Harmonic Currents on LED Lamps - Photometric and Power Losses Analysis

Bruno G. Serdeira[a], Lucas G. F. Silva[a], Luana M. Silva[a], F.Sass[a], Gilson B.A. Lima [a] and Marcio Z. Fortes[a*]

[a] Fluminense Federal University (UFF), Passo da Patria St. 156, Room 431-E, 24.210-240, Niterói-RJ, Brazil. (UFF).

E-mail: bgserdeira@id.uff.br; lucas_gappo@id.uff.br; luanamerenciano@id.uff.br; felipesass@id.uff.br; glima@id.uff.br; mzamboti@id.uff.br.

* Corresponding author

Abstract: Waveform distortion is classified as harmonic when the deformation exhibits a spectrum with only integer frequency multiples of the fundamental frequency. This type of periodic deformation is typically due to the nonlinear voltage/current relationship inherent in certain components. With the increasing prevalence of electronic equipment connected to the electrical network, concerns about these distortions have intensified, as the performance of other connected devices may be adversely affected. To mitigate such effects, several regulatory agencies have established limits on the presence of harmonic frequencies produced by equipment. In Brazil, lighting systems using LED technology are regulated to minimize harmonic distortions through INMETRO's Ordinance No. 69 of February 16,2022. This regulation aims to reduce harmonic distortions generated by LED lamps, particularly those used in residential settings. The objective of this study is to analyse the losses caused by harmonic currents in LED lighting devices, focusing on residential lamps. This analysis employs a controlled and stabilized power source, as well as a standard electrical network from a local utility, where voltage levels and harmonic distortions are not regulated. Using the data collected, both fundamental and non-fundamental powers of the samples were calculated. This allowed for an assessment of the impact of current harmonic distortions on performance and power quality, revealing a significant reduction in losses.

Keywords: Harmonic distortion, LED lamps, Photometric Analysis, Power Losses.

1 Introduction

Power electronics have been steadily developed since the 1970s, contributing to the expansion of nonlinear loads in electrical systems, as discussed by [1]. In addition, [2] presents the fundamental principles and design aspects of power electronic circuits, reinforcing their impact on system behavior.

Additionally, nonlinear behavior in electrical systems has been widely investigated in the literature, particularly in the context of modeling and analysis of complex systems.

When discussing residential lighting, it is important to consider its evolution within Brazil. During the electrical crisis of 2001, incandescent lamps were banned and replaced by Compact Fluorescent Lamps (CFLs), which are more energy-efficient devices [3].

In the pursuit of greater power efficiency and improved power quality, and to meet more stringent standards, LED-based lighting devices have been implemented nationally in Brazil since 2014. These devices have been widely distributed throughout the country and are regulated by the Instituto Nacional de Metrologia (INMETRO) under the regulations outlined currently in RTQ No. 69 of February 16, 2022[4].

Despite their greater efficiency, LED lamps can introduce harmonic distortions into the electrical network due to their control circuitry. Therefore, it is essential to analyze these effects during the certification process to prevent the use of devices that may adversely affect the operation of other electrical equipment. The influence of harmonic currents from lighting equipment on power losses in electrical networks is also highlighted in Radakovic and Nedic [5], who emphasize the importance of evaluating harmonic distortions to improve energy efficiency. The main characteristics analyzed to ensure compliance with device standards are as follows:

- For power efficiency and lighting quality: demanded power, luminous flux, color reproduction index and correlated color temperature are measured.
- For power quality: the power factor and the current harmonic distortions are measured.

Recent studies have shown that the presence of non-linear loads in low-voltage networks significantly impacts the power quality [6]. Considering the effects on power quality and current harmonic distortions, this article aims to study the impact of harmonic currents on loss rates and performance associated with the use of LED lamps. To achieve this, the power demands of the devices were analyzed based on their measured harmonic currents in two different scenarios: the first scenario involved powering the lamps with a stabilized power source and voltage harmonic filtering, while the second scenario used a standard electrical network without stabilization or filtration.

This article is organized as follows. Section 2 presents the IEEE’s standard to calculate harmonics. Section 3 describes some of the criteria adopted for LED lamps to allow its selling in Brazil. In Section 4, the methodology for the analysis is presented. Section 5 evaluates how harmonic currents affect photometric and power losses in the lamp. Finally, Section 6 brings the conclusions found from this study.

2 IEEE Standards for Harmonic Measurements

An electrical system can be classified according to the type of load that consumes energy. Some consumers are linear loads, which consume sinusoidal current and voltage, such as pure resistors (incandescent lamps, heaters, etc.). The other part is made up of nonlinear loads, such as switching power supplies, which distort the waveform, introducing harmonics into the electrical network. These harmonics are integer multiples of the fundamental frequency and can be represented as three-phase quantities, influencing the system symmetry and the resulting current or voltage waveform. In three-phase systems, harmonics can be represented in rotating coordinate systems, which facilitates the modeling of asymmetric components [7]. This behavior can also be mitigated with active filtering techniques, as demonstrated by Y. Han et al. [8], who analyzes robust control strategies for hybrid active filters in systems with a strong presence of nonlinear loads.

Total Harmonic Distortion (THD) quantifies the extent of this non-sinusoidal property in a given waveform and is interpreted as the percentage of the RMS value associated with frequencies other than the fundamental frequency [2].

