LED street lighting: A power quality comparison among street light technologies

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High-pressure sodium lamps are currently the main lamps used in public lighting. However, the possibility of using high-power light emitting diode (LEDs) for street lighting is growing continuously due to their greater energy efficiency, robustness, long life and light control. The aim of this paper is to study the power quality of high-power lighting networks based on LED and high-pressure sodium lamps. Both electromagnetic and dimmable electronic ballasts, which can dim the lamp output smoothly and uniformly, have been used connected to high-pressure sodium lamps. High-pressure sodium lamps connected to electronic equipment have been tested with different arc power levels using dimming on a 230 V power supply. The study presented in this paper is completely based on measurements, including harmonic currents in the frequency range up to 150 kHz for all the technologies. The main results show a broadband spectrum in LED lamps which confirms other research in fluorescent lamps powered by high-frequency ballasts. Results also indicate a decrease in the harmonic value with increasing harmonic order, and a decrease in the harmonic value at half load (60%) compared with full load (100%). Although total harmonic distortion of the current is lower with high-pressure sodium lamps connected to electronic rather than electromagnetic ballasts, LED lamps achieved the lowest total harmonic distortion of current.

1. Introduction

The public lighting systems in our cities are a basic and vital service for city councils and other public administrations. On the one hand, citizens demand high-quality service in accordance with our highly developed society. On the other hand, a lighting installation is an important consumer of energy that is affected by factors such as regulation and maintenance. A recent study carried out for the European Commission[1] has shown that between 30% and 50% of electricity used for lighting could be saved by investing in energy-efficient lighting systems. In most cases, such investments are not only profitable and sustainable but also improve lighting quality. The main recommendation[2] is that streetlights and other forms of outdoor lighting should be made more efficient as part of a comprehensive strategy to reduce CO_2 emissions, this strategy also including cleaner options for electricity generation, reduced vehicle emissions, more energy efficient buildings, and smart electric meters combined with smart appliances which shift electricity use from peak to off-peak periods. Sustainable lighting technology should meet at least three criteria: (i) high efficiency or energy saving, (ii) long product lifetime and (iii) recyclability.[2]

A suitable selection of the lamp type is important. The majority of light sources used in public lighting are high-intensity discharge lamps; but light emitting diode (LED) lamps are being presented as a more energy-efficient alternative. This is due to the fact that LED lamps, unlike conventional light sources, make a direct transfer of electrical energy into light and are being strongly promoted. As an example, the U.S. Department of Energy acts as a catalyst to drive R&D breakthroughs in efficiency and performance, and to equip buyers to successfully apply solid state lighting.[3] At the moment LED lamps are not commonly used in street lighting systems, although recent technology is gradually improving the LED efficiency and color quality in comparison with high-pressure sodium (HPS) lamps, which allows their application in lighting systems. Little power quality research has been carried out on this technology; moreover it is mainly focused on low power LEDs[4–6] and not on high-power LED street lights.

The minimum acceptable requirements for lighting controls are that they provide enough light for the users and reduce lighting levels without compromising users' satisfaction and productivity. Therefore, by having a good understanding of the lamps, ballasts, luminaires and control options available today, lighting can be produced that is energy efficient, cost effective and of better quality.[7] Results[8] show that it is important to encourage the installation of smart dimmable electronic ballasts. As well as receiving switching and dimming commands from a streetlight segment controller such an installation can also be used to auto-detect lamp and electrical failures.

To sum up, the following measures are recommended for decreasing the cost of public lighting[9]: Reduction of the luminance level (dimming) during hours with reduced traffic density. This will reduce electrical energy consumption, which in turn will lead to a cost reduction. Making the street classification compliant with international standards and establishing the light technical parameters based on this classification. Setting a special price for the electric energy used by public lighting, due to the consumption during the night. Installing a street lighting control system which makes it possible to minimise maintenance expenses by better managing the replacement of failed lamps through knowing their location in addition to the age of each lamp. This last proposal implies the introduction of a wireless control system,[10] which has advantages over other systems based on power line communication (PLC) protocols. Upgrading street lighting using lighting equipment with low radio frequency emissions, not only within the low but also within the high frequency range, can improve the power quality in the whole system, avoid malfunction of electronic equipment and allow the working of PLC, and save costs.

The reminder of this paper is organised as follows: Section 2 outlines the background to the paper. Results of an experiment with LED lamps and HPS lamps working from electronic and electromagnetic ballasts are shown and explained in Sections 3 to 5. Later Section 6 compares the results obtained in the experiments. Finally Section 7 offers some conclusions.

2. Background

The characteristics of the different lamp technologies used in public lighting are summarised in the Table 1.

Table 1 Main characteristics of lamp technologies

LED lamp	HPS lamp and electronic ballast	HPS and electromagnetic ballast
Long operating life (50 000 hours life with 70–80% lumen maintenance)	Long lifetime (from 40 000 to 60 000 hours)	Long lifetime (>30 years at 105°C)
Very low power consumption	Increased lamp life (on average up to 30% longer lamp life)	Low cost
Low installation and maintenance costs	No flickering effect	Suitable for extreme weather conditions (humidity, temperature variation, lightning)
Harmonised illumination	Dimmable	Recyclable materials (magnetic chokes are recyclable)
High efficiency	High efficiency (up to 15% savings)	Self-recovery feature (when the ac mains voltage recovers after a disturbance)
Dimming possibilities	Non audible noise	Very low maintenance costs
Contain no hazardous materials	Low weight	Not dimmable
Low temperature and function well in cold temperatures	Energy saving (up to 13%)	Not energy saving
Good vibration resistant characteristics	Relatively expensive	Flickering effect
Quick start and re-start (do not need to firstly cool the system as with HID)	Not environmentally friendly	No constant light output
Low glare and strobe-free		
Free from ultraviolet or IR		
Possible use with renewable energies		

A number of compatibility problems have occurred in the field of lighting as a result of installing electronic ballasts in energy-saving lamps in general without understanding how to avoid such problems. Examples of the problems include[11] early failure of ballasts and lamps and malfunctions of energy management systems, centralised clock systems, infrared-based remote controls and personal electronic devices such as a hearing aids, among others.

Lighting also affects the power quality (PQ) of the electrical distribution system. PQ is concerned with deviations of the voltage or current from the ideal single-frequency sine wave of constant amplitude and frequency. A consistent set of definitions can be found in Moreno-Muñoz.[12] Poor PQ is a concern because it wastes energy, reduces electrical capacity, and can harm equipment and the electrical distribution system itself. PQ deterioration is due to transient disturbances (voltage sags, voltage swells, impulses, etc.) and steady state disturbances (harmonic distortion, unbalance, flicker). This paper is focused on the latter, and, specifically, on harmonic distortion.[13]

The study presented in this paper is completely based on measurements. It follows other studies,[14,15] which present work on harmonics due to street lighting using both electromagnetic and electronic ballasts. Those ballasts were used connected to up to three lamps. The experimental results presented here include the introduction of the LED lamp within that harmonic study.

