# Differences in the performance between CFL and LED lamps under different voltage distortions

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***Abstract*—Measurements have shown that the harmonic currents emitted by lamps with electronic ballast depend on the circuit topology and the existing supply voltage distortion. This paper quantifies the impact of supply voltage distortion on the harmonic and supraharmonic current emission of individual Light Emitting Diode (LED) lamps and compact fluorescent lamps (CFL). It also characterizes several Power Quality (PQ) parameters when those lamps are connected to pure sinusoidal waveform.**

***Index Terms*—CFL; harmonics; LED lamps; power quality; THDi; supraharmonics; voltage distortion.**

## I. Introduction

Lighting accounts for 19% of electricity consumption worldwide and 14% in the European Union [1]. According to UK data [2], 55% of the lamps used in domestic installations in 2014 were compact fluorescent lamps (CFLs) or light emitting diode (LED) lamps, while 40% were halogen. LED lamps offer a reduction in the energy use with savings of 75–80% in terms of energy consumption compared to incandescent lamps [3].

It has been shown in references [4], [5], [6], that LED lamps presently on the market show a large variety of harmonic emission and displacement power factor, but also emission in the frequency range 2 to 150 kHz (also referred to as 'Supraharmonics' in the literature), mainly due to different topologies in LED drivers [7]. Such frequencies originate from the power-electronic converters, which are present in many of the household equipment, as in lighting equipment [8], [9].

The ideal low voltage single phase supply in Europe is 230 Vrms at a frequency of 50 Hz and with a sinusoidal waveshape. The actual supply voltage usually deviates from the ideal sinewave showing harmonic distortion and a magnitude lower or higher than 230 Vrms.

The effect of supply voltage distortion on the harmonic current emission of non-linear loads has e.g. been considered in [10], [11], where the impact of voltage distortion on the summation of multiple devices is analyzed and the accuracy of constant current source models is evaluated.

This paper investigates the effect of supply voltage distortion on the PQ performance of CFL and LED lamps, including the supraharmonic range. The paper is divided in 6 sections. Section II describes the measurement procedure with the description of the measurement setup. Section III considers some power quality parameters of the lamps under sinusoidal conditions, including low and high frequency analysis. The results are presented in Sections IV and V, where the impact of different voltage distortions on the lamps is studied both in low and high frequency. Section VI presents a discussion of the results providing some concluding remarks.

## II. Measurement Procedure

The data used for this paper is available in PANDA (equiPment hArmoNic DAtabase), a global web-based platform for exchanging harmonic emission measurements from all types of household equipment (single-phase) between different laboratories around the world (http://www.panda.et.tu-dresden.de) [12]. For this analysis, only data measured at IEEH (Institute of Electrical Power Systems and High Voltage Engineering of the Technische Universität Dresden) has been considered, in order to guarantee that all the lamps were measured under the same conditions. Two linear amplifiers have been used. Data measured before 2016 corresponds to measurements made with a 2.5 kVA amplifier, while lamps measured in 2016 were connected to a 15 kVA amplifier. The amplifiers were compared in [13], showing that both amplifiers are adequate for the characterization of low frequency emission.

Measurements made with a sinusoidal voltage and two distorted voltage waveforms were selected for the analysis. The distorted voltage waveforms correspond to a flat-top curve (THDv ~ 3%) and a pointed-top (also known as overswing in IEC 61000-4-13 [14]) curve (THDv ~4%), as shown in Fig. 1. These voltage distortions were selected because almost all residential LV grids show a more or less distinctive "flat-top voltage" that is caused by massive use of single-phase rectifiers, while industrial grids often have a "pointed-top voltage" generated by massive use of six-pulse rectifiers. For reference, the first odd harmonics used for the measurements are shown in Table I.