In the calculation model adopted by IEEE Std. 1459-2010 [9], active and reactive powers are presented in greater detail, distinguishing between fundamental and non-fundamental components, as shown in equations (1) and (2). Fundamental powers are derived solely from the fundamental frequency, as demonstrated by equations (3) and (4). Non-fundamental powers, on the other hand, include contributions from harmonic components, and are expressed by equations (5) and (6). Additionally, the apparent power for each individual harmonic order can be determined, as illustrated by equation (7).

$$P = P_f + P_h \quad (1) \qquad Q = Q_f + Q_h \quad (2)$$

$$P_f = V_{rms,1} I_{rms,1} cos(\theta_1 - \phi_1) \quad (3) \qquad Q_f = V_{rms,1} I_{rms,1} sen(\theta_1 - \phi_1) \quad (4)$$

$$P_h = V_0 I_0 + \sum_{n=2}^{\infty} V_{rms,n} I_{rms,n} cos(\theta_n - \phi_n) \quad (5)$$

$$Q_h = \sum_{n=2}^{\infty} V_{rms,n} I_{rms,n} sen(\theta_n - \phi_n) \quad (6) \qquad S_{h,n} = V_{rms,n} I_{rms,n} \quad (7)$$

Apparent power is also divided into distinct components corresponding to fundamental and non-fundamental contributions, as described by equation (8). The non-fundamental portion, referred to as non-fundamental apparent power, is defined by equation (9).

$$S = \sqrt{{S_f}^2 + {S_N}^2} \quad (8) \qquad S_N = \sqrt{{D_I}^2 + {D_V}^2 + {S_H}^2} \quad (9)$$

The fundamental apparent power, corresponding to the first term in equation (8), is derived exclusively from the system's fundamental frequency, as expressed in equation (10).

$$S_f = \sqrt{P_f{}^2 + Q_f{}^2} = V_f I_f \quad (10)$$

The harmonic apparent power, corresponding to the final term in equation (9), results from the interaction between harmonic voltages and currents, as expressed in equation (11).

$$S_H = V_H I_H = S_f THD_V THD_I \quad (11)$$

Voltage and current distortion powers arise from the interaction between harmonic voltage and fundamental current, and between fundamental voltage and harmonic current, respectively, as presented in equations (12) and (13).

$$D_V = V_H I_f = S_f THD_V \quad (12) \qquad D_I = V_f I_H = S_f THD_I \quad (13)$$

With all components of a system's apparent power identified, it becomes evident that its magnitude increases as voltage and/or current distortions rise. Consequently, when high harmonic distortions are present, a significant reduction in the equivalent power factor may occur, as these power components do not contribute to active power. Accordingly, equations (14) and (15) represent the system's fundamental power factor and equivalent power factor, respectively.

$$pf_f = \frac{P_f}{S_f} \quad (14) \qquad pf = \frac{P_f + P_H}{\sqrt{S_f{}^2 + S_N{}^2}} \quad (15)$$

In addition to equations (11), (12), and (13), equations (16) and (17) demonstrate the calculation of total harmonic distortion for voltage and current, respectively, based on the RMS values of their total and fundamental components.

$$THD_V = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \quad (16) \qquad THD_I = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \quad (17)$$

The spectral decomposition of harmonics has also been successfully applied in diagnostic methods in distribution networks, demonstrating its practical applicability in the characterization of distortions [8].

3 Current Standards for LED lamps

Ordinance No. 69 of February 16, 2022, outlines the evaluation criteria for establishing the minimum requirements that any LED lamp must meet to be sold in Brazil. According to item 3.1.1 of this ordinance, the lamp's power consumption during operation must not exceed 10% of the declared rated power [10].

Energy efficiency is also subject to minimum evaluation criteria. For compact lamps, the assessment is based on the type and rated power, as detailed in Table 1. In contrast, tube lamps are evaluated according to their length and base type, as outlined in Table 2.

Luminous flux is another critical parameter for evaluation. During testing, the lamp must not exhibit a luminous flux lower than 90% of its rated nominal value. Additionally, the standard establishes equivalence criteria with incandescent and fluorescent lamps, which compact and tubular LED lamps must meet, thereby specifying the minimum luminous flux required [10].

The Color Rendering Index (CRI), a parameter related to lighting quality, is also addressed by the standard. According to item 6.1.1.4.1.1.1 of Ordinance No. 69, the general color rendering index (Ra) is calculated as the average of the chromatic indices from R1 to R8. For compact LED lamps, the measured Ra must be greater than 80. Additionally, the R9 index, which refers to the rendering of red color, must have a value greater than 0 [10].

The lifespan of the device is another critical parameter for analysis, determined by performance criteria for maintaining luminous flux over a specified period of use. According to Ordinance No. 69, lamps must undergo seasoning cycles of 3000 hours and 6000 hours. New measurements are taken at the end of each cycle to compare with the initial values, thereby assessing the device's lifespan, as outlined in Table 3.

Table 1 - Minimum efficiency ratio for compact lamps [10].

Lamp type	Lamp Rated Power (W)	Minimum Efficiency (lm/W)
Non-Directional	< 15	55
Semi-Directional	≥ 15	60
Directional	< 20	45
	≥ 20	50
Decorative	< 15	45
	5 - 25	
	≥ 25	

Table 2 - Minimum efficiency ratio for tube lamps [10].

Lamp type	Nominal Length (mm)	Base type	Minimum Efficiency (lm/W)
LED tube	550 - 1150	G5	100
	600 - 2400	G13	85

Table 3 - Lifespan determining limits [10].