The main objective must be to provide guidelines for minimising any PQ impacts resulting from the application of energy-saving technologies with regards to lighting. The primary focus of this paper is both LED and HPS lamps for street lighting. Energy saving is often used as one of the selling features for these devices and customers need to have a clear understanding of the energy-saving potential of these technologies.

Harmonic analysis is a primary aspect of PQ assessment. With the widespread use of power electronics equipment and nonlinear loads in industrial, residential and commercial office buildings, the modelling of harmonic sources has become an essential part of harmonic analysis.[16] This paper focuses on the harmonic analysis of existing lamps but also the lamp of the future, the LED lamp.

As is well known upgrading to lighting equipment with low emissions (high power factor and low harmonic distortion) can improve the power quality of the electrical system. Furthermore, upgrading with higher efficiency and higher power factor lighting equipment can also free up valuable electrical capacity. This benefit alone may justify the cost of a lighting upgrade.

Another field of interest is the possible interference with PLC (using a frequency range 9–95 kHz) resulting in communication losses. Two studies[17,18] distinguised five different types of interactions between communication and end-user equipment. One interaction is due to the emission by end-user equipment, but the most important is due to the low impedance created by end-user equipment. They will all cause the communication system not to work.

3. Experiment with LED street lamp

Lighting designed for outdoor applications must address multiple issues such as proper light distribution, glare, light pollution, energy usage and lifetime. Although it is not widely used in street lighting, there are many advantages from the use of LED lamps such as very low power consumption, and high efficiency (124 lm/W in 2010[19]), among others. On the other hand, some drawbacks include the need for effective cooling, and the most determining aspect, the price, although this is becoming less.

In this section, an experiment including LED street lights has been developed. The experiment has involved the individual monitoring of two different LED lamps. The current taken by the lamps was measured using a Dranetz PX5 power-quality monitor in order to obtain 1-second values for all the typical power-quality parameters as well as a 200 ms waveform of the voltage and current every minute with a sampling frequency equal to 12.8 kS/s. The measurement was carried out in day time to avoid disturbing the night traffic. Switch-on and switch-off processes were forced and the parameters of the lamps were registered during steady state and warm up.

The first street light monitored was a Thorn lamp, with an active power of 25 W, and according to our measurements other values are 6.8% total harmonic distortion of the current (THDI) and a displacement power factor (DPF) of 0.96. First, regarding the active power, the lamp was monitored over 30 minutes but it was not stable within that time. In fact, the active power is decreasing over time. The variation is relatively low (2.6%), but even after 30 minutes, the lamp did not achieve stabilisation of the active power. This can be explained by the dependence of the LED on temperature.[20] The forward voltage drops with temperature which leads to a decrease in the power. Also, the variation of the temperature of the aluminium base and fin with operating time was recorded. Even after about 3 hours the temperature was still increasing.[21] This fact could be the reason for the decreasing tendency in the LED active power.

Second, both the voltage and current waveforms of the LED street light lamp are represented in Figure 1. The almost pure sinusoidal waveform of the current can be seen but there are also some spikes around the zero-crossing.

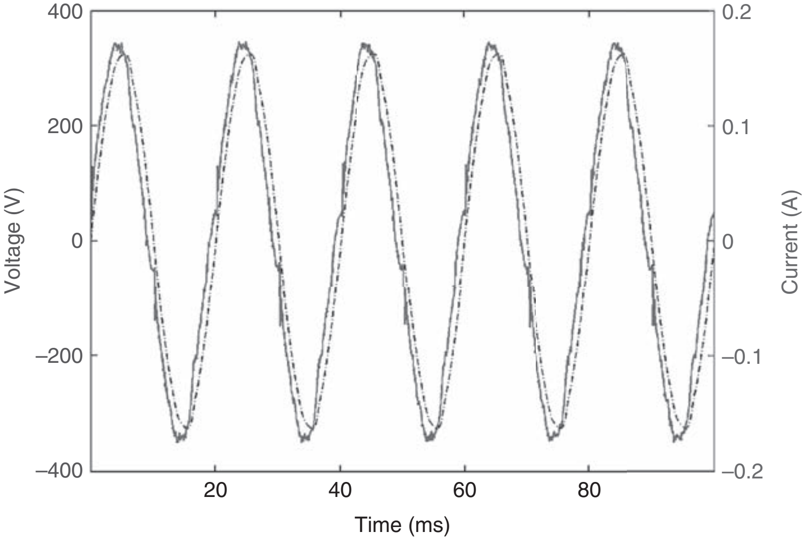

Figure 1 Current (solid) and voltage (dash-dot) waveforms for a LED street light lamp

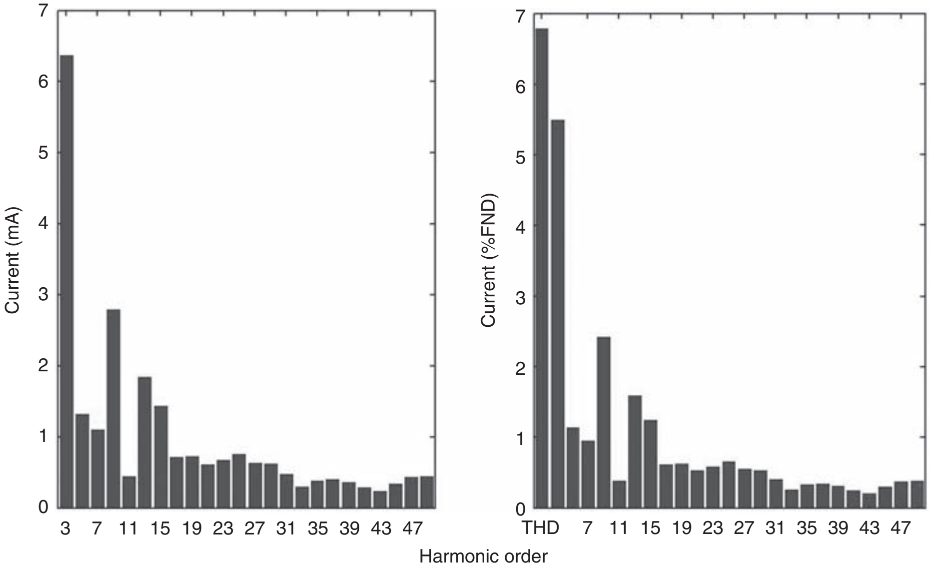

Figure 2 Harmonic current spectrum from a LED street light lamp in milliaamps and percentage of fundamental

