rated power declared between 5 W and 25 W. There is no definition in the regulation for limits of harmonic currents in this power range (INMETRO, 2014, 2015a).

Inmetro ordinance No. 144, dated March 13, 2015, established the criteria for compulsory certification of LED lamps with an integrated device that complies with the criteria established by the aforementioned ordinances, through the National Energy Conservation Label - ENCE, illustrated in Figure 1, and stipulated the deadlines for manufacturers, importers and retailers to tailor their products to these requirements (INMETRO, 2015b).

Figure 1 – ENCE Tag Model for LED Lamps

Source: INMETRO (2015b).

Harmonic Analysis

It is of great interest, especially during the application of digital techniques, the discretization of functions. The Discrete Fourier Transform (DFT) provides an excellent approximation of the Fourier Series coefficients of periodic functions and for particular cases, this approximation is considered to be exact. However, in practical applications the DFT is usually approximated by the Fast Fourier Transform (FFT) (GIRGIS; HAM, 1980; BERGLAND, 1969). A much more efficient, but not very intuitive, algorithm that is considered one of the biggest contributions ever made to numerical analysis.

The FFT, applying the concept of successive splits, calculates the DFT of N points by dividing it into DFTs of fewer points. The division of the FFT calculation allows to achieve the desired results with a significant reduction of computational effort. In practice, in three-phase electric networks, the harmonic components of greatest interest are the odd order harmonics, usually up to the order of 30. However, electricity distributors, when supervising and compensating for harmonics, are restricted to harmonic compensation of order 3 to 13, but it is described by electrical equipment manufacturers that a good compensation should also take into account the harmonics up to order 25 (SCHNEIDER ELECTRIC PROCOBRE, 2003).

Experimental methodology

In order to constitute the sample, first it was chosen to select 15 (fifteen) manufacturers and two models of lamps of each manufacturer. This selection was made based on the brands with greater availability in the market, and was still carried out in the period of adaptation provided by Inmetro regulations (year 2017). Thus, the sample included lamps already adapted, labeled ENCE, and others still outside this scope. The wattage of each lamp was initially specified at 5 W and 9 W. However, due to the regulatory transition period, it was not possible to find lamps with the same wattage for each manufacturer on the market and therefore it was necessary to choose power lamps between 3 W and 10 W, two lamp models were tested from eight of the fifteen manufacturers and only one model from the seven remaining manufacturers, as shown in Figure 2.

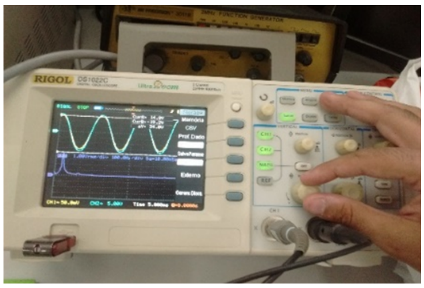
Obviously, the power factor and harmonic distortion could easily be measured by power quality analyzers. However, due to the unavailability of such equipment, the solution used was to collect voltage and current data using a digital oscilloscope and then to use the native MATLAB functions to obtain the power quality indicators of the analyzed lamps.

Figure 2 – Experimental bench

Source: The authors.

The procedure used was to connect the lamps to the mains, one model at a time and with the help of an oscilloscope with digital storage through the USB port, waveforms of voltage and current in the lamps were measured at a sample rate of 200 Msa/s, as shown in Figure 3.

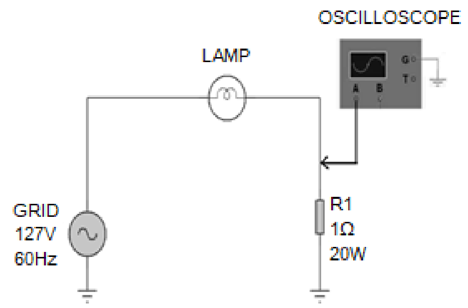
Figure 3 – Rigol-DS1022C Oscilloscope



Source: The authors.

Figure 4 shows the setup diagram of the experimental bench used. For each measurement a resistor of 1 Ω and 20 W in series with the lamp was connected, making the voltage waveform measured in the resistor a good approximation of the current in the circuit.