Lamp type	3000h	6000h	Maximum Lifespan (h)
Decorative	93.1%	86.7%	15000
Omni-directional Directional Semi-Directional LED Tube	95.8%	91.8%	25000

The final aspect related to power quality is the power factor and harmonic currents. The power factor must meet the criteria outlined in Table 4, based on lamp power. However, tubular lamps must always exhibit a power factor greater than 0.92, regardless of the criteria, as they are typically intended to replace fluorescent lamps or be used in systems that already have a high-power factor [10].

Table 4 – Minimum Power Factor for Compact LED Lamps [10].

Lamp Power (W)	Minimum Power Factor
< 5	Not applied
5 – 25	0.7
> 25	0.92

Regarding current harmonic distortion, the criteria and values specified by the standard are based on IEC 61000-3-2 - Limits for Harmonic Current Emissions (Equipment with Supply Current Less Than or Equal to 16A per Phase) [11], which establishes fixed limits for each harmonic order up to the 39th order. However, the limit for the 3rd harmonic order is dependent on the power factor of the analyzed device. These limits are detailed in Table 5. To assess equipment compliance with harmonic distortion limits, standards such as IEC 61000-3-2 are adopted. For instance, Laufer et al. [12] discuss laboratory procedures applied to the measurement of harmonic currents in electronic products, reinforcing the importance of accuracy in tests to ensure compliance with the established limits. In addition, digital control approaches have been widely adopted to mitigate harmonic emissions in switching power supplies [13].

Table 5 – Harmonic Current Limits [10].

Harmonic Order (n)	Maximum Permitted Harmonic Current (%)
2	2
3	30 x *pf*
5	10
7	7
9	5
11 < n < 39 (Only odd orders)	3

4 Methodology

To determine the losses generated by harmonic currents in LED lamps, various models must be adopted, as Ordinance No. 69 [10], in item 3.12, defines limits for power factor and harmonic currents based on the lamp's active power or whether it is tubular. To obtain the necessary data, five different models were employed, with each model tested in sets of 10 samples, as detailed in Table 6.

Table 6 – LED Lamps Models.

Model	Nominal Parameters
A	A55 4.8W 6000K PF≥0.4
B	A60 9W 6000K PF≥0.7
C	A70 15W 3000K PF≥0.7
D	T100 30W 6000K PF≥0.92
E	T8 20W 4000K PF≥0.92

All necessary tests were conducted in the LabLux – UFF laboratory, which maintains the required temperature and humidity conditions as specified by Ordinance No. 69 [10]. To assess how losses are affected by fluctuations in power parameters, each model was tested with both a stabilized and controlled supply voltage and a conventional network. Moreover, to ensure that the performance of the samples met the nominal values proposed by the manufacturers, all lamps were stabilized by operating them for 30 minutes to minimize variations in electrical characteristics before commencing the testing procedures.

4.1 Used Equipment

In cases where a stabilized and controlled supply voltage was used, the samples were connected to the programmable power source Pacific 110-ADX. This equipment, when operating without load, exhibited a THD_V at 220V and 127V, as detailed in Table 7. When powered by the conventional network, the electrical characteristics, including supply voltage and THD_V, were variable. Consequently, the values presented in Table 8 represent the mean values of the measurements obtained under these conditions.

Table 7 – Source Total Harmonic Distortion of Voltage for Nominal Values.

Supply Voltage (V)	Mean THD of Voltage (%)
220.0	0.10
127.0	0.19

Table 8 – Power Grid Total Harmonic Distortion of Voltage for Nominal Values.

Supply Voltage (V)	Mean THD of Voltage (%)
220.0	1.68
127.0	1.71

The photometric characteristics were measured using a system comprising the Ulbricht Integrating Sphere, the Everfine HAAS-2000 Radiometer Spectrum, and the Everfine HAAS Suite software. The photometric characteristics assessed include Luminous Flux, Correlated Color Temperature (CCT), Color Rendering Index (CRI), and the R9 Chromaticity Index.

The electrical characteristics of each sample were measured using the Yokogawa WT-210 digital wattmeter in conjunction with its WT-Viewer software, via the

GPIB (General Purpose Interface Bus) communication port. The electrical characteristics evaluated include: Total Apparent Power, Total and Fundamental Active Power, Total Reactive Power, Total and Fundamental Power Factor, Total and Fundamental Voltage, Total and Fundamental Current, as well as the Total Harmonic Distortion of Voltage and Current. All acquired data was saved in Excel Spreadsheets for further analysis and missing variables calculation.

4.2 Calculations

Since the wattmeter does not provide all the variables necessary for the analysis, certain values must be calculated. Using the electrical data obtained for each tested sample, the fundamental apparent power (*Sf*) was calculated based on the fundamental voltages and currents, as shown in equation (10). Subsequently, the fundamental reactive power (*Qf*) was estimated using the calculated fundamental apparent power and the fundamental active power. With the total and fundamental power components, the non-fundamental apparent power (S_N) was estimated according to equation (8).
The distortion powers were calculated using the THD_V and THD_I values. The voltage distortion power (D_V) was determined based on the fundamental apparent power (*Sf*) and the THD_V value, as shown in equation (12). Similarly, the current distortion power (D_I) was estimated using the fundamental apparent power and the THD_I value, as described in equation (13). Finally, the harmonic apparent power (S_H) was calculated using the fundamental apparent power along with the THD_V and THD_I values, as outlined in equation (11).