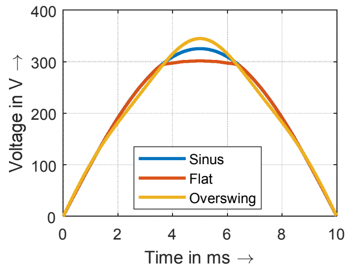


Figure 1. Voltage waveforms

TABLE I. HARMONIC CONTENT DISTORTED VOLTAGE WAVEFORMS

| | Flat-top | | Pointed-top | |
|---|---|---|---|---|
| h | \|V\| | φ | \|V\| | φ |
| 1 | 224 | 0 | 230 | 0 |
| 3 | 5.3 | 0 | 6.9 | 180 |
| 5 | 3.7 | 180 | 6.9 | 0 |
| 7 | 1.9 | 0 | 0 | 0 |
| 9 | 0.5 | 180 | 0 | 0 |

Although two amplifiers were used, comparison is possible as every individual lamp was connected to the same amplifier under different supply voltage conditions, therefore the impact will be the same on every lamp. The current waveform from the lamps under these conditions has been measured over at least 2 cycles after the Irms variation was less than 0.1 mA, which has been the criteria to get an almost constant emission. The spectrum over this window was calculated with the use of the Discrete Fourier Transform (DFT). The sampling rate for all measurements is at least 1 MSamples/s.

The total power factor (TPF) and the displacement power factor (DPF) at fundamental frequency have been calculated for all lamps used in the experiment.

$$DPF = cos\varphi_1 = \frac{P_1}{S_1} \quad (1)$$

The TPF includes the harmonic part of the active and apparent power as defined in IEEE 1459-2000 [15].

$$TPF = \frac{P}{S} = \frac{P}{\sqrt{\sum U_n^2} * \sqrt{\sum I_n^2}} \quad (2)$$

For the harmonic analysis, the total harmonic distortion of the current (THDi), was calculated from the harmonic components of order 2 till 40. The THDi was expressed as a percentage of the fundamental component (%FND). Also, the Total Harmonic Current (THC) as it is defined in IEC 61000-3-2 [16], and the Total Harmonic Distortion expressed as a percentage of the reference current (THDIr) were calculated. The reference current has been calculated from the rated active power of the lamp stated by the manufacturer and the rated voltage (230 V).

For the higher frequency analysis, the spectral components were grouped in 200 Hz bands according to the IEC 61000-4-7 [17]. To facilitate the analysis, different frequency bands have been considered 9-30 kHz, 30-95 kHz and 95-150 kHz. For them, some indices in the frequency domain proposed in [14] have been used. In this case, the maximum component (magnitude and frequency), the Total Supraharmonic Current (TSHC) and the Total Supraharmonic Distortion expressed as a percentage of the reference current (TSHD_Ir) were calculated for each frequency band. The TSHC and TSHD_Ir are defined as:

$$TSHC = \sqrt{\sum_{i=1}^{740} I_i^2} \quad (3)$$

$$TSHD\_I_r = \sqrt{\frac{\sum_{i=1}^{740} I_i^2}{I_r}} = \sqrt{\sum_{i=1}^{740} I_i^2 \frac{U_n}{P_r}} \quad (4)$$

where $i$ is the index of the 200 Hz frequency band starting at 2 kHz, $I$ is the magnitude of the current at the corresponding frequency band, $Ir$ is the reference current, $Pr$ is the rated active power and $Un$ is the rated voltage (230 V) of the lamp.

## III. LAMP CHARACTERIZATION UNDER SINUSOIDAL CONDITIONS

The basis for the analysis in this paper is a set of 142 lamps (69 CFL and 73 LED lamps) from different rated powers (CFL up to 46 W, and LED lamps up to 17 W) and manufactured from 2009-2016.

The THDi, THDIr and THC of the lamps under sinusoidal conditions are represented with box and whiskers plots in Fig. 2, showing quartiles, and the mean (cross). The 'whiskers' indicate variability outside the upper and lower quartiles, and any point outside those lines is considered an outlier (removed here from the figure).

Although the THDi average value is similar between CFL and LED lamps, the spread in values is higher for LED lamps, One reason is the larger diversity in the circuit topology. It is important to notice that LED lamps have a lower active power (between 1 W and 10 W) compared to CFLs, which results in a lower fundamental current and, in case of similar harmonic current magnitudes in higher THDi. Therefore, in this case it is more convenient to compare the THDIr and the THC. According to the figures, the average value of the THDIr is slightly higher for LED lamps than CFLs, but there are even LED lamps with very high distortion with THDIr higher than 200%. Contrary to THDi, the average THC value in LED lamps is two times lower than for CFL, and it shows lower spread.