Later on, in order to study the distortion in this technology, the odd harmonic spectrum of the current up to 2500 Hz was measured. The result is shown in Figure 2. The harmonic groups, as defined in IEC 61000-4-7,[22] have been calculated for each of the 60 basic measurement windows of 200 ms duration, obtained at 30-second intervals. Shown in

Figure 2 is the average of these 60 values. Because the harmonic spectrum during this 30-minute period was very constant, the figure shows a typical spectrum. Low frequency distortion has been studied in depth. The first conclusion to be drawn from Figure 2 is that 3rd, 9th, 13th and 15th harmonics are dominant. The rest of the odd harmonics have the same level. The fundamental harmonic of the current is 117 mA. The 3rd harmonic of the current is the highest in magnitude, but it is relatively low if we compare it with other light technologies, only 6.5 mA (5.4% of the fundamental (FND)). The other orders are around 1 mA (1% FND). The 9th, 13th and 15th harmonics are also higher than the frequencies around them. They are 2.85 mA (2.5% FND), 1.8 A (1.6% FND), and 1.5 A (1.25% FND), respectively.

If we compare these results with some other measurements made on high-power LED street lighting,[23] we can see a similar broadband spectrum, with a high 3rd, 5th and 7th harmonics; but they have higher magnitude than the lamp used in the current paper (between 8.1% and 19.1% of FND for the 3rd harmonic; around 3% of FND for 5th harmonic; and between 2.1% and 5.5% for 7th harmonic). The THDI is also different, in reference 22 this value varies between 9.3% and 21.5%, and in this case, the THDI is 6.8%. But the main difference among those lamps is the power. In our experiment the active power is 25 W and in reference 22 the two measured lamps were 144 W and 68 W.

Measurements have also been made of the harmonic spectrum within the high frequency distortion (from 2 to 150 kHz). Frequency aggregation has been taken into account as IEC 61000-4-7[22] indicates within Annex B for frequencies up to 9 kHz. For these calculations, the sampling speed used was 10 MS/s over a 200 ms window. The spectrum resulting after applying the discrete Fourier transform has been aggregated into 200-Hz bands. Although Annex B mentioned above requires measurements up to 9 kHz, in this study they have been made up to 150 kHz, and this range (from 2 to 150 kHz) is plotted in Figure 3. There are two peaks, one at 6.3 kHz, and other around 41 kHz. Overall, a broadband spectrum can be seen.

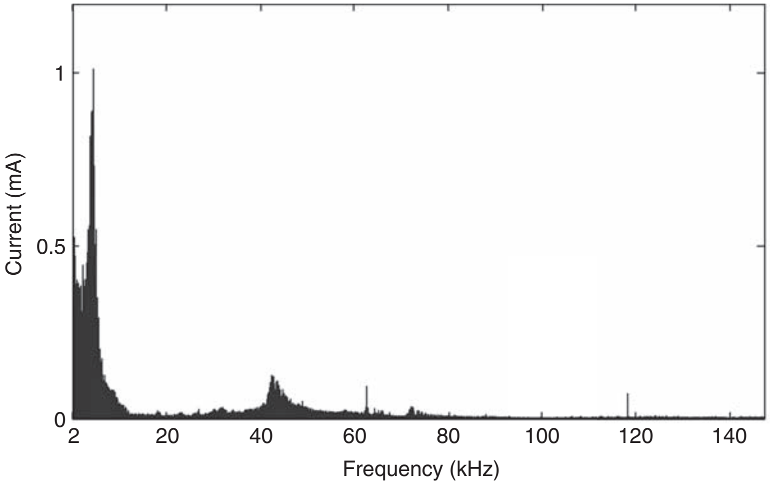

Figure 3 The 200-Hz band spectrum of the current feeding the LED lamp in the range from 2 to 150 kHz

From the peak at around 41 kHz, the shape of the spectrum, the shape of the current waveform in Figure 1 and the rated power we can assume that the driver is using active power factor correction.

A further analysis has been described in fluorescent lamps powered by high-frequency ballasts,[24,25] and the spectrum showed narrowband components at 28 kHz and at 123 kHz. Moreover, it was shown that an increase in amplitude associated with the switching frequency around 40 kHz occurred, which decreased with frequency. From this we can conclude that in the LED lamps, the peak around 40 kHz is also due to the switching frequency of the active power factor correction circuit. From Figure 3 we can conclude that, even though there is a peak around 6.3 kHz, the spectrum is rather broadband.

After studying this LED street lamp, another LED lamp with high power was also recorded and analysed. The power quality monitor used was again a Dranetz PX5. The luminaire was a matrix of 30 LEDs, and the LED driver belongs to UE Electronic (output 52 V, 0.7 A). With an AC mains voltage of 230 V, the total input power is 42 W and the output power consumed by the LED load is 36 W. The driver loss is only 6 W. Thus, a high efficiency of 83.3% has been achieved. Other data are THDI 18.16% and a DPF of 0.961. In this case, the fundamental of the current is 188 mA, and the peak current absorbed is little higher than in the previous case, 0.25 A (70 mA higher). On the other hand, the maximum of the voltage does not occur at the same time as the maximum of the current. However, voltage and current zero-crossing do occur at the same time (Figure 4).

All the harmonics have higher magnitudes than the previous LED lamp, in absolute value as well as in percentage of the nominal current (Figure 5). Whereas in Figure 2, the 3rd harmonic has a magnitude of 6.5 mA; in this case it is around 28 mA (15% of the FND); the same occurs with the 5th and 7th harmonics, which in the previous lamp were 1 mA, and in this case 15 mA and 8mA (7% and 4% of FND respectively). Another important difference is that in Figure 2 it is possible to see that after the 3rd harmonic, the rest of the harmonics are mostly around 1 mA. However, in the current lamp, until the 21st harmonic this constant value is not present.

