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Efficiency Evaluation in Public Lighting by Using LED and HPS Technologies

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Abstract

A worldwide discussion about new forms of energy consumption and energy efficiency has been a target of study for many years. Therefore, it has been identified that the lighting is an important part of the energy consumed in the world and Street Lighting (SL) contributes to it especially in urban areas. Researches related to fixtures with high durability and low cost are relevant to technical lightings, such as intelligent systems that can control energy consumption. This paper presents an evaluation between Light-Emitting Diode (LED) and High-Pressure Sodium (HPS) lamps regarding the luminous efficiency, energy efficiency, power consumption, and some aspects of power quality. The methodology test is based in international standard using an accredited laboratory (Lablux – UFF) to confirm the measurement. This article also discusses what happens when voltage decreases are applied to the LED, compared to the nominal conditions because this control method can be used to reduce the energy consumption in LED lamps (as intelligent SL control) and a critical analysis is necessary.

Keywords

New Lighting Technologies, Energy Efficiency, Power Quality, Lighting Systems

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1. Introduction

Lighting systems are responsible for 20% of global building electricity consumption and represent approximately 3,000 TWh / year [1]. The Street Lighting (SL) is an important public service that impacts directly the human activities and promotes transportation and pedestrian safety [2]. SL is one of the physical attributes studied and discussed in researcher that explore the analysis of quality and livability of cities streets [3]. In Brazil, SL is responsible for an average of 3% of the annual electricity consumption (14 GWh). However, due to government incentives related to access and public safety, there will be a steady increase in electricity consumption for SL over the years [4]. Therefore, SL is an extremely important issue in the Brazilian scenario, and the reduction of energy consumption in compliance with the national standards is often discussed on forums, including aspects related to the problems for society (especially regarding security aspects and quality of life in the cities). An import review about energy efficiency fundamentals including indicators of energy use is presented in Perez-Lombard et al. [5].

In 2015, initiatives developed by Eletrobrás (Procel Reluz) reduced energy consumption by 120.6 GWh and demand during peak hours by 25.5 MW [6]. In recent years, Brazil had a water crisis with an impact on power generation, which has increased the use of thermal electric plants, raising electricity prices over 60%, according to IBGE [7]. Researches indicate the energy and luminous efficiency of the Light-Emitting

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Diode (LED) for SL as a promising alternative, enabling cost reduction and high durability by up to 50,000 hours. It is estimated that, worldwide, there will be an increase of 12% on the acquisition of this technology by 2018 [8].

Recent research focusing lighting systems include: intelligent control using artificial intelligence (IA) and computational techniques to SL in smart cities [9, 34], reducing power consumption and/or power quality in lighting systems [10-13], energy efficiency in lighting systems [14-16], performance of different lamps technology applied in urban spaces [17-18], public street lighting remote operational and supervision [19-20], influence of natural/artificial light on structured steel buildings [21], economic analysis comparing LED, HPS lights for exterior lighting integrate with solar PV energy source [22], LED lighting systems technologies applied in rural/remote areas [23], evaluating methods to analyse lighting projects and economic impacts of the technology [24] and safety and well-being of residents of urban areas [25].

This article intends to contribute to the research related to HPS and LED lamps us and it is organized as follows. Section 2 summarizes the application of the sodium vapor lamp for SL. Section 3 provides information about the LED. Section 4 explains the methodology used to carry out the tests between LED and HPS lamps for SL. Section 5 details the results of the performed tests in the laboratory and evaluates the data obtained for the HPS and LED applied for SL, related to current, voltage, active power, Power Factor (PF), luminous flux, luminous efficiency, and Total Harmonic Distortion of the Voltage and Current (THDV and DHTI). Finally, Section 6 presents comments and conclusions about this research.

1.1. Technology Discussion About Sodium Vapor Lamp

Concerning light sources, it is possible to identify several relevant features of light, among which should be highlighted the color temperature and Color Rendering Index (CRI). The color temperature is an important issue for deciding to use a light source; for example, light sources with cool colors are used to public areas and greater coverage. CRI is often used to analyze light fixtures, aimed at classifying on a scale from 0 to 100 in relation to the level of color perception from a surface illuminated by a light source when compared with a reference light source. The CRI for an incandescent lamp is 100 and for the sodium vapor lamp is 25, which means that the HPS has a low color reproduction.

Another relevant issue in the technical lighting area is the luminous efficiency of lamps, which can be defined by the number of lumens (a measure of luminous flux) provided by the lamp when compared to the required electrical power in Watts. Figure 1 shows several types of lamps, comparing their efficiency. It is verified that sodium-vapor lamp is the most used for SL with a luminous efficiency of 120 lm / W (may fluctuate according to model and manufacturer).