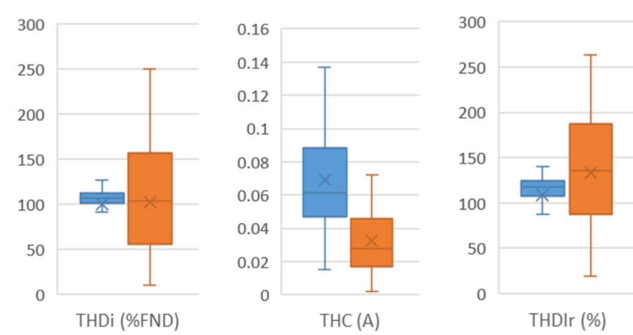


Figure 2. THDi, THC and THDIr for CFL (blue) and LED lamps (orange).

Regarding TPF and DPF, the average values of CFL and LED lamps are similar, as shown in Fig. 3. However, LED lamps reach lower values for both TPF and DPF. The minimum TPF is 0.5 for CFL, and 0.1 for LED lamps (they are outliers and are not included in the plot), mainly due to the lack of standards for LED lamps.

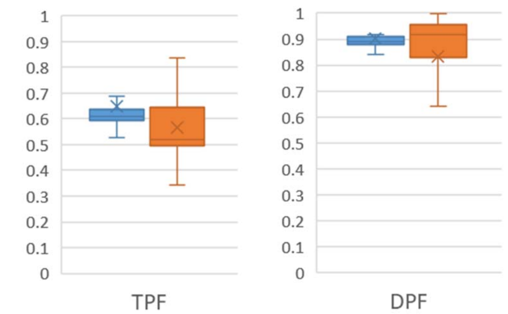


Figure 3. TPF and DPF for CFL (blue) and LED lamps (orange).

## A. *Low frequency study*

Fig. 4 shows the relation between DPF and TPF for CFL and LED lamps and sinusoidal voltage, which can be divided into three areas. All lamps with DPF below 0.7 (region ‘a’ in Fig. 4) (19%) are LED lamps, mostly bought in 2016. Active power is usually below 5 W and THDi is in the range from 40-70%.

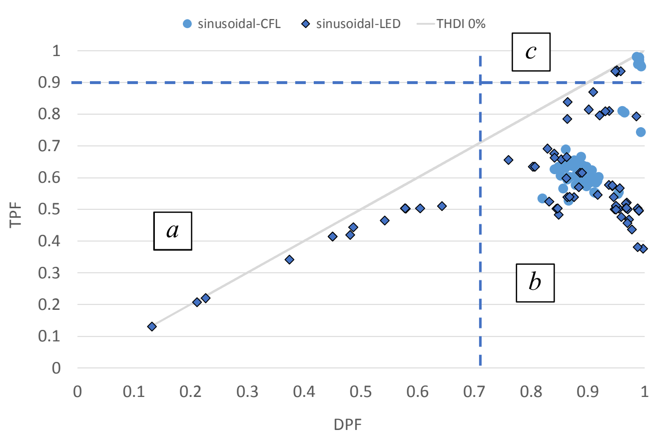


Figure 4. DPF vs TPF for CFL (circles) and LED lamps (diamonds) with sinusoidal voltage. Grey line for THDI 0%.

Fig. 5 shows the typical current and voltage waveforms of those LED lamps which corresponds usually to a capacitive-divider topology.

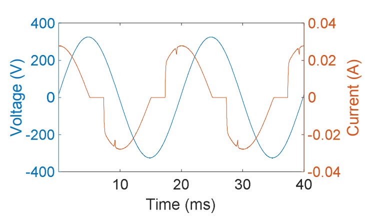


Figure 5. Current and voltage waveforms of LED lamps with DPF<0.7.

LED lamps with DPF higher than 0.7 can be divided in two groups. The first group (region ‘b’ in Fig. 5) corresponds dominantly to lamps containing a diode bridge rectifier without PFC (no-PFC) (THDi ranging from 50-250 %). An example waveform is shown in Fig. 6a. The third group (region ‘c’ in Fig. 5) with TPF > 0.9 corresponds in most cases to lamps with active-PFC topologies. THDi is usually below 50%. An example waveform is shown in Fig. 6b. For more details about topologies, please consult reference [8].