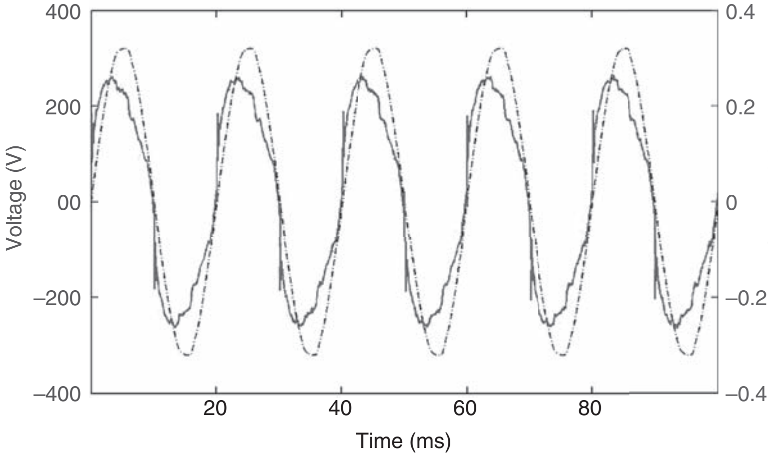

Figure 4 Current (solid) and voltage (dash-dot) waveforms for another LED street light lamp

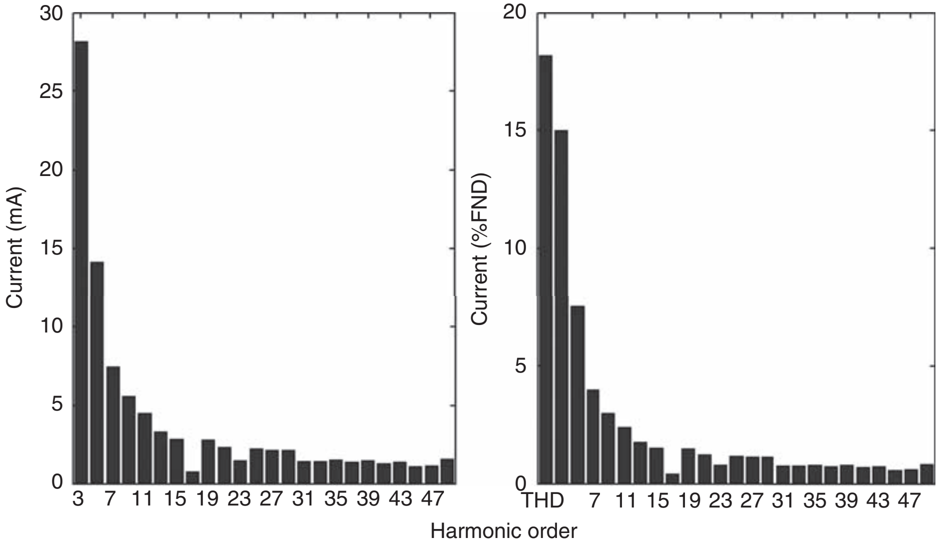

Figure 5 Harmonic current spectrum from another LED street light lamp in milliamps and percentage of fundamental

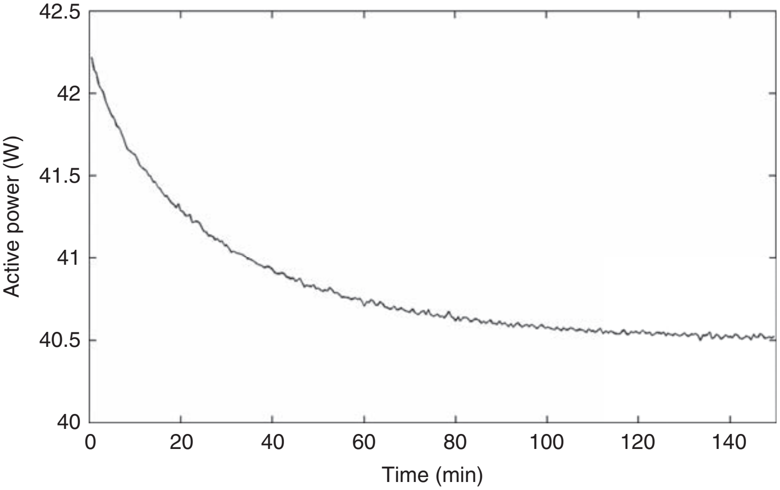

Figure 6 Change in active power in a LED street light lamp over time

In spite of those comments, overall the harmonic emission corresponds, as it does in the previous lamp, with a broadband spectrum, with a relatively high 3rd harmonic, a decreasing tendency from this order up to 15th, followed by stabilisation around 2.5 mA. The emission has a minimum for harmonics 17 and 23. There is no specific reason for this, but it is a common feature of diode rectifiers.[26]

It is also worth to considering the change in active power over time, as was done for the previous lamp. Although the variation is not significant (4%), the active power follows an exponential decreasing curve (Figure 6). It seems that it never achieves a constant power, even after more than 140 minutes. However it should be noted that this decreasing tendency has no impact on power quality, because the difference is small, even more so because these lamps usually operate for several hours.

4. Electronic ballasts connected to HPS lamps

Electronic ballasts have been promoted as replacements for electromagnetic ballasts for the last decade. It is usually thought that electronic ballasts have a higher efficacy than electromagnetic ballasts (typically claimed to be 10–15%). Further, the use of electronic ballasts makes it possible to deliver constant power to the lamp during its entire useful life, unlike electromagnetic ballasts where the output power is dependent on lamp impedance variations. In fact, electronic circuitry is more energy efficient than conventional ballasts. To sum up, some advantages of dimmable electronic ballasts are their energy savings (up to 50%), wider dimming range through wired or wireless central dimming control, and their robustness and reliability.

The current taken by this group was measured using a Dranetz PowerGuide 4400 to obtain 30-second values for all the typical power quality parameters as well as a 200 ms waveform of the current every 30 seconds with a sampling frequency equal to 12.8 kS/s. In order to have a stable current, the spectrum was measured over 4500 consecutive 30-second intervals. This will allow us to characterise the harmonic emission because it is rather constant over these samples.

The lamp was connected and measured at the equipment terminals. The equipment tested was a Philips SON 70W/220 I E27 1CT[27] connected to an electronic ballast OSRAM Powertronic® PTo DALI 70/220-240 3DIM.[28] Usually the power loss of each electronic ballast is around 10 W. For high frequency control, the lamps cannot be fully dimmed to extinction, and residual light output and power consumption will appear. However, such system operation may be less noticeable and less annoying to pedestrians. Ballasts are dimmable from 60% to 100% of the lamp input power, but we have chosen three discrete values from this range, 60%, 76% and 100% (we have chosen three equally distanced points following the logarithmic dimming curve in Annex E of IEC 60929[29]). More details about the energy efficient street lighting remote management system used in this experiment can be found in reference 10. Some data measured from the lamps are THDI at 100% of arc power level is 12.83%; at 76% it is 14.94%; and at 60% it is 16.78%. As for DPF, at 100% of light output it is 0.9745; at 76% it is 0.9654; and at 60% it is 0.9523.

Figure 7 shows the voltage and current waveform of one of these lamps with the arc power level set to 100%. As we can see, the peak current is 0.5 A, about 18 times higher if we compare it with 28 mA, which is the maximum reached by a LED lamp. The zero crossing of the voltage into the current waveform can also be seen. This zero crossing distortion is similar to the one observed in reference 24 for a 2 × 49 W ballast for fluorescent tubes.