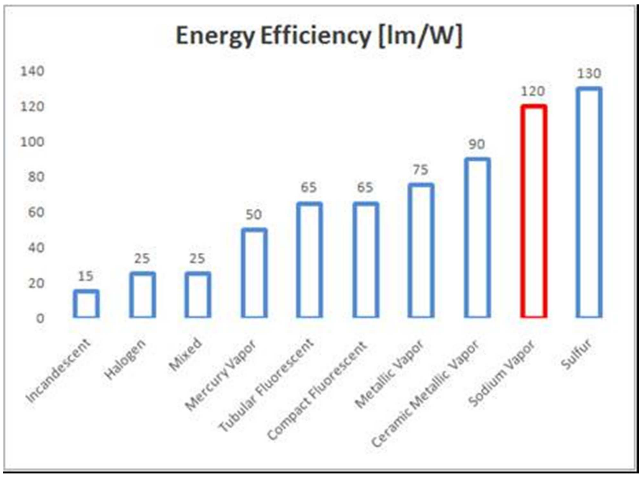


Figure 1. Comparative graph of energy efficiency for some lamp types.

Note - (Mercolux Brazil Site 2016).

The sodium vapor lamp was first commercially produced in 1932 by Philips in Holland, and thereafter, significant technological increments occurred. This technology is widely used today mainly for industrial purposes. The sodium vapor lamps are comprised of a tube containing gas; light is emitted as a result of the discharge of the reaction gas contained in the tube. Due to the high chemical reactions in an electric discharge, the tube is made of translucent aluminum oxide. This discharge reaction between the electrodes results in a glow of light emitted by excited molecules.

The technology for sodium vapor lamps is divided into low and high pressure, and the low-pressure lamp is also known as monochromatic yellow. The lamp is composed of a quartz tube, and light emission occurs when the current flowing therein, where the electrons collide with the vaporized metal atoms. This type of lamp requires a ballast for starting the operation and has a high efficiency and a low CRI. When this type of lamp appeared, several concerns also appeared, such as the difficulty in selecting a glass that supports high temperatures of the metal vapor. As another example, some were concerned about the difficulty in relation to the reaction of the electrodes with the metal vapor and the need to ensure that the electrode wires were sealed without breaking the casing. In 1965, after the development of high-pressure lamps, it was possible to improve the color reproduction of this lamp model and achieve a high CRI. Today, an HPS 400W reproduces 50,000 lumens on average.

Related to quality and energy conservation, this technology has ballast starting as one of the critical elements. This element is an inductive load, due to the number of coil winding turns that provides a low power factor and energy loss by heating. To improve the use of sodium vapor technology in SL systems, it is recommended that capacitors or electronic ballasts be used to avoid waste with reactive power. Although there is a loss caused by the need for ballast, the HPS lamp is still the most used in SL, because it is more efficient compared with other high-pressure discharge lamps (with an average efficiency of 120 lm/W and a useful life of 20,000 hours). The major problem with this type of lamp is CRI, which is not suitable for scenarios where the identification of colors is relevant. An important research discussing about use of HPS technology lamp is presented in Pipattanasomporn et al. [26].

1.2. Light-Emitting Diodes (LED)

According to Schubert [27] in the early twentieth century, the emission of light from a material in solid phase was caused by a power source that generated the phenomenon known as electroluminescence.

In 1891, Eugene G. Acheson established a commercial process for a new synthetic material (silicon carbide - SiC), which he called carborundum. The synthesis procedure was performed in a high-temperature oven that was heated electrically, in which the glass (silicon dioxide, SiO_2) and carbon (Carbon C) reacted to form SiC, according to the chemical reaction described in Equation 1 [28].

$$SiO_2 \text{ (gas)} + C \text{ (solid)} \rightarrow SiO \text{ (gas)} + CO \text{ (gas)} \qquad (1)$$

$$SiO \text{ (gas)} + 2C \text{ (solid)} \rightarrow SiC \text{ (solid)} + CO \text{ (gas)}$$

Round announced that the light was emitted by a crystalline SiC, and thus, he developed the first LED. At that moment, the material properties were poorly controlled, and the issuing process was not well understood. However, he immediately reported his remarks to the editors of Electrical World. This information was reported in Schubert [27].

LED technology had significant growth in the last decade, and its market will provide half of the lamps in the world in Ahn et al. [29]. Furthermore, the LED has a great potential to replace the traditional types of the indoor artificial lighting of buildings, such as fluorescent and halogen lamps, due to its high luminous efficiency, useful life, flexible design, dimming, and many positive environmental effects. The LED will reach 74% of the market in 2030, with a large increase in all sectors, which will result in 297 TWh of electricity consumption. In Europe, it is expected that the LED will provide two-thirds of all non-residential lighting in 2030. In 2011, the South Korean government announced a government incentive for the LED, aimed at achieving 60% of all buildings' lighting systems by 2020 [29].

In the lighting field, the light device must have the following properties: (i) high performance, (ii) high power capability, (iii) good color reproduction capability, (iv) high reliability, (v) low-cost manufacturing, and (vi) no environmental impact. These properties allow the LED to compete with conventional lighting sources, such as incandescent and fluorescent lamps [27].