4.3 Data Validation

Using the estimated values of D_I, D_V, and S_H, the non-fundamental apparent power (S_{Nc}) was recalculated according to equation (9). The S_N and S_{Nc} values were then compared to validate the analysis within IEEE's harmonic measurements standards, with the percentage difference between them presented in Table 9. The comparison revealed that the error was above the acceptable threshold, exceeding 10% in most cases (highlighted in red). For instance, in Model B, the error reached 67% when tested on a 127V power grid. In all observed cases, the difference between the values increased significantly when the samples were tested on the power grid.
However, it was noted that the wattmeter used has a measurement limit for total harmonic distortion, being capable of measuring up to the 50th harmonic order (3000Hz). Consequently, if the tested samples contain harmonic content with significant amplitude at frequencies beyond the equipment's capacity, the use of the provided THD values may account for the observed errors.
To investigate this potential issue, the total harmonic current distortion (THD_{IC}) was calculated using the total current (*I*) and the fundamental current (I_f), as described in equation (17). Since the difference between the total voltage (*V*) and the fundamental voltage (V_f) was not greater than 0.5V in all cases, voltage distortion

did not significantly contribute to the total non-fundamental apparent power. Therefore, THD_V was not recalculated. Furthermore, D_I and S_H were recalculated, and a new value for S_{Nc} was obtained, which was then compared with S_N, as shown in Table 10. In this case, the errors were significantly smaller, remaining below 10% in all cases. Consequently, THD_{IC} will be the value considered for the analyses presented in this study.

Table 9 – Calculation of error involved.

Model	**Connection Type**	**Nominal Voltage (V)**	**Non-fundamental Apparent Power (S_N) [VA]**	**Non-fundamental Apparent Power (S_{Nc}) [VA]**	**Error (%)**
A	Source	220	9.61	9.42	2.0
		127	6.77	6.70	1.2
	Grid	220	10.38	9.83	5.3
		127	7.40	5.96	19.4
B	Source	220	3.23	2.61	19.3
		127	1.58	1.24	21.7
	Grid	220	5.78	2.69	53.6
		127	4.67	1.54	67.0
C	Source	220	6.94	5.93	14.5
		127	4.61	4.29	7.0
	Grid	220	13.07	6.57	49.7
		127	11.82	4.95	58.1
D	Source	220	6.74	4.96	26.4
		127	3.95	3.47	12.2
	Grid	220	15.27	6.33	58.5
		127	9.76	4.04	58.6
E	Source	220	3.40	2.80	17.5
		127	4.60	4.50	2.3
	Grid	220	10.07	3.35	66.7
		127	7.63	5.04	33.9

Table 10 – Errors involved from the THD_{IC} calculation.

Model	**Connection Type**	**Nominal Voltage (V)**	**Non-fundamental Apparent Power (SN) [VA]**	**Non-fundamental Apparent Power (SNc) [VA]**	**Error (%)**
A	Source	220	9.61	9.62	0.1
		127	6.77	6.78	0.1
	Grid	220	10.38	10.32	0.6
		127	7.40	7.36	0.4
B	Source	220	3.23	3.24	0.4
		127	1.58	1.57	0.2
	Grid	220	5.78	5.83	0.8
		127	4.67	4.73	1.3
C	Source	220	6.94	7.06	1.8
		127	4.61	4.61	0.0
	Grid	220	13.07	13.10	0.2
		127	11.82	11.53	2.4
D	Source	220	6.74	7.13	5.8
		127	3.95	4.00	1.3
	Grid	220	15.27	15.29	0.1
		127	9.76	9.98	2.3
E	Source	220	3.40	3.74	9.9
		127	4.60	4.73	2.9
	Grid	220	10.07	9.93	1.4
		127	7.63	7.64	0.1

4.4 Proposed Analysis

After a preliminary data validation, several assessments between the total and fundamental values were conducted to quantify the influence of harmonic currents on the power quality degradation in the tested lamps. Ratios were calculated between the fundamental and total apparent power, fundamental and total reactive power, fundamental and total active power, fundamental and total current, and fundamental and total power factor. Additionally, the lamp's luminous efficiency was evaluated using three different approaches, calculating the ratio between the luminous flux and the total active power, as well as between the luminous flux and both the fundamental and total apparent power. Since luminous efficiency is expressed in lumens per watt, this comparison aimed to quantify the performance loss due to current harmonics in the device. Finally, by comparing the currents it was possible to estimate the increase in system losses, which was obtained by squaring the ratio between the total and fundamental current.

5. Evaluation

The results presented and analyzed represent the averages of the electrical and photometric characteristics obtained from ten samples of each lamp model. The first part of the analysis focuses on assessing whether the performance of the tested lamp models was influenced by changes in their power supply, with particular attention to their photometric characteristics and energy efficiency. Subsequently, the analysis examines whether the harmonic content affects the luminous efficacy of the tested models.

5.1 Photometric Results

According to Table 11, the power source used does not significantly affect the photometric characteristics or energy efficiency of the lamps, which were calculated based on luminous flux and the total active power demanded. In all cases, the observed variations are considered negligible given the magnitude of the data obtained. Additionally, the photometric results reported comply with the values required by Ordinance No. 69 [10].

Table 11 – Results obtained for efficiency and photometric characteristics.