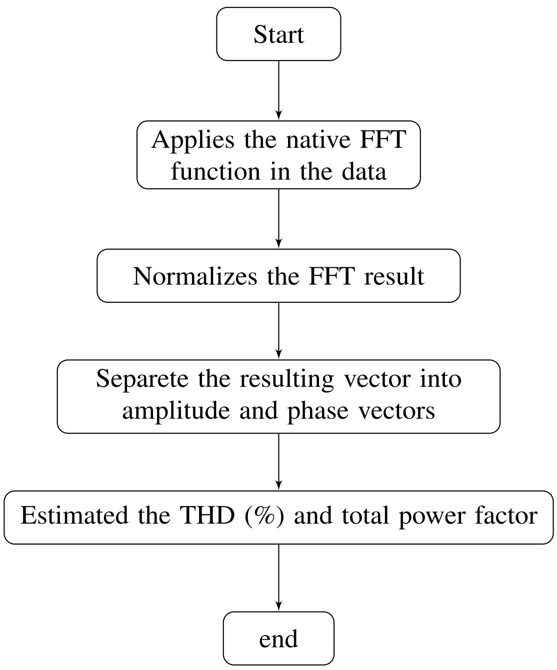
Figure 4 – Schematic diagram of experimental bench



Source: The authors.

The data obtained with the oscilloscope were stored and properly formatted, so that they could be easily used in MATLAB. A program was written in the MATLAB software as shown in the flowchart of Figure 5, based on the algorithm proposed by Oliveira (2009), so that it was possible to apply the FFT and condition the data for the elaboration of comparative graphs and tables.

Figure 5 – Flowchart of the program written in MATLAB to estimate the harmonic components



Source: The authors.

The program, after separating the module and phase components of each harmonic component of the signal, calculates the THD using the components up to order 25, as proposed in Schneider Electric Procobre (2003), using equation (1)

$$\text{TDH}\ (\%) = \frac{\sqrt{\Sigma_2^N (I_n)^2}}{I_1} \text{x}100\% \qquad (1)$$

where THD (%) is the harmonic percentage distortion of current, In the modulus of the nth harmonic current and I_1 the modulus of the current in the fundamental frequency. With the THD values of each of the lamps and using the Nominal Power Factor (PF) value reported by the manufacturers, through equation (2), the Total Power Factor values for each of the lamps used in the experiment were calculated

$$\text{PF}_{\text{TOTAL}} = \frac{cos(\varphi)}{\sqrt{1+\text{TDH}^2}} \qquad (2)$$

where PF_{TOTAL} is the power factor corrected by THD influence and $cos(\varphi)$ the rated power factor at 60 Hz.

Experimental results

The results obtained with the experiment were organized as shown in Table 1.

Table 1 – Nominal active power values and calculated THD.

Manufacturer	Power (W)	THD (%)
A	9.5	53.9228
B	3	172.6415
C	**7	52.2669
	**9	55.6712
D	5	139.9821
	9	121.7988
E	6	124.8865
	10	120.9832
F	9	110.0041
G	7	105.8619
H	5	128.4986
	9	131.2082
I	5	147.3240
	10	137.0035
J	**6	52.7949
	9	112.1785
K	5.5	52.0415
	9	113.4984
L	6	128.1088
M	9	51.4604
N	5	129.8846
	9	114.2727
O	5	130.4739

** are bulbs already marketed, on occasion, labeled ENCE.

Source: The authors.

The data in the Table 1 are grouped by manufacturer and power respectively. The power values are the nominal values provided by the manufacturers, since the values of THD and Total Power Factor, which considers the impact of the harmonic distortion, were calculated with MATLAB.

The nominal power factors supplied by the manufacturers and the calculated total power factors were organized as shown in Table 2, as in Table 1, the data are grouped by manufacturer and power respectively.

Table 2 – Values of nominal power, nominal power factor and calculated total power factor.

Manu-facturer	Power (W)	Nominal PF ≥	Calculated PF
A	9.5	0.7	0.879
B	3	0.6	0.4875
C	**7	0.7	0.8821
	**9	0.7	0.8707
D	5	0.6	0.5308
	9	0.6	0.5789
E	6	0.85	0.5742
	10	0.55	0.5815
F	9	0.6	0.6285
G	7	0.7	0.6021
H	5	0.6	0.5495
	9	0.6	0.5617
I	5	0.7	0.5266
	10	0.7	0.5585
J	**6	0.8	0.8581
	9	0.6	0.5927
K	5.5	0.8	0.8818
	9	0.6	0.5878
L	6	0.6	0.5556
M	9	0.8	0.8848
N	5	0.7	0.5594
	9	0.7	0.6048
O	5	0.6	0.6056

** are bulbs already marketed, on occasion, labeled ENCE.

Source: The authors.