White light generation can be achieved with a large number of spectra. The creation of white light emitting monochromatic visible in the spectrum can be based on dichromatic, trichromatic, tetrachromatic, or higher chromaticity approaches. The optical sources can be classified in terms of their luminous efficacy of radiation, the light source efficiency, and color irradiation properties. Places such as museums, homes, offices, and stores require a high capacity in the color value of irradiation [27].

However, there are numerous applications in which the color reproduction capability has a lower priority, such as the lighting of streets, parking lots, and stairwells. Finally, in signage applications, the color irradiation is irrelevant. There is a difference between the luminous efficiency and emission color by the light source. Generally, the dichromatic white light has a higher luminous efficacy and a lower capacity for CRI. A white trichromatic source has more acceptable properties (greater than 80 CRI) and a higher luminous efficacy at 300 lm / W, while tetrachromatic sources may have a CRI greater than 90. Another important fact is that the light source efficiency decreases with increasing multi chromaticity. Thus, the dichromatic sources have the highest luminous efficacy of radiation and the greatest potential for light source efficiency. Color irradiation is lower for dichromatic sources, and it increases with multichromatic sources; the CRI can achieve values close to 100 for tetrachromatic sources [27].

Based on Ryckaert et al. [30], the LED is emerging commercially, and properties such as longer service life, dimming, variability, unlimited switching, flexible design, high luminous efficacy, and low heat transfer in the light beam make this lighting a better alternative for sources of traditional light. Systems using the LED are available not only for architectural lighting, but also for other applications, and they already compete with traditional compact fluorescent lamps in terms of efficiency and lighting quality. This survey described an experience in which a student room (38 men and 6 women) with an illumination by fluorescent lamps T8-36W / 840, were replaced by LED tubes. People were divided into groups of 4 to 6 to evaluate the new lamps. The result was a reduction of energy consumption and lighting quality of the work plan, possibly caused by an incorrect technical specification. Thus, the survey did not get real results to improve the environment with its changes, which leads to a need for research with different settings and lighting technologies to be developed and presented to the academic world and society, information that contributes to knowledge and correct application of this new equipment, which, once installed, will have at least 10 years of use and impact for users.

A comparison conducted in Wang and Tan [31] demonstrated that the LED technology is competitive, energy efficient, and has great potential for replacing traditional lamps, such as fluorescent and halogen lamps. An interesting area of research on the subject is the use of the neural network for comparing the brightness in work plans and its gain for the lighting system, bringing advantages in lighting control to achieve optimum performance.

As mentioned above and in Silva [32], the advantages of using the LED are a reduced energy consumption; They have lifetime up to 50,000 hours; smooth operation at low temperatures (-40 °C); efficient source of light for short distances and small areas; high shockproof; do not contain mercury; instant starting at 100% light; environmental colors return with varying combinations; do not emit heat by encapsulating (infrared); and enables directivity of light, which is useful in some applications to reduce light pollution (for example, diffuse street lights).

2. Method

The tests were performed in the technical lighting laboratory of the Fluminense Federal University (LABLUX / UFF), which has the equipment necessary for the intended simulations. Aiming to achieve the objectives, we conducted the test of lamps HPS 150W and 130W LED.

2.1. Equipment

For the electrical and photometric parameters for the study of both lighting systems, the following equipment was used, as shown in Figure 2 to 4: (i) a programmable source, (ii) a goniophotometer (applied for photometric measurement at defined directions by two angles, usually called horizontal and vertical, to determine the light distribution of a lamp or luminaire, reproducing the average relative sensitivity of the human eye to different wavelengths (Inmetro 2016), (iii) a goniometric source with a digital power meter, (iv) free Yokogawa software, and (v) luminaire sample.

(i) (ii) (iii) (iv)-(v)

Figure 2. Testing Equipments.

The Figure 3 shows an internal photo of the goniophotometer room.

Figure 3. Goniophotometer Room.

A traditional goniophotometer usually consists of a mechanical two-axis scanner that moves a photodetector around the sample in small angular steps through space. The main disadvantage of a scan with a goniophotometer is the long acquisition time. Several applications in lighting and virtual simulation systems generally require a large number of measurements to determine the Bidirectional Distribution Function Diffusion (BDFD), which must consider the number of surfaces, illumination angles, and wavelengths that are typically detected in the devices tested [33].