Thus, by knowing the harmonic spectrum we are able to see the similarities between this technology and LED lamps. In order to do this, the harmonic current spectrum has been calculated as recommended in IEC 61000-4-7[23] with the grouping method, up to 2500 Hz. Only odd harmonics are shown. The three dimming step 60%, 76% and 100% were used for calculating the spectrum. The fundamental of the current is 0.33 A. As we can see in Figure 8, 60% and 76% dimming follows a decreasing tendency with increasing harmonics order (from 3rd to 15th), but in the case of 100% the 7th harmonic is higher than the orders around it (14 mA). The highest

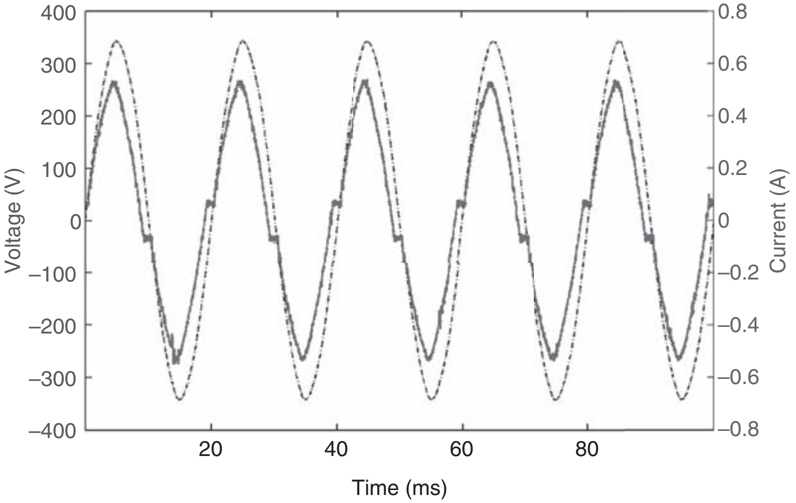

Figure 7 Current (solid) and voltage (dash-dot) waveforms for a HPS lamp connected to an electronic ballast

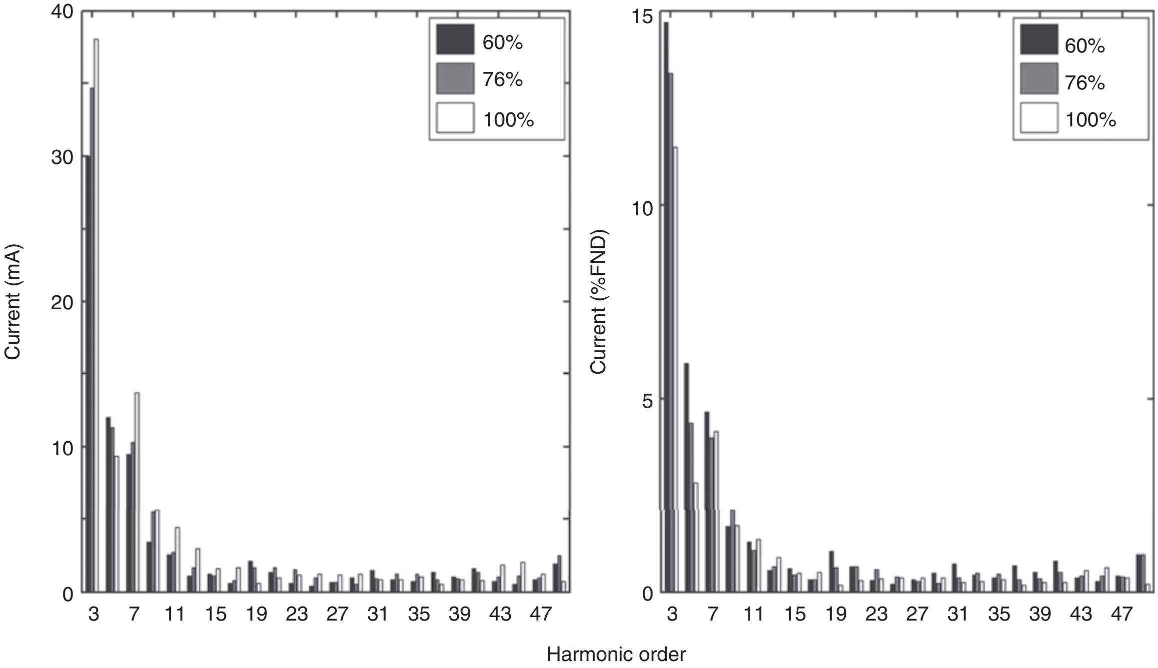

Figure 8 Harmonic current spectrum for a HPS lamp connected to an electronic ballast according to light output in milliamps and percentage of the fundamental (FND)

magnitude is reached by the 3rd harmonic, varying between 30 mA (15% of FND) to 38 mA (11.5% FND) depending on the dimming. This value is followed by the 5th and 7th harmonics which have a similar magnitude, around 11 mA (5% of FND). The higher orders are around 1.4 mA (0.5% of FND).

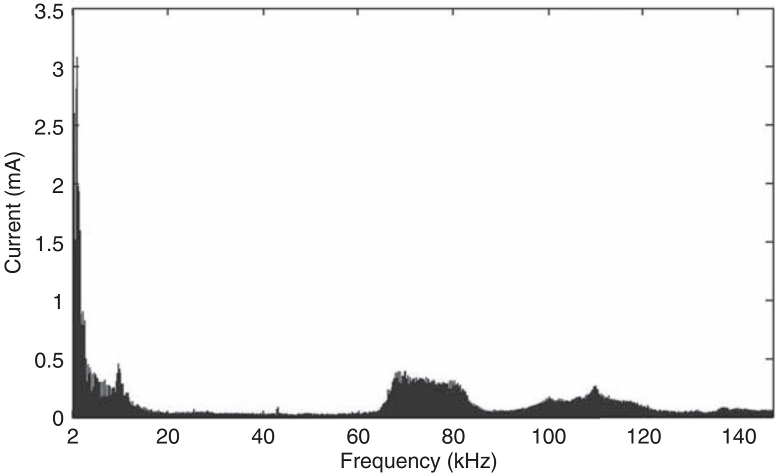

Figure 9 The 200-Hz band spectrum of the current feeding the HPS lamp connected to electronic ballast in the range from 2 to 150 kHz

As we did with the first LED lamp, we have studied the harmonic spectrum (from 2 to 150 kHz) in a lamp set to 100% arc power level. For these calculations, the sampling speed used was 5 MS/s over a 200 ms window. It is worth noting that, compared with the LED high-frequency spectrum, the peak is not sharpened and it does not appear in the same range, but in the range from 68 to 80 kHz (Figure 9). This is the same pattern as observed for high-frequency ballasts, due to the switching frequency. Therefore it is concluded that this peak is most likely due to the switching frequency here as well. There is another peak around 110 kHz, which could also be related to the switching pattern used.