Figure 6 shows the harmonic content graphs generated by MATLAB of four lamp models among the ones used in the experiment, two with low THD (less than 55%) and two with high THD (greater than 100%).

It was observed from the data in Table 1 that only the lamps of manufacturers A, model 9.5 W, manufacturer C, both models, manufacturer J, model 6 W, manufacturer K, model 5.5 W and manufacturer M, model 9 W presented THD lower than 60% in the tests performed. The other lamp models presented DHT greater than 105%. The analysis of Table 2 revealed that the same six models that had less than 60% THD in Table 1 met the power factor specifications more than or equal to 0.7 as determined by Inmetro and 61% (fourteen out of twenty-three) of the analyzed models do not meet the nominal technical specifications, regarding the factor of power informed in their packaging, being below the level informed.

It was also evidenced that the three bulbs evaluated that contained the ENCE label were within the limits established by the Inmetro for the power factor, as well as presented total power factor higher than the one reported in the respective packages.

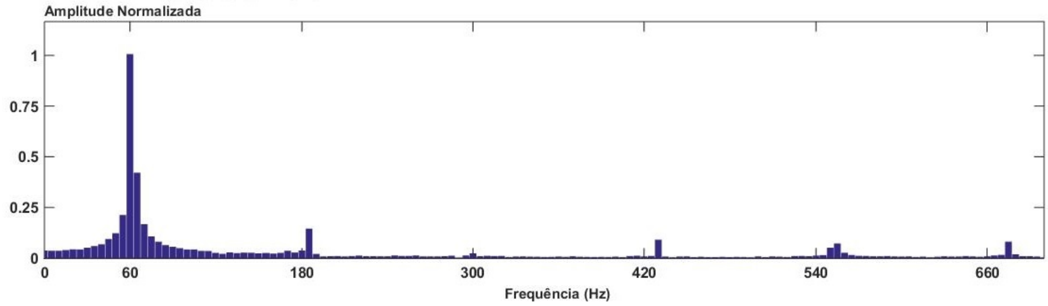
Evaluation of internal electronic circuits

Among the sample lamps, the four models whose graphs were presented in the previous section were disassembled and had their internal circuits analyzed. Structurally, all circuits were composed of the same basic structure: rectifier bridge, filtering and stabilization circuits, an integrated circuit responsible for DC / DC conversion and regulation of voltage and current levels at the output, as well as some auxiliary components, diagram of Figure 7.

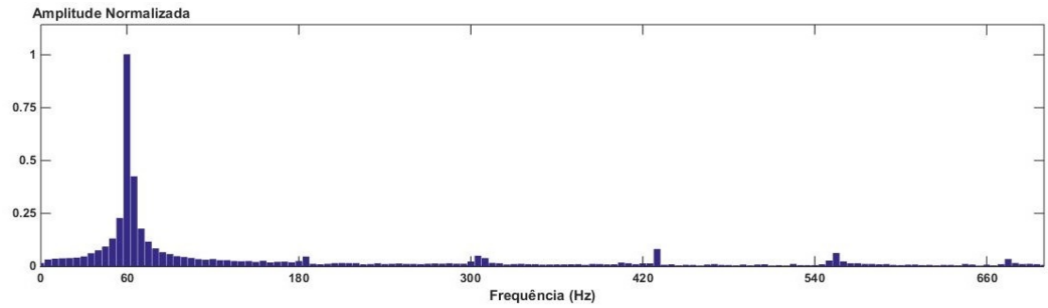
In each of the lamps was found an integrated circuit (IC) responsible for the functions of conversion and control of current and voltage in the LEDs. The electrical diagrams of Figure 8 were taken entirely from the technical specifications of the IC contained in each of the lamps (BRIGHT POWER SEMICONDUCTOR, 2019a; BRIGHT POWER SEMICONDUCTOR, 2019b; FAIRCHILD SEMICONDUTOR, 2003; WINSEMI ELECTRONICS, 2019).

The main difference, which seems to be essential, is the existence of the active Power Factor Correction (PFC) function in the lamp ICs of the manufacturer A model 9.5 W and manufacturer J model 6 W, both presented low levels of THD, 53.9228% and 52.7949% respectively, and high-power factor, 0.879 and 0.8581 respectively.