The data measured by a goniophotometer are described by Equation 2, which is the bidirectional transmission or reflection function, defined by the Commission Internationale de l'Eclairage (CIE):

$$BT(R)DF_v\left(\theta_{t(r)},\varphi_{t(r)},\theta_i,\varphi_i\right)=\frac{L_v\left(\theta_{t(r)},\varphi_{t(r)},\theta_i,\varphi_i\right)}{E_v(\theta_i)}\ [sr^{-1}] \tag{2}$$

Where:

BT(R)DFv - Bidirectional transmission or reflection function [sr-1];

θt(r), φt(r), θi, φi - Imerging and emerging polar coordinates (transmitted and reflected) of luminous flux, expressed in [º];

Lv (θt, φt, θi, φi) - Imerging and emerging luminance (transmitted and reflected) of an element [cd/m²];

Ev(θi) - Iluminance on the sample plane due to the incident luminous flux. [lux].

2.2. Testing in Laboratory - Description

The lamps used in the test were an LED (130W) and an HPS (150W). Thus, it was possible to execute data extraction for the voltage, current, THD for voltage and current, PF, luminous flux, luminous efficiency and distribution light intensity of the devices tested.

All of the early tests were performed at a nominal voltage (220V) at a controlled temperature of 25°C (± 1°C), a controlled voltage of ± 0.2%, and a THDv of less than 1% during periods of stabilization and measurement. The electrical and photometric characteristics were measured by the Everfine goniophotometer Model GO2000, which is a goniophotometer with a photodetector. To power the lamps, it was used as a DPS Everfine energy source. The evaluation of the power quality was verified by a Yokogawa Wattmeter Model WT-210, and free software was available from the manufacturer. Data were collected by a computer via USB communication and software; thus, all of the data and graphics needed for an analysis of the experiments were obtained.

Figure 4. Test illustration of LED luminaire using the Gonio photometer.

The following methodology was used for the reproduction and comparison between different technologies: an LED luminaire of 130W, measuring initially with nominal voltage (220V), then decreasing the voltage by 5% (achieving 90V voltage), with respect to the parameters mentioned as a condition for the tests, and an HPS luminaire of 150W, measuring only with nominal voltage (220V) and the above-mentioned conditions. Figure 4 shows its initial vertical position and the initial test to collect data with its position directly to the photodetector.

3. Results

Based on the procedures described in the previous section, it was possible to collect data regarding the two technologies used in SL, selected for this work (HPS and LED). Table 1 shows the measured values of current, active power, PF, luminous flux, luminous efficiency, and THD_I when 220V of the nominal voltage is applied to both lighting systems.

Table 1. The data collection to 220V of nominal voltage applied.

Parameter/Model	HPS	LED
Current [mA]	789.5	623
Active Power [W]	168.7	134.2
Lagging PF	0.9685	0.975
Luminous Flux [lm]	8965	11321
Luminous Efficiency [lm/W]	52.91	84.39
THD_I [%]	25.28	13.23

As can be seen in Table 1, the LED has lower current values, even for active power and THDI. The PF has almost the same values, but the luminous flux and luminous efficiency have higher values with respect to the HPS. Figures 5 and 6 show the waveforms of current and voltage obtained by the test oscilloscope for the HPS and LED when submitted to 220V of nominal voltage. In the figures, the yellow lines represent the voltage, and the green lines represent the current.

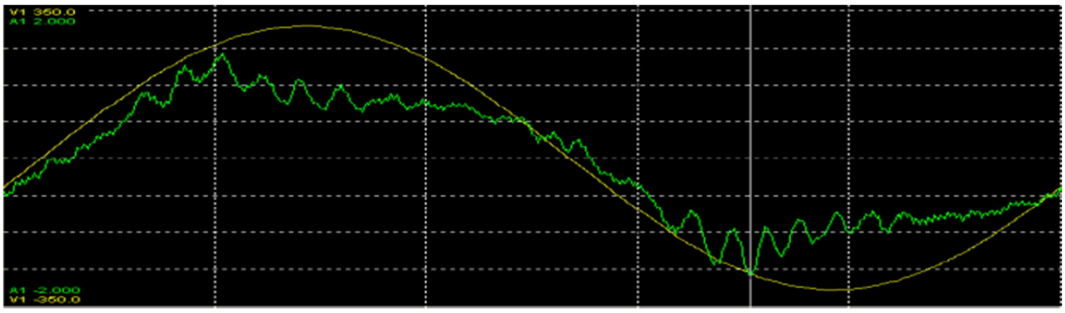


Figure 5. Waveforms of current and voltage by HPS.

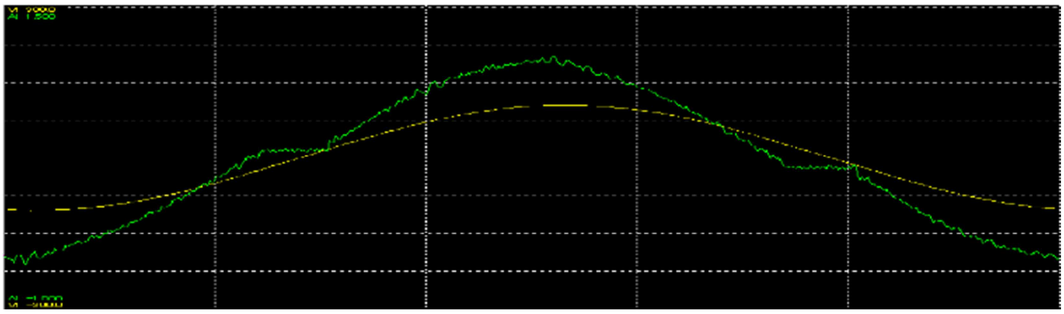


Figure 6. Waveforms of current and voltage by LED.