Model	Connection Type	Nominal Voltage (V)	Flux (lm)	Efficiency (lm/W)	CCT (K)	CRI	R9
A	Source	220	390.11	82.60	6066.70	87.11	31.8
		127	377.35	84.26	6061.90	87.10	31.7
	Grid	220	393.35	84.06	6079.70	87.15	31.9
		127	386.83	86.15	6062.90	87.00	31.3
B	Source	220	705.19	92.31	5899.30	85.59	22.3
		127	700.84	92.78	5897.30	85.56	22.1
	Grid	220	720.57	94.19	5920.80	85.59	22.1
		127	717.41	94.61	5912.70	85.54	22.0
C	Source	220	1315.37	96.60	3012.10	84.14	16.1
		127	1313.12	97.55	3009.20	84.10	16.0
	Grid	220	1343.03	97.82	3020.90	84.11	15.9
		127	1356.12	101.73	3019.30	84.14	16.0
D	Source	220	2398.95	103.61	5957.80	85.76	19.8
		127	2347.14	103.01	5956.80	85.74	19.7
	Grid	220	2491.63	107.89	5974.90	85.73	19.4
		127	2449.37	107.11	5952.60	85.47	18.0
E	Source	220	1866.13	92.69	4019.90	84.27	14.0
		127	1854.68	90.55	4019.80	84.26	14.8
	Grid	220	1867.09	92.53	4017.10	84.30	14.9
		127	1874.04	90.68	4012.70	84.25	14.8

However, an analysis from Table 12 reveals that, while the performance is not significantly affected by the power source when luminous efficiency is calculated using the fundamental apparent power, there is a slight loss of efficiency across all models when reactive power is considered. When luminous efficiency is calculated using the total apparent power, the significant performance loss due to harmonic contributions becomes apparent. In this case, the power supply used has a notable impact on the results, as all models exhibited additional losses when supplied by the local utility. If that criterion were used for luminous efficiency, Model A would not meet the standard.

Table 12 – Results obtained for efficiency analysis.

Model	Connection Type	Nominal Voltage (V)	Efficiency (lm/W) [P]	Efficiency (lm/VA) [Sf]	Efficiency (lm/VA) [S]
A	Source	220	82.60	81.10	36.31
		127	84.26	79.57	45.63
	Grid	220	84.06	82.00	34.39
		127	86.15	82.11	44.11
B	Source	220	92.31	82.50	77.15
		127	92.78	91.56	89.67
	Grid	220	94.19	84.86	70.12
		127	94.61	93.92	80.09
C	Source	220	96.60	87.40	79.31
		127	97.55	96.47	91.36
	Grid	220	97.82	86.41	66.11
		127	101.73	100.84	75.69
D	Source	220	103.61	98.10	94.56
		127	103.01	101.22	99.76
	Grid	220	107.89	101.30	85.92
		127	107.11	104.85	96.58
E	Source	220	92.69	87.23	86.04
		127	90.55	90.02	87.84
	Grid	220	92.53	88.02	79.49
		127	90.68	90.21	84.65

5.2 Electrical Results

In the second part of the analysis, the electrical data were evaluated in pairs: total (S) and fundamental (S_f) apparent power, total (I) and fundamental (I_f) current, total (Q) and fundamental (Qf) reactive power, total (P) and fundamental (P_f) active power, and total (FP) and fundamental (FP_f) power factor. Table 13 presents the values obtained for apparent power. The data demonstrates the impact of harmonic content on increased power consumption across all models, particularly when the samples are connected to the electrical network, where the THD_{IC} is higher.

Table 13 – Results obtained for power analysis.

Model	Connection Type	Nominal Voltage (V)	S (VA)	S_f (VA)	S/S_f	THD_{Ic} (%)
A	Source	220	10.74	4.81	2.23	199.97
		127	8.27	4.74	1.74	142.94
	Grid	220	11.44	4.80	2.38	215.16
		127	8.77	4.71	1.86	156.27
B	Source	220	9.14	8.55	1.07	37.94
		127	7.82	7.65	1.02	20.56
	Grid	220	10.28	8.49	1.21	68.68
		127	8.96	7.64	1.17	61.95
C	Source	220	16.59	15.05	1.10	46.91
		127	14.37	13.61	1.06	33.85
	Grid	220	20.32	15.54	1.31	84.22
		127	17.92	13.45	1.33	85.69
D	Source	220	25.37	24.45	1.04	29.14
		127	23.53	23.19	1.01	17.23
	Grid	220	29.00	24.60	1.18	62.11
		127	25.36	23.36	1.09	42.65
E	Source	220	21.69	21.39	1.01	17.46
		127	21.12	20.60	1.02	22.96
	Grid	220	23.49	21.21	1.11	46.78
		127	22.14	20.77	1.07	36.76

Model A was the most affected, as lamps with active power below 5W do not have a minimum power factor requirement. This lack of a requirement is reflected in the results, with samples from this model showing a power factor below 0.5 when powered at 220V. In contrast, Models D and E, which require a power factor greater than 0.92, were the least susceptible to distortions both from the power source and the power grid. Consequently, when powered by the power source, the increase in power consumption for these models was less than 5%.

Table 14 presents the results related to the current. The data indicates a significant increase in total current compared to the fundamental current, primarily due to the harmonic distortion indicated by the THD_{IC}.

Table 14 – Results obtained for the current analysis.