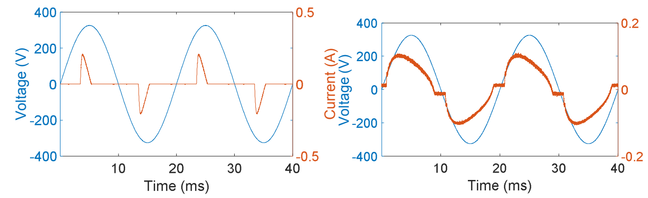


Figure 6. Current and voltage waveforms of LED lamps with DPF>0.9 and TPF 0.93 (right) and TPF 0.5 (left).

The CFLs in region ‘c’ have a rated active power higher than 25 W, which require according to IEC 61000-3-2 [16] an active power factor correction circuit in order to meet the specified limits.

Fig. 7 shows the TPF vs. the THDi (% of FND) including the separation line introduced in Figure 4. Two different branches are observed in the region with TPF below 0.7 (regions ‘a’ and ‘b’). The main one shows a decrease in the THDi with increasing the TPF. This branch is mainly composed of CFL and LED lamps with no-PFC topology. The other branch, where the TPF increases with the THDi, is mainly composed of LED lamps below 5 W with capacitive-divider topology. Finally, the group of lamps with TPF higher than 0.9 and low THDi corresponds to lamps with active PFC topology (region ‘c’).

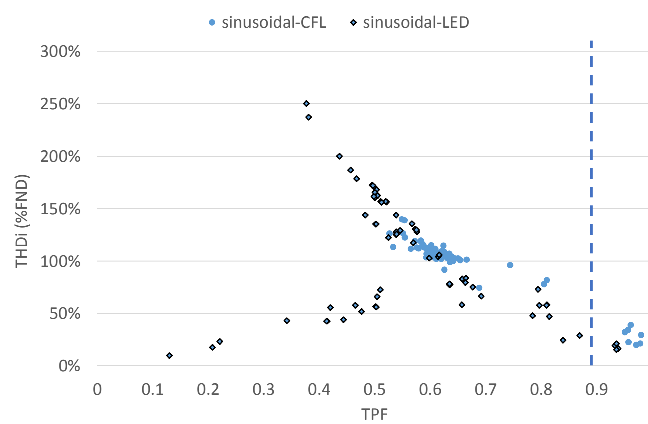


Figure 7. TPF vs THDi (%FND) for CFL (circles) and LED lamps (diamonds) with sinusoidal voltage.

## B. *High Frequency Study*

This section analyses lamps with a significant signal to noise ratio at frequencies higher than 2 kHz (emission magnitude greater than 25 µA). The current drawn by each of the lamps contains primary and secondary emission [18]. The primary emission is the emission caused by the lamp itself. The secondary emission is the emission seen by a lamp coming from nearby devices. In this measurement dataset, no other equipment was connected apart from the lamps, but the power amplifiers used to generate the voltage have a certain background emission in this frequency range. Consequently, the lamp can draw current at these frequencies since most of this equipment contains a capacitor on the input side (secondary emission). Because two different amplifiers have been used, different secondary emission applies to lamps before and after 2016. However, as it was stated in the previous section, the aim of the paper is to compare the behavior of the lamps under different voltage distortions, and for the same lamp, the different voltages were applied with the same amplifier, i.e. the lamps are subjected to the same secondary emission for the tests with sinusoidal, flat-top and pointed-top voltages.

Measurements done seven years after the work in [19], still confirm that it is not possible to use standard supraharmonic models for LED lamps, as each device appears to be unique. From the whole set of LED lamps overall three groups can be observed. Group I is formed by lamps with emission only in the frequency range. In the sample, 22% of LED lamps and no CFL are within this group. Fig. 8 shows a LED example from Group I. It includes the typical STFT (Short Time Fourier Transform) of the current to the left, and the FFT of the current to the right.