According to the THDI data indicated in Table 1, as well as Figures 5 and 6, both systems show distortions in current waveform, although the HPS shows higher values than LED. Table 2 shows the same parameters in Table 1 but reduces the nominal voltage of LED in the following percentages: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60.

With reference to Table 2, the values of current, active power, and PF increased. However, the values of luminous flux, luminous efficiency, and THDI decreased. Figures 7, 8, and 9 represent the percentage graphs of harmonic components in the following way: the values between the HPS and LED; the LED values with reduced voltage; and their values between the nominal voltage (220V) and lowest voltage (90V) applied.

Table 2. The data collection when reducing the nominal voltage applied to LED.

Voltage [V]	Current [mA]	Active Power [W]	Lagging PF	Luminous Flux [lm]	Luminous Efficiency [lm/W]	THD$_I$ [%]
220	623.0	134.2	0.975	11321	84.39	13.2
209	654.2	134.3	0.979	11497	85.59	12.8
198	687.6	134.2	0.982	11311	84.28	11.7
187	726.6	134.3	0.985	11307	84.19	11.4
176	770.9	134.5	0.988	11306	84.08	11
165	821.6	134.7	0.990	11303	83.93	10.5
154	880.9	134.9	0.992	11304	83.77	10
143	949.5	135.3	0.993	11304	83.54	9.5
132	1031	135.9	0.995	11326	83.35	9
127	1073	136.1	0.995	11301	83.06	8.8
121	1130	136.5	0.996	11293	82.74	8.4
110	1253	137.6	0.997	11377	82.66	7.9
90	1543	139	0.998	11201	80.57	5

Figure 9 shows that LED technology has lower harmonic distortion values (almost 11.8% for third order) than the HPS values (almost 21.6% for third order) when applied to 220V voltage. There are low variations of amplitudes in other harmonic frequencies, but the HPS has a higher percentage of harmonic amplitude than LED in most measures.

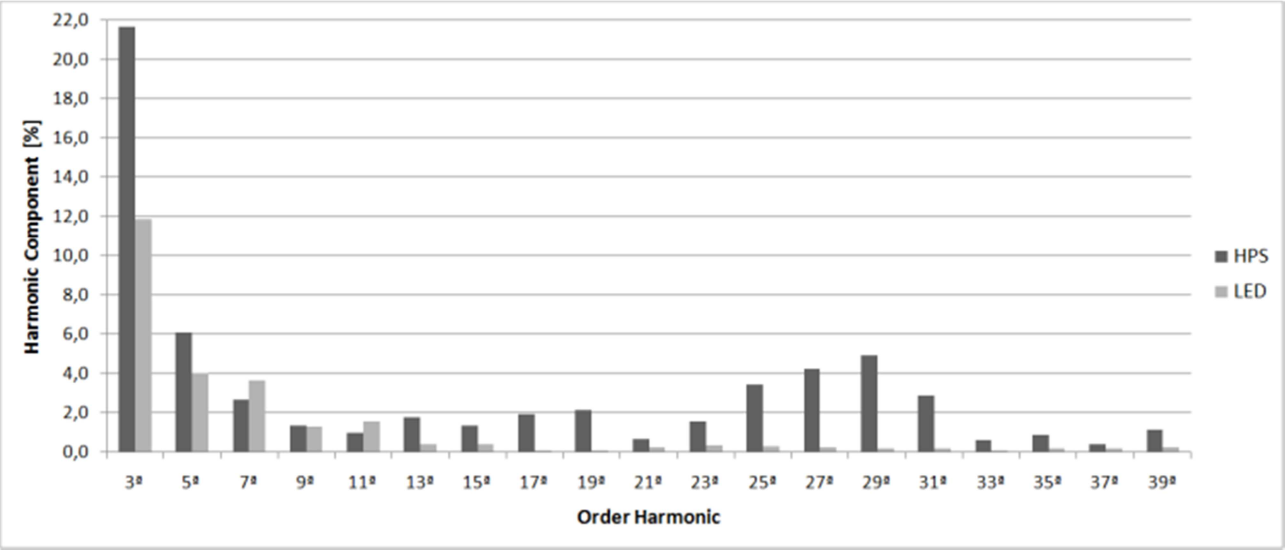
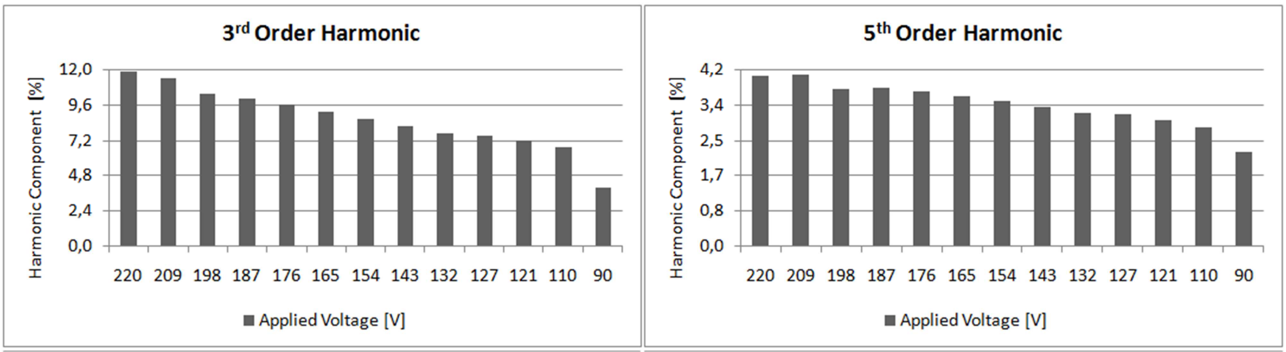