Model	Connection Type	Nominal Voltage (V)	I (mA)	I_f (mA)	I/I_f	THD_{Ic} (%)
A	Source	220	48.83	21.84	2.24	199.97
		127	65.07	37.30	1.74	142.94
	Grid	220	51.96	21.90	2.37	215.16
		127	69.48	37.45	1.86	156.27
B	Source	220	41.51	38.81	1.07	37.94
		127	61.47	60.21	1.02	20.56
	Grid	220	47.47	39.13	1.21	68.68
		127	71.84	61.07	1.18	61.95
C	Source	220	75.53	68.38	1.10	46.91
		127	113.07	107.10	1.06	33.85
	Grid	220	90.17	68.97	1.31	84.22
		127	135.54	102.92	1.32	85.69
D	Source	220	115.67	111.05	1.04	29.14
		127	185.17	182.48	1.01	17.23
	Grid	220	129.35	109.88	1.18	62.11
		127	197.36	181.54	1.09	42.65
E	Source	220	98.61	97.14	1.02	17.46
		127	166.34	162.12	1.03	22.96
	Grid	220	109.65	99.32	1.10	46.78
		127	179.92	168.87	1.07	36.76

Once again, Model A was the most affected, with the total current more than doubling relative to its fundamental component when powered at 220V. Comparing results between the power source and the network, the fundamental current component remains nearly unchanged across all tested models. However, the total current increased significantly due to the rise in THD_{IC}.

Table 15 presents the results related to reactive power. The data reveals a notable difference between the total and fundamental portions of reactive power in the tested models, especially when powered at 220V. This discrepancy highlights the significant contribution of current harmonics to the substantial increase in total reactive power.

Table 15 – Results obtained for reactive power analysis.

Model	Connection Type	Nominal Voltage (V)	Q (var)	Q_f (var)	Q/Q_f	THD_{Ic} (%)
A	Source	220	9.65	0.94	10.22	199.97
		127	6.96	1.54	4.51	142.94
	Grid	220	10.42	1.05	9.90	215.16
		127	7.50	1.36	5.50	156.27
B	Source	220	5.02	3.81	1.32	37.94
		127	2.01	1.25	1.61	20.56
	Grid	220	6.85	3.68	1.86	68.68
		127	4.79	1.21	3.96	61.95
C	Source	220	9.51	6.51	1.46	46.91
		127	5.04	1.98	2.54	33.85
	Grid	220	14.96	7.27	2.06	84.22
		127	11.66	2.08	5.61	85.69
D	Source	220	9.94	7.45	1.33	29.14
		127	4.76	2.56	1.86	17.23
	Grid	220	17.13	7.43	2.30	62.11
		127	9.72	2.71	3.59	42.65
E	Source	220	8.16	7.00	1.17	17.46
		127	5.20	2.10	2.48	22.96
	Grid	220	11.97	6.58	1.82	46.78
		127	7.92	1.83	4.34	36.76

Model A exhibited the greatest discrepancy, which can be attributed to its low power factor. Other models also showed sensitivity to harmonic content, despite having a minimum power factor requirement. Notably, except for Model A, the Q/Q_f ratio was higher at 127V, indicating that these models are more susceptible to harmonic distortions at this voltage, despite having lower reactive power consumption.

Table 16 presents the results related to active power. In contrast, compared to other electrical characteristics, active power remained largely unchanged across all cases, with no significant difference between the total and fundamental portions, despite the presence of harmonic content in the tested models. Furthermore, neither the supply voltage nor the power source significantly affected consumption, which remained consistent for all tested models.

Table 16 – Results obtained for active power analysis.

Model	Connection Type	Nominal Voltage (V)	P (W)	P_f (W)	P/P_f	THD_{Ic} (%)
A	Source	220	4.724	4.716	1.002	199.97
		127	4.480	4.485	0.999	142.94
	Grid	220	4.681	4.680	1.000	215.16
		127	4.493	4.509	0.996	156.27
B	Source	220	7.639	7.653	0.998	37.94
		127	7.554	7.551	1.000	20.56
	Grid	220	7.651	7.652	1.000	68.68
		127	7.584	7.541	1.006	61.95
C	Source	220	13.617	13.568	1.004	46.91
		127	13.461	13.467	1.000	33.85
	Grid	220	13.732	13.733	1.000	84.22
		127	13.332	13.285	1.004	85.69
D	Source	220	23.389	23.292	1.004	29.14
		127	23.039	23.046	1.000	17.23
	Grid	220	23.344	23.441	0.996	62.11
		127	23.122	23.200	0.997	42.65
E	Source	220	20.133	20.215	0.996	17.46
		127	20.483	20.495	0.999	22.96
	Grid	220	20.181	20.166	1.001	46.78
		127	20.666	20.693	0.999	36.76

Table 17 presents the results related to the power factor of the tested models. The data indicates that current harmonic distortion directly contributes to the deterioration in sample quality, as all models exhibit a power factor greater than 0.9 when considering only the fundamental spectrum. It is noteworthy that this parameter is influenced by the supply voltage but not by the power source. However, when evaluating the total power factor, both the supply voltage and the power source have a significant impact on its value.

Table 17 – Results obtained for power factor analysis.