Compared with LED, the peak is not around 6 kHz, but around 2.8 kHz. Another difference is the value of that peak. In the LED lamp, the peak current was 1 mA (0.8 %FND), and in this lamp, the peak is 3 mA (0.9%FND). After this peak, the high-frequency harmonics follow a decreasing tendency in both cases.

On the other hand, as we did with the LED lamps, we try to study how stable is this type of load. To do so we have monitored the active power over time (1.15 h). It is possible to see that after 4 minutes the lamp appears to be stable in Watts (Figure 10), but if we remove the four first minutes, a decreasing tendency also appears. As in the LED lamp, this decreasing tendency has no impact on power quality, because the difference is small (now 1 W) and slow (their working time is several hours, so the four first minutes has no impact either).

5. Electromagnetic ballasts connected to HPS lamps

Conventional electromagnetic ballasts are equipment commonly used in old fashioned street lighting and consist of a magnetic choke, a starter, and a power factor correction capacitor. The structure of the ballast system is simple, robust, and reliable. However, the ‘conventional’ magnetic ballast has its own shortcomings, i.e. poor power regulation ability and high power loss caused by the iron and copper losses in the magnetic choke.

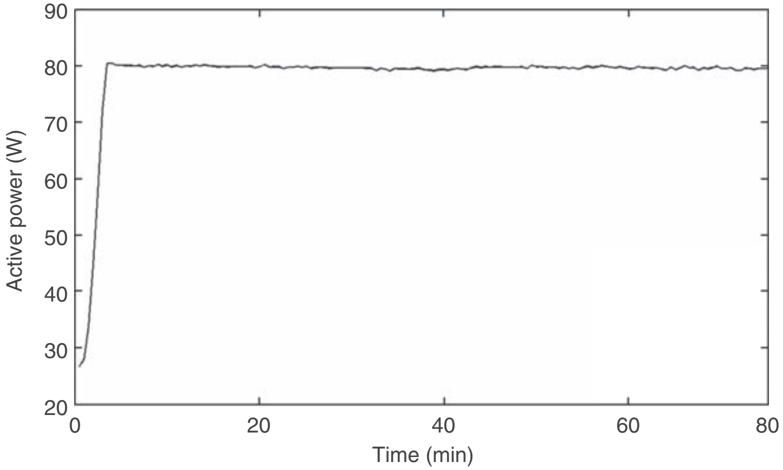

Figure 10 Change in active power in a HPS lamp connected to an electronic ballast (100% of the load) over time

In order to compare the current waveform between the LED and other technologies, we have also represented this waveform when using the electromagnetic ballast. In this section, the equipment used was a Thorn luminaire (electromagnetic ballast Tridonic Atco Z603W, ignitor VOSSLOH SCHWABE Z 400 MS A1, capacitor CCL 10nF) with 50 W Philips HPS lamp. The equipment used for measuring this lamp was a Dranetz PX5 power quality monitor. It was used to obtain 1-second values for all the typical power-quality parameters as well as 200-ms waveform of the current every second. In this case, the ballast has an active power of 15 W, so the combined consumption of the lamp and the ballast is 65 W. According to our measurements, the THDI is 35.5%, and the DPF is 0.9989.

The main difference between Figure 4 and Figure 11 is the lower consumed current of the LED lamp. The LED lamp draws 0.25 A while the HPS lamp with the electromagnetic ballast draws 0.5 A. Then, if we consider the harmonic spectrum, the harmonic spectrum in amps and the percentage of the fundamental are shown (Figure 12). Moreover, the THDI from 0 to 2 kHz has been included within the right hand figure. The first remarkable aspect is the high values for harmonic orders up to the 17th, and a decrease in the higher frequencies. Even though those values are low, the harmonic orders 25th, 27th and 29th are 10 mA, roughly four times higher than the LED lamps for the same orders (2.5 mA). In the HPS lamp with an electromagnetic ballast they represent 3% of FND, and in the LED lamp they are 1% of FND.

Another aspect is the difference in the shape of the spectrum. For the HPS lamp with the electromagnetic ballast, the lower harmonic orders up to the 17th are relatively high, almost half of the distortion; whereas from the 19th onwards they decrease in magnitude.

As with the previous technologies, the high-frequency spectrum is plotted (Figure 13). In order to do so, measurements were repeated with a sampling speed of 10 MS/s, over a 200 ms window. No peak is observed, because the system does not have any switching component. The higher is the frequency, the lower is the current. So there is a clearly decreasing tendency. This pattern is not followed by any of the previous analysed lamps.

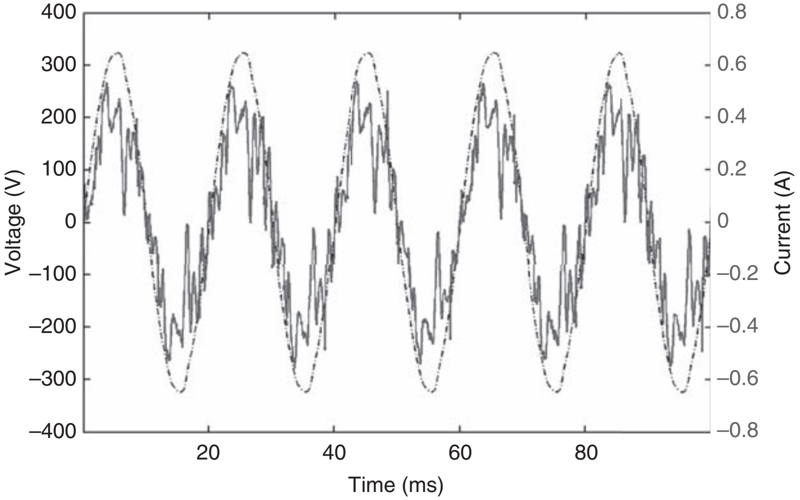

Figure 11 Current (solid) and voltage (dash-dot) waveforms for a HPS lamp connected to an electromagnetic ballast

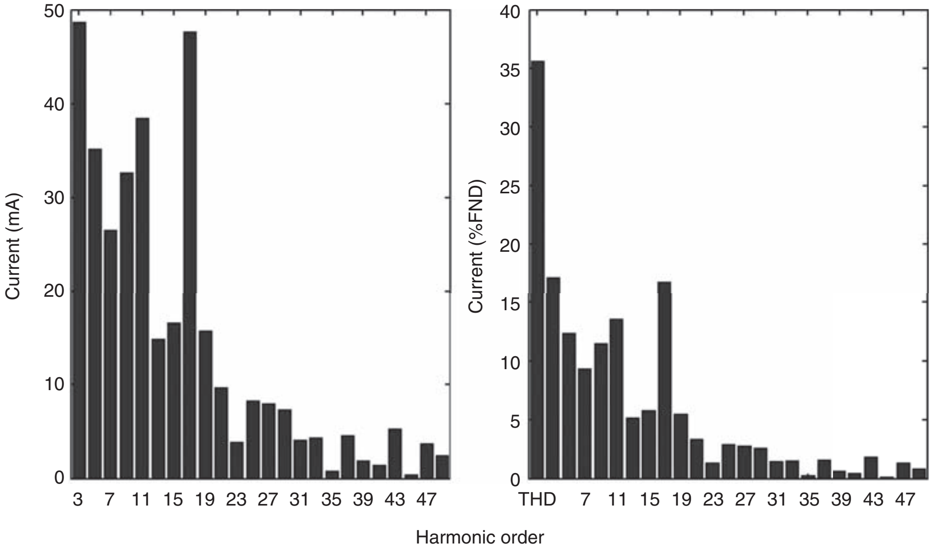

Figure 12 Harmonic current spectrum for a HPS lamp connected to an electromagnetic ballast in milliamps and percentage of the fundamental (FND)