Figure 7. Harmonic spectrum of HPS and LED currents.



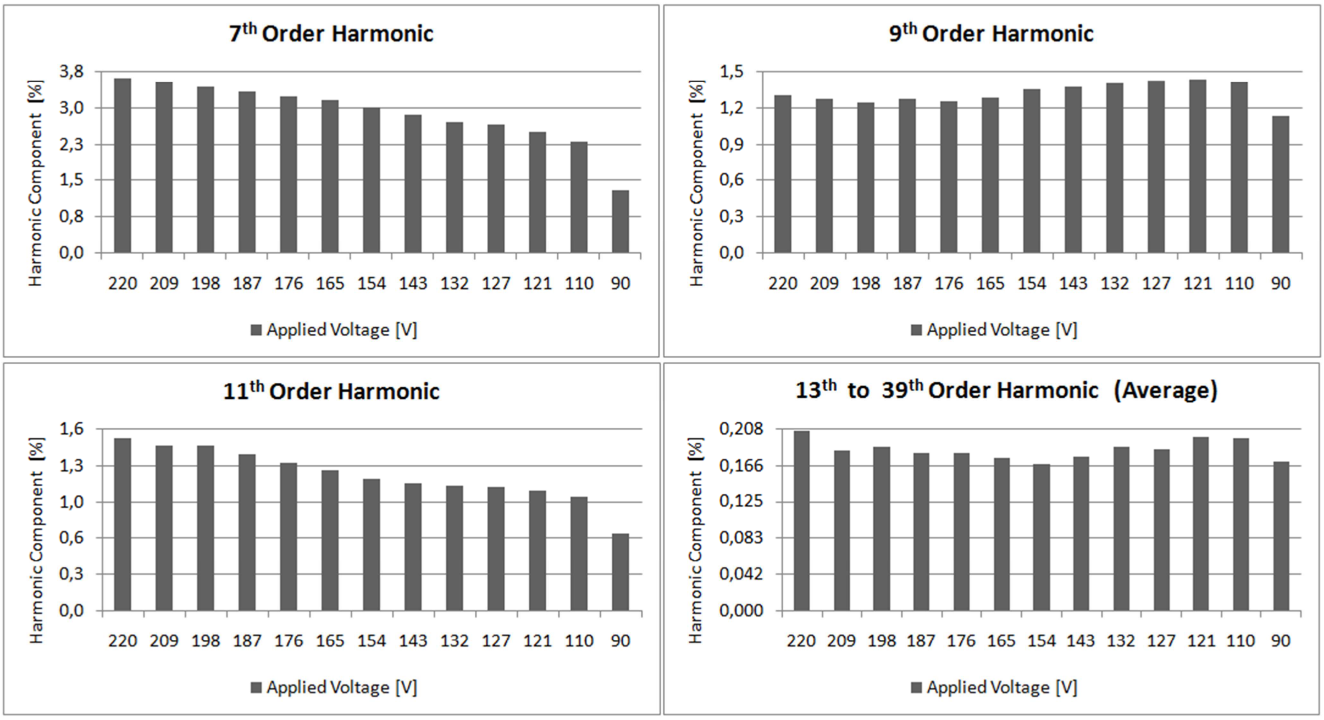


Figure 8. Harmonic spectrum of LED currents with reduced voltage.