Model	Connection Type	Nominal Voltage (V)	FP	FP_f	FP/FP_f	THD_{Ic} (%)
A	Source	220	0.44	0.98	0.45	199.97
		127	0.54	0.95	0.57	142.94
	Grid	220	0.41	0.98	0.42	215.16
		127	0.51	0.96	0.54	156.27
B	Source	220	0.84	0.90	0.93	37.94
		127	0.97	0.99	0.98	20.56
	Grid	220	0.74	0.90	0.82	68.68
		127	0.84	0.99	0.86	61.95
C	Source	220	0.82	0.90	0.91	46.91
		127	0.94	0.99	0.95	33.85
	Grid	220	0.68	0.88	0.76	84.22
		127	0.75	0.99	0.76	85.69
D	Source	220	0.92	0.95	0.97	29.14
		127	0.98	0.99	0.99	17.23
	Grid	220	0.81	0.95	0.85	62.11
		127	0.91	0.99	0.92	42.65
E	Source	220	0.93	0.94	0.98	17.46
		127	0.97	0.99	0.97	22.96
	Grid	220	0.86	0.95	0.91	46.78
		127	0.93	1.00	0.94	36.76

In this case, the results obtained using the power source, for all models and at both supply voltages, are within the limits required by Ordinance No. 69 [10]. However, when powered directly from the grid, models B, C, and E appear to be non-compliant, as the observed power factor falls below the minimum required limits (marked in red). This non-compliance is attributed to an increase in reactive energy consumption due to harmonic distortions in the current.

5.3 Distortion Power Results

In the third part of the critical analysis of the obtained results, the contributions of voltage distortion power (D_V), current distortion power (D_I), and harmonic apparent power (S_H) to the non-fundamental total power (S_{Nc}) demanded by the tested models will be evaluated. Table 18 presents the results of this analysis. Given that the total harmonic distortion of current is significantly higher than that of voltage, it becomes evident that, regardless of the power source or supply voltage used, the current distortion power accounts for nearly the entire non-fundamental apparent power in all tested models (marked in blue), with the contributions of the other two components not contributing significantly.

Table 18 – Results obtained for distortion power analysis.

Model	Connection Type	Nominal Voltage (V)	D_V (var)	D_I (var)	S_H (VA)	S_{Nc} (VA)	THD_V (%)	THD_{Ic} (%)
A	Source	220	0.01	**9.62**	0.01	**9.62**	0.11	199.97
		127	0.01	**6.78**	0.01	**6.78**	0.18	142.94
	Grid	220	0.06	**10.32**	0.14	**10.32**	1.34	215.16
		127	0.07	**7.36**	0.10	**7.36**	1.39	156.27
B	Source	220	0.01	**3.24**	0.00	**3.24**	0.08	37.94
		127	0.01	**1.57**	0.00	**1.57**	0.16	20.56
	Grid	220	0.10	**5.83**	0.07	**5.83**	1.23	68.68
		127	0.10	**4.73**	0.06	**4.73**	1.30	61.95
C	Source	220	0.02	**7.06**	0.01	**7.06**	0.11	46.91
		127	0.03	**4.61**	0.01	**4.61**	0.21	33.85
	Grid	220	0.38	**13.09**	0.32	**13.10**	2.45	84.22
		127	0.34	**11.52**	0.29	**11.53**	2.52	85.69
D	Source	220	0.03	**7.13**	0.01	**7.13**	0.13	29.14
		127	0.05	**4.00**	0.01	**4.00**	0.21	17.23
	Grid	220	0.52	**15.28**	0.33	**15.29**	2.13	62.11
		127	0.48	**9.96**	0.20	**9.98**	2.04	42.65
E	Source	220	0.02	**3.74**	0.00	**3.74**	0.09	17.46
		127	0.03	**4.73**	0.01	**4.73**	0.17	22.96
	Grid	220	0.27	**9.92**	0.13	**9.93**	1.26	46.78
		127	0.27	**7.64**	0.10	**7.64**	1.30	36.76

5.4 Assessment of Losses

In the final part of the analysis, the losses in the tested models will be evaluated considering the increase in current due to the presence of harmonic content, as presented in Table 14. Figure 1 presents the results of the analysis of losses caused by harmonic distortions. The impact of harmonic distortions on the increase in losses in the tested models is evident, particularly when powered by the electrical grid, where both voltage and current distortion indices are higher. Additionally, the losses are greater when the lamps are powered at 220V. This outcome is consistent with previous findings, which showed that reactive power is higher at this voltage, leading to an increase in the total current consumption. Regarding the influence of harmonic distortions, a similar behavior was observed by M. J. Ghorbani et al. [14], whose findings demonstrated an increase in resistive losses and heating of conductors caused by harmonic currents in distribution networks.

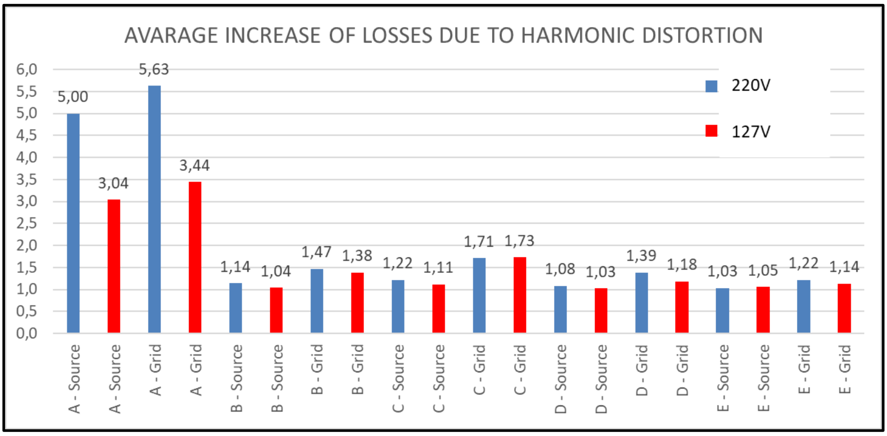

Figure 1 – Average increase in losses due to harmonic distortions.