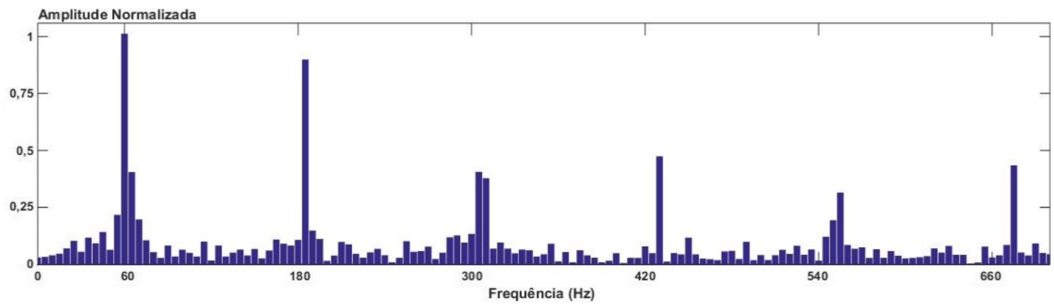
Figure 6 – Electrical diagram of the integrated circuits found in the lamps



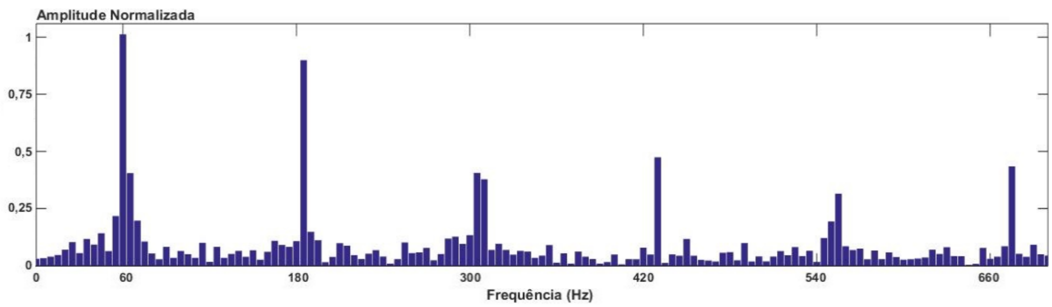
(a) Lamp A model 9.5 W and THD of 53.9228%



(b) Lamp J model 6 W and THD of 52.7949 %



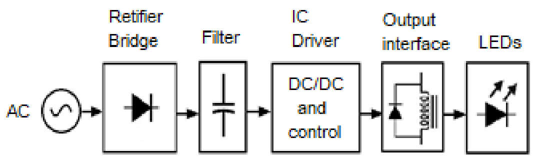
(c) Lamp J model 9 W and THD of 112.1785%



(d) (Lamp B model 3 W and THD of 172.6415%

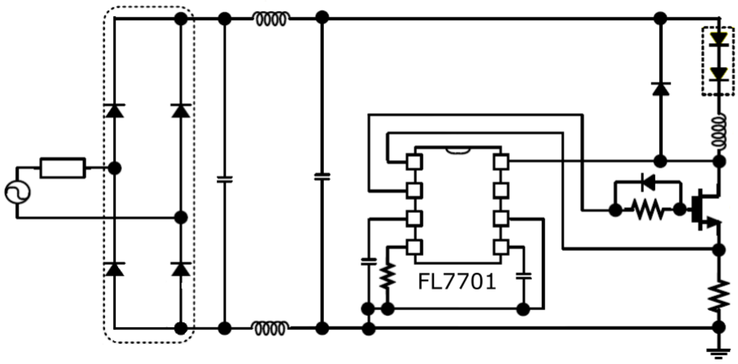
Source: The authors.

Figure 7 – Internal electronic circuit block diagram of an LED lamp

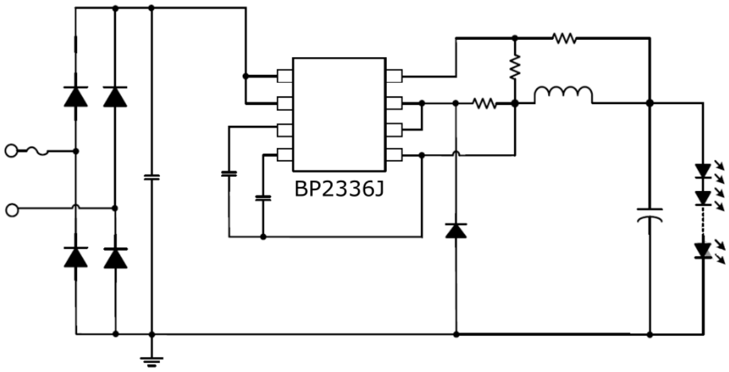


Source: The authors.