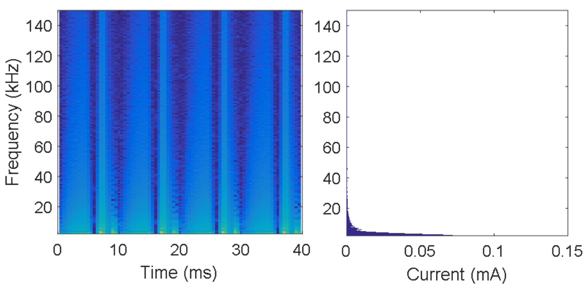


Figure 8. Group I. STFT (left) and FFT (right) of the current.

This spectrum is typically seen in LED lamps that have no switching component corresponding to a capacitive-divider topology. Therefore, this group is not further analyzed in this paper.

The second group is formed by lamps with a high frequency spectrum mainly characterized by the switching frequency of the driver and its harmonics. This is the type of spectrum seen in all CFL, and in 39.7% of LED lamps. This spectrum will be of interest in this paper as the observable change in the switching frequency when feeding with different voltage waveforms can be discussed. Fig. 10 shows a LED lamp from Group II. Broadband components are seen from 35-55 kHz, as well as recurrent oscillations are seen below 9 kHz.

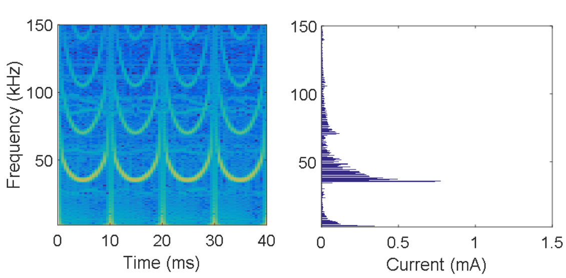


Figure 9. Group II. STFT (left) and FFT (right) of the current.

Finally, the third group contains lamps with a high frequency emission basically dominated by secondary emission coming from the amplifier. As example, Fig. 11 shows the obtained spectrum for one of these lamps, where clearly only the high-frequency emission of the amplifier is visible. The remaining 38.3% of LED lamps are within this group, and they are all measured in 2016, i.e. with the 15 kVA amplifier. Some of the lamps are pure capacitive (with TPF around 0.1), but there are other LED lamps in this group with higher TPF (close to 0.9) that also behave as a capacitor taking the distortion of the power source at their terminals. As the switching frequency component is not clearly visible, this group is also excluded from the further analysis.

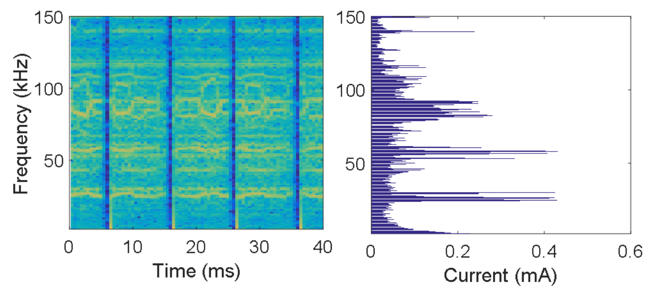


Figure 10. Group III. STFT (left) and FFT (right) of the current.

The characterization of the high-frequency emission is very difficult, as it is highly influenced by the power source, the measurement equipment, and the load itself, as the topology, more concretely the electronic components will cause that secondary or primary emission is seen at the terminal of the lamp at the same time. More precisely, the impedance relation between the amplifier and the lamp is what determines the secondary emission. Future work is therefore needed to identify the secondary emission and how to keep it as low as possible in order to measure only the primary emission.

## IV. Low Frequency Comparison between Different Voltage Distortions

Table II shows the percentage of lamps that show an increase in different parameters when the supply voltage waveform changes from sinusoidal to flat-top and pointed-top. If more than 55% of the measured lamps show an increase, the cell appears in grey color. All the dataset of lamps has been considered for this low frequency study.