The most critical case is observed, once again, in model A, where the high harmonic distortion in the current leads to losses that can be up to 5.63 times greater when comparing the fundamental current to the total current consumed. It is important to note that this model does not have a minimum power factor requirement. Conversely, when such a limit is imposed, as demonstrated by the other models, the losses are significantly reduced.

6. Conclusion

Based on the results obtained and subsequent analysis, not requiring a minimum power factor is extremely detrimental to power quality, as model A exhibited the worst performance in all cases analyzed. Conversely, when models comply with the requirements of INMETRO Ordinance No. 69, although they remain sensitive to the effects of harmonic content, the potential for performance degradation and loss of quality is significantly reduced. Models D and E, which are considered to have a high-power factor, better exemplify this improved behavior.

It was found that distortion powers directly influence the apparent power of the models, with current distortion power being almost entirely responsible for the increase in non-fundamental apparent power and, consequently, the total apparent power demanded by the lamp. Since the active power values remained unchanged regardless of the distortion indices observed, the increase appears to manifest as reactive energy, thereby raising the effective values in the system and, consequently, the potential for losses.

Another point to highlight is that the photometric characteristics were not significantly affected by the distortion, remaining unchanged regardless of the voltage and power supply used. However, if the total apparent power were used to calculate luminous efficiency, there would be a considerable loss in performance due to the influence of harmonic distortion. Additionally, the voltage and power supply have a direct impact on the lamps' performance.

Finally, the direct influence of current harmonic distortion on increasing losses in all analyzed models, particularly when connected to the power grid, is evident. This underscores the importance of regulations that limit these values, ensuring that these devices exhibit a predominantly fundamental profile, which ultimately reduces losses caused by harmonic currents in the system.

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References

[1] M. M. Cattaneo, R. S. Pacheco, and T. Chinazzo, "Harmonic analysis in LED lamps available in Brazil," Universidade Tecnológica Federal do Paraná, Brazil, 2017.

[2] D. W. Hart, **Power Electronics – Circuit Analysis and Design**, 1st ed. Porto Alegre, Brazil: Bookman, 2012.

[3] A. M. P. Estrela, M. Z. Fortes, A. P. Fragoso et al., "Power quality in LED lamps – Comparison in their usual voltages 127 and 220V," in **Proc. XI Conf. Bras. Qual. Energia Elétrica (CBQEE),** 2015. doi: 10.13140/RG.2.1.3607.7284.

[4] B. G. Serdeira, **Harmonic Currents in LED Devices – Loss and Photometric Characteristics Analysis**. Niterói, Brazil: Universidade Federal Fluminense, 2021.

[5] V. Grosu, E. David, L. Goras, and G. Pelz, "On the Modelling Possibilities of Integrated Circuits Behavior Using Active Learning Principles," **Romanian Journal of Information Science and Technology,** vol. 27, no. 2, pp. 183–195, 2024.

[6] M. Davidovic et al., "Voltage distortion in LED street lighting installations," **Electrical Engineering**, 2021.

[7] P. Holcsik, J. Pálfi, Z. Čonka, and I. B. Kocsis, "Fault point location method, based on harmonics analysis of a distribution system," **Acta Polytechnica Hungarica,** vol. 19, no. 4, pp. 147–164, 2022.

[8] Y. Han, J. Hou, Z. Ma et al., "Control strategies, robustness analysis, digital simulation and practical implementation for a hybrid APF with a resonant AC-link," **Acta Polytechnica Hungarica**, vol. 7, no. 5, pp. 81–99, 2010.

[9] IEEE, **Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions**, IEEE Std 1459-2010, 2010.

[10] **INMETRO**. Portaria nº 69, de 16 de fevereiro de 2022. Aprova o Regulamento Técnico da Qualidade e os Requisitos de Avaliação da Conformidade para Lâmpadas LED com Dispositivo de Controle Integrado à Base – Consolidado. Rio de Janeiro: Inmetro, 2022.

[11] IEC, **IEC 61000-3-2 Electromagnetic Compatibility (EMC) – Part 3-2: Limits – Limits for Harmonic Current Emissions (Equipment Input Current ≤ 16 A per Phase),** Geneva, Switzerland, 2001.

[12] R. Laufer and L. F. D. M. Vieira, "Procedimento de medição de corrente harmônica segundo a norma IEC 61000-3-2 em produtos eletroeletrônicos," in **Proc. 37° Congresso Brasileiro de Engenharia Elétrica (COBEE)**, 2022.

[13] S. Buso and P. Mattavelli, **Digital Control in Power Electronics**. Oxford, UK: Elsevier, 2006.

[14] M. J. Ghorbani and H. Mokhtari, “Impact of Harmonics on Power Quality and Losses in Power Distribution Systems,” **International Journal of Electrical and Computer Engineering (IJECE),** vol. 5, no. 1, pp. 166–174, Feb. 2015.