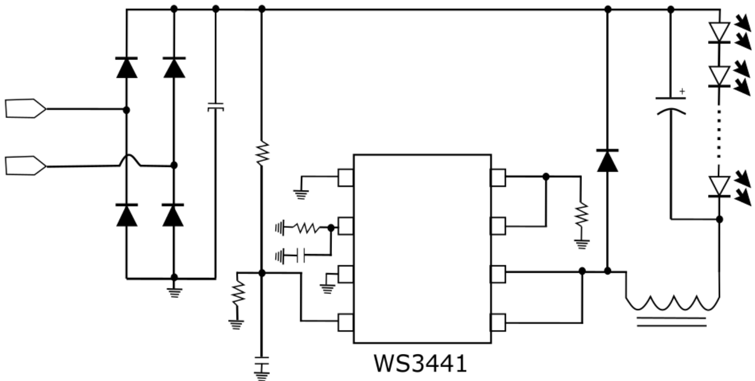
Figure 8 – Standard harmonic content of four lamp models



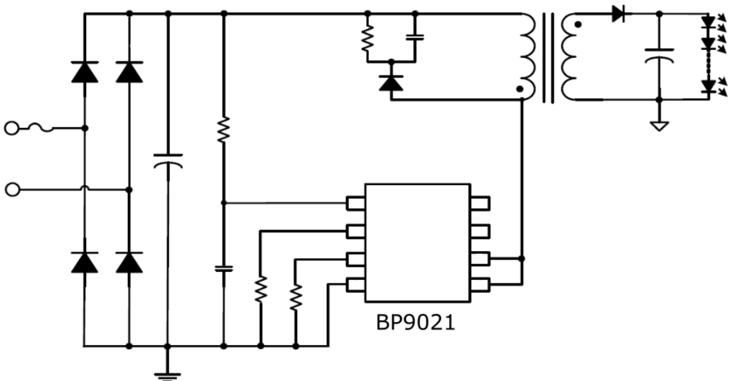
(a) Electrical diagram of the IC (FAIRCHILD SEMICONDUCTOR, 2003) present on the manufacturer's lamp “A” model 9.5 W and THD estimated at 53.9228%



(b) Electric diagram of the IC (BRIGHT POWER SEMICONDUCTOR, 2019a) present on the manufacturer's lamp "J" model 6 W and THD estimated at 52.7949%



(c) Electrical diagram of the IC (WINSEMI ELECTRONICS, 2019)) present on the lamp of the manufacturer "J" model 9 W and THD estimated at 112.1785%



(d) Electrical diagram of the IC (BRIGHT POWER SEMICONDUCTOR, 2019b) present on the manufacturer's lamp "B" model 3 W and THD estimated at 172.6415%

Source: The authors.

Conclusion

An analysis of the harmonic distortions caused by LED lamps from several manufacturers available in the national market was presented. The differences between the actual and nominal power factor for each model were analyzed. Finally, a circuit analysis of 4 of the analyzed models was exposed and a possible reason for performance regarding THD was found. An analysis of the current national regulations was also carried out.

The research showed that the current national regulation only specifies limits regarding the Power Factor of lamps based on LED technology. Likewise, no academic or technical works were found, at least with a national focus and on E27 lamps, to evaluate the technical aspects proposed in this work.

It was observed that the presence of active PFC function in some lamps provided significant improvements in THD levels. The improvement in power quality indicators produced by the active PFC function is not surprising, but the results show the apparent relevance of the resource to the observed improvement.

The research also showed that the lamps with the best performance in the tests, except one, had the ENCE label, which shows the benefits of the technical regulations imposed by regulatory agencies on the quality of the lamps. There is no definition in the regulation for limits of harmonic currents or THD in this power range, but the results showed that the improvements in the power factor imposed by Inmetro regulation brought reductions in harmonic currents, even if indirectly and apparently unintentional, producing a positive effect for the quality of LED lamps found in the Brazilian market.

The results obtained may also suggest the need for more efficient regulation covering power quality indicators such as current THD. As well as more efficient enforcement, as most of the lamps tested were purchased on the market and most of them failed to meet nominal specifications.

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