TABLE II. Percentage of Lamps Showing Increase in Low Frequency Parameters Under Different Voltage Distortions

| | | flat vs sinusoidal (%) | | pointed vs sinusoidal (%) | |
|---|---|---|---|---|---|
| | | CFL | LED | CFL | LED |
| | TPF | 5.8 | 23 | 4 | 31 |
| | DPF | 3 | 16 | 97 | 93 |
| | H1 | 4 | 62 | 7 | 30 |
| | H3 | 1 | 58 | 90 | 45 |
| | H5 | 28 | 43 | 99 | 78 |
| | H7 | 87 | 51 | 99 | 81 |
| 0-2 kHz | THDi | 90 | 74 | 100 | 81 |
| | THCi | 51 | 86 | 100 | 77 |
| | THDIr | 51 | 86 | 100 | 77 |

The behavior between different parameters is not equal for all the lamps, nor even equal among a technology. For example, the TPF mostly decreases for CFL and LED lamps when subjected to different voltage distortions. The DPF mostly shows a decrease in both types of lamp technologies when connected to flat-top (compared to sinusoidal), but an increase when connected to pointed-top (compare to sinusoidal).

Regarding harmonics, the third current harmonic shows different behavior between technologies (Fig. 12 shows the average and quartile values, not including the outliers). With flat-top voltage waveform, the third current harmonic decreases in almost every measured CFL compared with sinusoidal voltage, while increases in more than half of LED lamps. However, with a pointed-top voltage waveform, the third current harmonic increases in almost every measured CFL compared with sinusoidal voltage, while increases in less than half of LED lamps (as shown in Table II) and with lower average increase (seen in Fig. 12). Therefore, the tendency (decreasing with flat-top and increasing with pointed-top) appears to be in CFL while not in LED lamps.

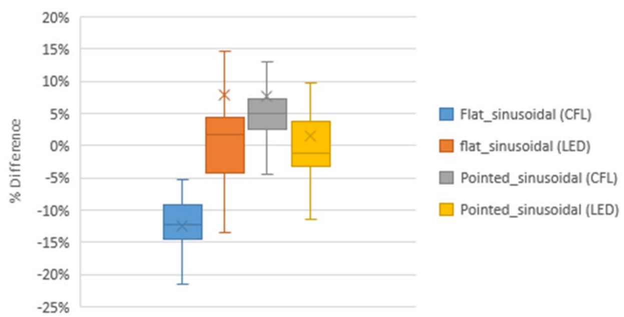


Figure 11. Variation in third harmonic current magnitude between flat-top and pointed-top compared with sinusoidal.

A similar behavior between technologies is observed for the fifth current harmonic when connected to flat-top and pointed-top voltage waveforms. In this case, the fifth harmonic decreases with a flat-top waveform, while it increases with a pointed-top waveform in most of the lamps.

Table II also shows that the THDi increases in most of the lamps, independent of the technology or the type of distorted waveform. The increase of the THDi has an average of 4% for CFLs and 7.39% for LEDs with flat-top waveform. In case of pointed-top voltage waveform, in average the THDi increases 20% for CFLs and 11.11% for LEDs.

However, the THDIr is influenced by the technology. Table II shows that for half of the CFL lamps and almost 90% of the LED lamps an increase is seen when connected to flat-top compared to sinusoidal. Therefore, although there is a large diversity in topology used in LED lamps, almost 90% of increase in this kind of lamps can be considered to represent the whole sample, however, if only 51% increase as happens in CFL, it cannot be concluded anything about them. On the other hand, 100% of the CFL lamps increased it when connected to pointed-top compared to sinusoidal, while 77% also increases in LED lamps, but with lower average increase.

To better appreciate the dependency of THDIr with the technology and the voltage distortion, Fig. 13 shows the difference in THDIr (expressed in percentage of the reference current) for different DPF ranges (below 0.7, from 0.7 to 0.9, and above 0.9) when lamps are fed with flat-top compared to sinusoidal voltage waveform. Lamps to the left of the dashed line are CFL, while lamps to the right are LED lamps.

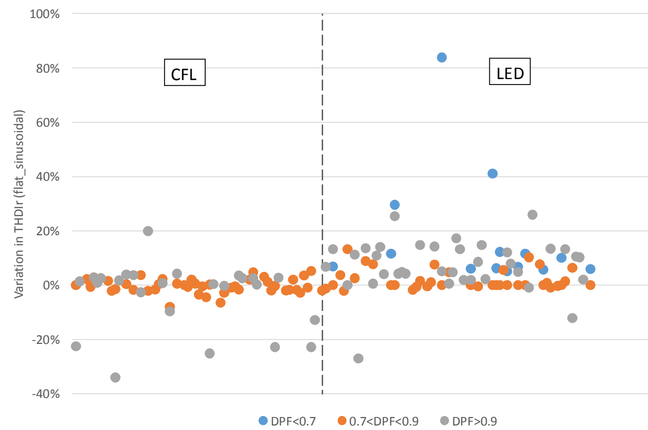


Figure 12. Variation in THDIr (flat-top vs sinusoidal) for different DPF. (CFL to the left and LED lamps to the right of the vertical dashed line)