6. Comparison of all experiments

The main benefit of reducing the THDI in street lighting lamps occurs because such lamps are always connected in groups, so the total emission can be large. Moreover, because PLC uses the frequency range 9–95 kHz, emissions within this range should be avoided so as to avoid interference with this communication system.

In order to evaluate what is happening with harmonic currents for different lamp types,

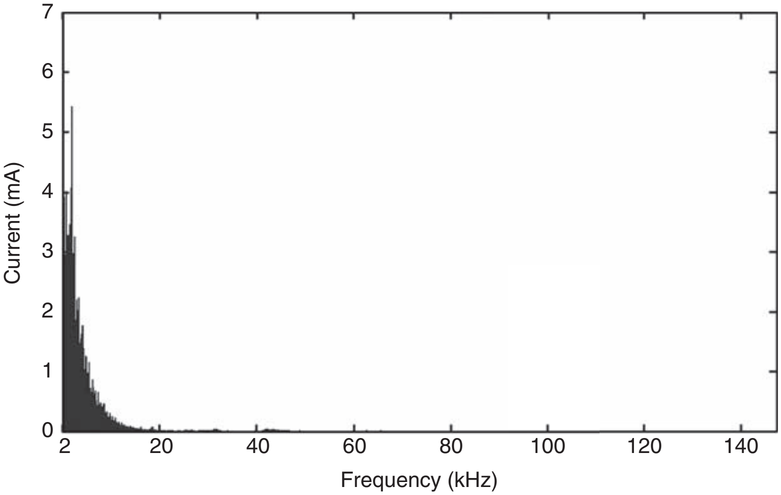

Figure 13 The 200-Hz band spectrum of the current feeding the HPS lamp connected to an electromagnetic ballast in the range from 2 to 150 kHz

Table 2 Power quality parameters for the lamps

	Fundamental rms (A)	THDI (% FND) 0–2 kHz	S(VA)	P(W)	DPF
LED one	0.12	6.8	26.6	25	0.960
LED two	0.19	18.2	43.0	36	0.961
HPS and electronic ballast (100%)	0.33	12.8	79.0	78	0.975
HPS and electromagnetic ballast	0.28	35.5	64.7	65	0.999

Table 2 shows some important parameters among the different technologies used. Specifically, the fundamental of the current, total harmonic distortion of the current (THDI), reactive (S) and active (P) power, and the displacement power factor (DPF) have been measured. The highest power is consumed by the HPS lamp with an electronic ballast set to 100% of the load; but this load does not have the highest harmonic distortion. In fact, this value is reached by the HPS lamp with the electromagnetic ballast (which has roughly the same active power). On the other hand, the second LED lamp does not have a high power (36 W), but higher current harmonic distortion (18.16%) compared with the HPS lamp with an electronic ballast (12.83%).

More data are shown in Figure 14, where it is possible to see the differences between LEDs and the HPS lamps with electromagnetic and electronic ballasts, the last being set to the three dimming steps 60%, 76% and 100%. It is important to point out that these lamps are all similar in lumen output, and they are all used for street lighting. As you can see from Figure 14, the difference between the electronic ballast with power set to 100% and the electromagnetic ballast is more than double (65%). Even when the quantity of harmonic distortion is higher in the case of electronic ballast, such as at 60% of the load, the difference is double (46%). This pattern is almost the same for all the harmonic orders except for the 5th order, which is between 75% and 100% of that of the electronic ballast.