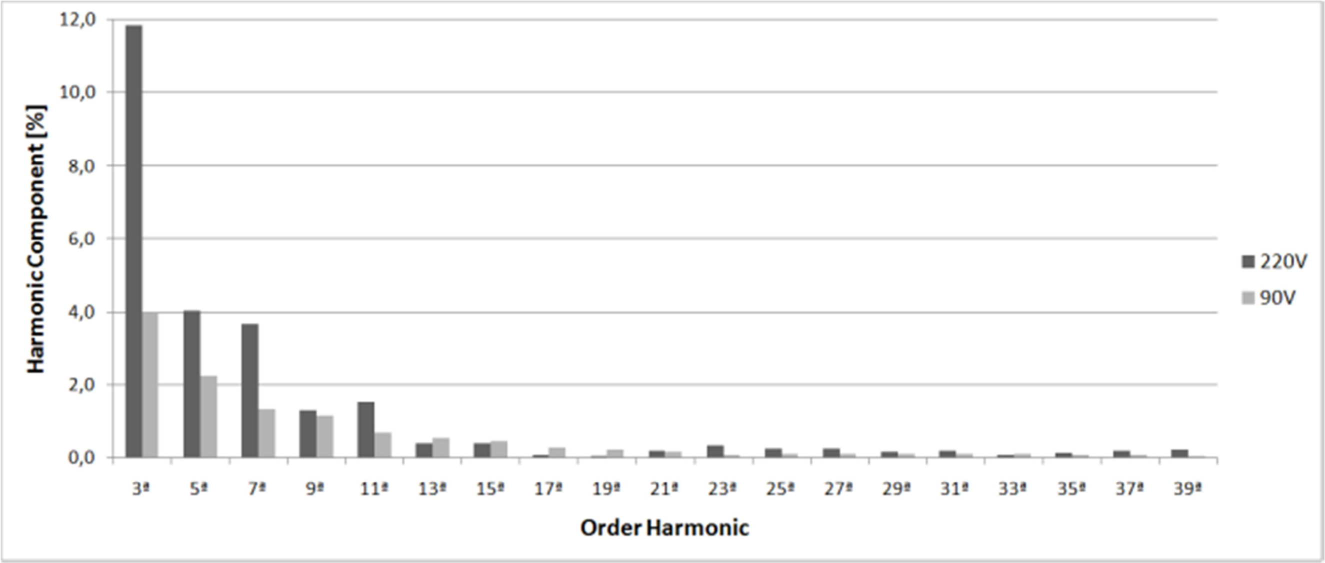


Figure 9. Harmonic spectrum of LED currents for 90 and 220 V applied.

Based on Figure 8, there was an average reduction in the harmonic components for each reduced voltage applied to LED. This analysis can be seen in Figure 9, which shows a reduction of the harmonic distortion at 90V compared to 220V (from 11.8% to 4% for third order).

The Figure 10 illustrates an example of a curve and distribution diagram of light intensity for LED when a nominal voltage (220V) was applied, using a Gonio photometer for testing.

According to the other tests carried out, the curve and distribution of light intensity for the LED did not have major changes when voltages were reduced by 5% (0.95 pu) to 60% (0.4 pu) when compared with the nominal voltage condition depicted in Figure 10. To confirm, Figure 11 shows this measure when the 90V voltage applied to the LED.

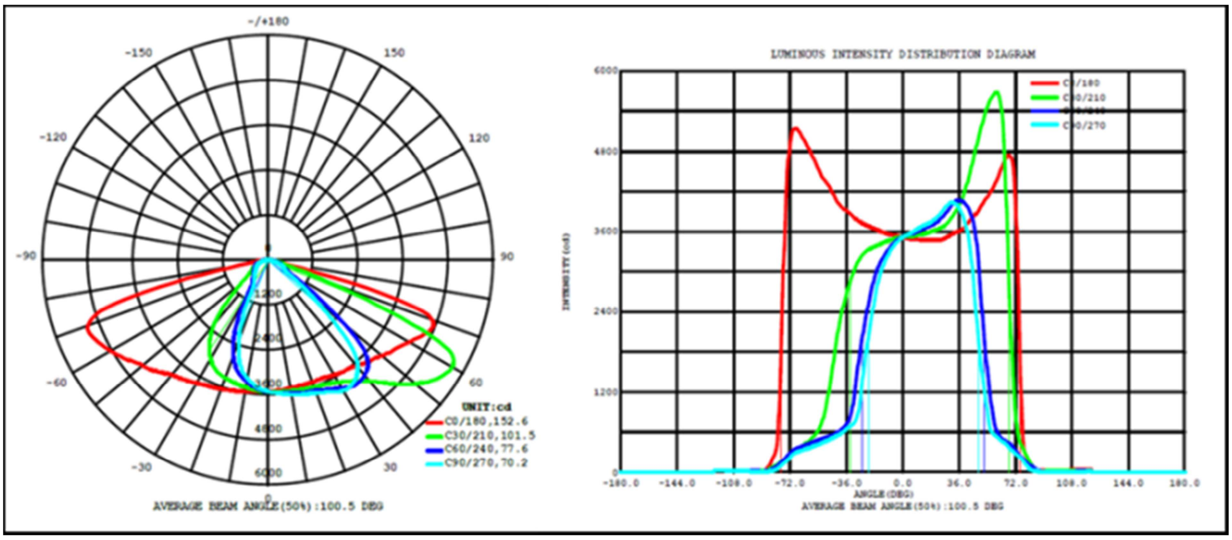


Figure 10. Curve and distribution diagram of light intensity for LED, when a nominal voltage is applied.