CFL with DPF below 0.9 has an average decrease of 0.31% (56.8% of CFL in this group decrease when flat-top compared to sinusoidal), while all the LED lamps with DPF below 0.7 show an increase in the THDIr (average increase of 17.34%), with DPF between 0.7 and 0.9 shows an average increase of 3.52 (68% of LED lamps in this group increase when flat-top compared to sinusoidal).

CFL with DPF above 0.9 has an average decrease of 3.91% (36% of CFL in this group decrease when flat-top compared to sinusoidal), while LED lamps show an overall increase of 7.38% (92% of LED lamps in this group increase when flat-top compared to sinusoidal).

In the case of pointed-top compared to sinusoidal voltage (not shown here), the percentages are higher both in CFL and LED lamps. CFL with DPF below 0.9 has an average increase of 9.15% (within this group, all CFL increase when pointed-top compared to sinusoidal), while LED lamps with DPF below 0.7 show an overall decrease of 4.68% and LED lamps with DPF between 0.7 and 0.9 also show an increase (average increase of 7.96%) (82% of LED lamps in this group increase when pointed-top compared to sinusoidal).

## V. High Frequency Comparison between Different Voltage Distortions

As mentioned in section III.B only lamps belonging to group II are analyzed with respect to their change in primary emission depending on different supply voltage distortions. Several measurements with different amplifiers have been done in order to clearly validate results.

As the main emission of lamps in group II is located in the frequency band 30-95 kHz, only this has been calculated for sinusoidal, flat-top and pointed-top voltage waveforms. As it can be seen from a certain set of LED lamps, the TSHC in this range decreases when the lamp is connected to a flat-top voltage compared to the sinusoidal waveform. Contrary it increases when connected to pointed-top compared to sinusoidal voltage waveform.

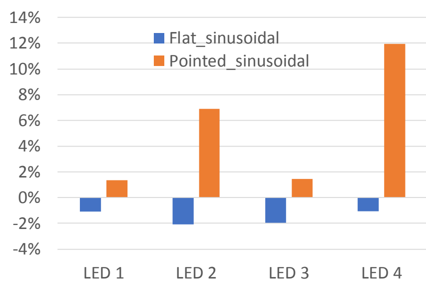


Figure 13. Variation in TSHC (30-95 kHz) between flat-top and pointed-top compared with sinusoidal.

Consequently, the supply voltage distortion can also considerably affect the supraharmonic emission of lamps with electronic ballast.

## VI. Conclusion

The investigation on a large set of lamps, both CFLs and LED lamps shows that there is a difference in emission behavior not only between the two types of lamps but also within the same type. The impact of supply voltage distortion has been investigated and the conclusion is that most lamps are affected but the level of influence varies between lamps. For example, in the low frequency band, parameters as DPF, TPF, and individual current harmonics mostly decrease their values for CFLs connected to flat-top and increase when connected to pointed-top. However, LED lamps do not show the same behavior, and as there is nearly 50% of lamps showing an increase, no clear conclusion can be drawn from that.

Three groups of lamps have been identified based on their supraharmonic emission characteristic. The three different groups have been linked to the topology used within the lamp. All CFLs measured belong to the same group whereas LEDs are somewhat equally spread over the groups. The circuit topology presents in group III causes the secondary emission to dominate the measurements; so that an evaluation of the primary emission is not possible. More research is needed in this case. From a limited number of LED lamps belonging of group II it has been observed that the TSHC within the frequency 30 to 95 kHz decreases when flat-top compared to sinusoidal, whereas increases when pointed-top compared to sinusoidal. It is recommended to extend the study to include other lamps.

The results of this paper can also contribute to discussions to review the (sinusoidal) testing conditions that are exclusively applied nowadays according to IEC 61000-3-2, but which might be not realistic anymore for novel device technologies.

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