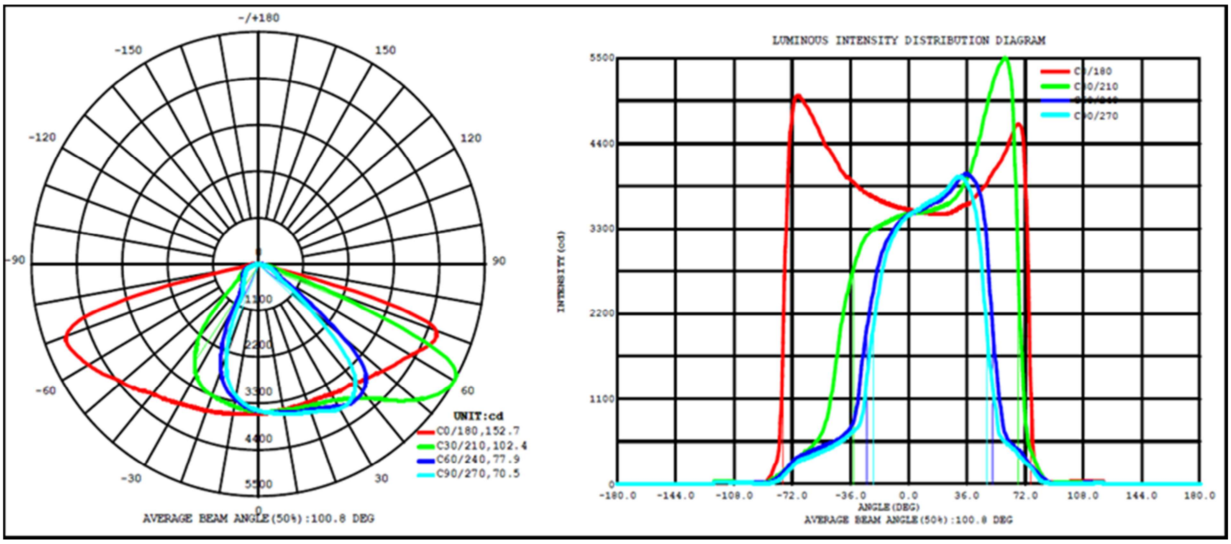


Figure 11. Curve and distribution diagram of light intensity for the LED, when a 90V voltage is applied.

4. Conclusion

This study aimed to evaluate and compare some parameters between two lighting technologies: the LED and HPS. Furthermore, tests were performed in a technical lighting laboratory (LABLUX) at Fluminense Federal University.

In general, we determined that the LED (130W) has better parameters compared to HPS (150W). The measured consumption of active power in the HPS was 168.7W (12.46% higher than nominal), while that of the LED was 134 W (3.2% higher than nominal); this means that the LED has a low deviation compared to what is reported by the manufacturer. The difference in the luminous efficiency parameter was 59.5% (52.9 lm / W for the HPS and 84.4 lm / W for the LED), and the THDI was 47.7% (25.8% for the HPS and 13.23% for the LED). This proves, quantitatively and qualitatively, that it is efficient to replace the HPS lighting systems with the LED.

It was also determined that the effects were caused by a decrease of the voltage of the LED, comparing the data obtained when applied to the nominal voltage of 220V. There was a 4.5% drop in luminous efficiency (from 84.39 lm/W to 80.57 lm/W) and a 62% drop in THDI (from 13.23% to 5.02%) when the voltage is reduced to 0.4 pu. There was a current increase of 147% (from 623 mA to 1543 mA), with a low impact on the active power of 3.5% (from 134.2W to 139W), and a PF improvement of 2.3% (from 0.975 to 0.998). Although there was a THDI decrease, a PF increase, and low change in luminous efficiency, there was an excessive current increase on the LED, compared to its nominal condition. This can lead to problems, such as the overheating of components and reduction in its service life.

The LED systems are available with a remote control to change the voltage values. Thus, to reduce energy consumption, it is possible to use the LED in SL in timetables, with few people walking. However, it must be applied to the equipment a system with current limiting and/or to protect against overcurrent, avoiding overheating the components and physical structure of luminaire, as well as fatigue and reduced service life of electronic components that can lead an increase of failures for LED system above the HPS. This article also provides laboratory test information (performed on equipment marketed in Brazil) that present real parameters for comparisons of energy efficiency in retrofit activities or other technology exchange evaluations.

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