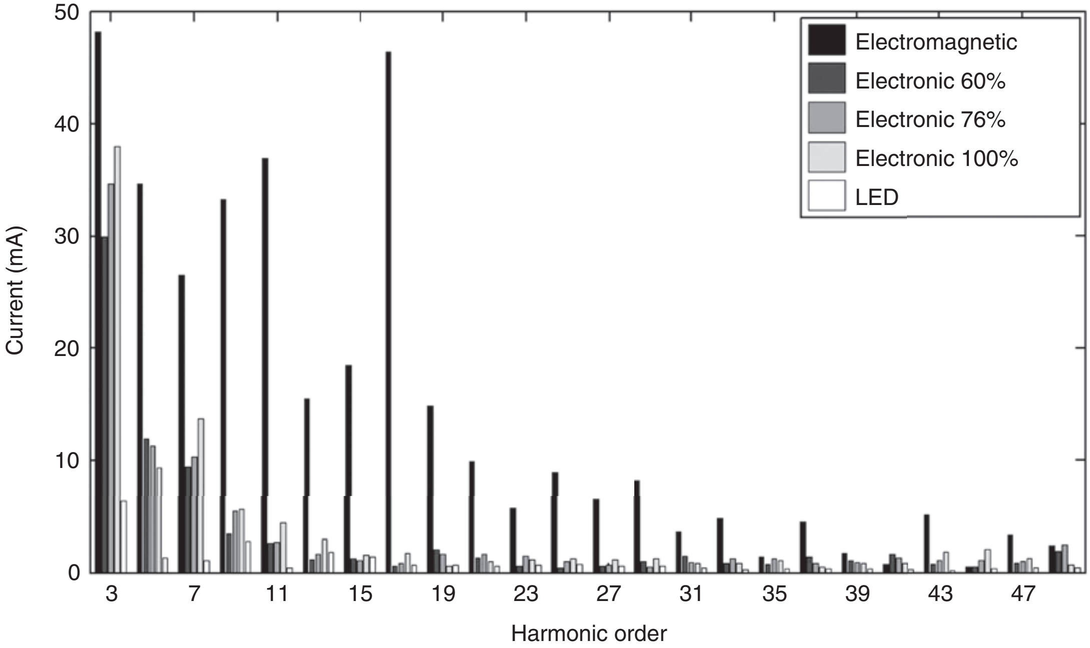

Figure 14 Comparison of harmonic current spectra in milliamps

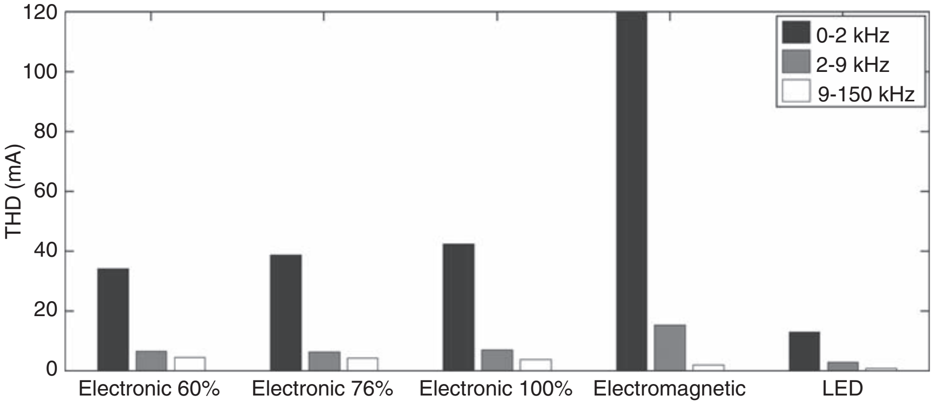

Figure 15 Comparison of total harmonic distortion of the current (THDI) in milliamps among all the technologies within different frequency ranges

Regarding the THDI; it is necessary to distinguish between different frequency ranges. From 0 to 2 kHz, the HPS lamp with the electromagnetic ballast has the higher total harmonic distortion, three times higher than with the electronic ballast at whatever arc power level. The lowest value is reached by the LED lamp (13 mA) (Figure 15).

The total harmonic distortion of the current has also been calculated over the frequency bands 2–9 kHz and 9–150 kHz (Table 3). In the range 2–9 kHz, the differences in emission between the technologies are smaller. But even here, the highest emission is produced by the HPS lamp with the electromagnetic ballast and the lowest by the LED lamp.

Table 3 Total harmonic distortion for different frequency ranges

	THD (mA) from 0 to 2 kHz	THD (mA) from 2 to 9 kHz	THD (mA) from 9 to 150 kHz
HPS + Electronic 60%	34.2	6.5	4.4
HPS + Electronic 76%	38.7	6.4	4.2
HPS + Electronic 100%	42.5	6.9	3.8
HPS + Electromagnetic	119.7	15.2	1.9
LED	13.0	2.9	0.703

However, within the frequency range 9–150 kHz, the HPS lamp with the electromagnetic ballast has a lower emission than the one with the electronic ballast. Also in this frequency range the LED lamp has the lowest emission. The measurements also show that the arc power level for the HPS lamp with the electronic ballast has only a small impact on the emission, in any of the frequency ranges.

This means that the THDI up to 9 kHz is lower with HPS lamps working with electronic than with electromagnetic ballasts, but from 9 to 150 kHz it is the other way round. Conversely, the LED lamp has the highest efficiency and the lowest emission.

Regarding the high-frequency spectrum, the highest current peak is reached by electronic and electromagnetic ballasts connected to HPS lamps, being 3 mA (around 1% of FND) for the electronic ballast and 6 mA for the electromagnetic ballast (2% of the FND). However, the LED lamp has a 1 mA peak (0.8% of FND). The trend followed by the two spectra from the HPS lamp with the electronic ballast and the LED lamp both show a peak (one around 2.8 kHz and the other around 6.1 kHz), whereas the trend of the HPS lamp with the electromagnetic ballast shows a decreasing tendency.

7. Discussion

In this paper a harmonic analysis on HPS and LED street lights is presented. To this end, several experiments were carried out, two tests with two LED lamps, and two tests with HPS lamps connected to electromagnetic and electronic ballasts. They all are similar in lumen output. Their current and voltage waveforms, THDI for different frequency ranges, and active power have been calculated as it is described in IEC 61000-4-7.[23] LED and HPS lamps operating from electronic ballasts not only have higher luminous efficiency, they also emit fewer harmonics into the grid at lower frequencies. Even in percentage terms, such LED and HPS lamps have lower emissions. There is thus no risk that a higher emission level per street-lamp feeder will occur because more lamps can be connected on one feeder.

This analysis has been compared with others made by different authors using LED and HPS lamps. The results obtained are partially similar, i.e. the decrease in the harmonic value as the harmonic order increases, and also the decrease in the harmonic value at half load (60%) compared with full load (100%). But the pattern is not the same because it changes with higher harmonic orders.

This study found that the THDI up to 9 kHz is lower with HPS lamps working with electronic than with electromagnetic ballasts, but from 9 to 150 kHz it is the other way round. Conversely, the LED lamp has the highest efficiency and the lowest emission. Moreover, if we replace one electromagnetic ballast with one LED (both with similar lumen output), the emission becomes less.

Regarding the high-frequency spectrum, two peaks have been observed in these spectra for the LED lamp and the HPS lamp connected to an electronic ballast. These peaks are due to the switching frequency of the active power factor correction circuit. This is not the case for the HPS lamp connected to an electromagnetic ballast, because there is then no switching device. In addition to this, a broadband spectrum has been observed in the LED lamps.

Finally, even though the active power follows a decreasing tendency curve within each technology, the power losses are higher in the HPS with an electromagnetic ballast (15 W) than in the LED (with only 6 W). In between them, the HPS lamp with an electronic ballast has 10 W of losses. Therefore, another advantage for using a LED street light is lower power losses compared with earlier technologies.

The results produced here should not be taken as definitive because, in the case of the HPS lamp connected to the electronic ballast, the connection might have been interfered with by other loads. This is not the case for the LED lamps and the HPS lamp connected to the electromagnetic ballast. On the other hand, as different small LEDs have rather different spectra, the same could occur for LED street lamps. Thus, more measurements are needed.

8. Conclusion

Various types of lamps used for street lighting have been analysed for their electrical properties using laboratory measurements. As is well known upgrading to lighting equipment with low emission (high power factor and low harmonic distortion) can improve the power quality of the electrical system. This will in fact help to avoid the malfunction of electronic devices which can be very sensitive to high levels of high frequency emission.

The measurements presented in this paper show that the harmonic emission from LED street lamps is less than that from HPS lamps. This holds for all frequency bands. Replacing HPS lamps with LED lamps will thus not result in an increase in harmonic levels in the grid. In other words, power quality concerns are not a reason for not using LED lamps.

Some increase in efficiency can be obtained by replacing the electromagnetic ballast of an HPS lamp by an electronic ballast. It is also shown that the harmonic emission becomes smaller for the frequency range up to 9 kHz. In the frequency range above 9 kHz the emission from the electronic ballast is higher than from the electromagnetic ballast. This is however not seen as a serious concern as the levels are still low and it should not be a barrier against changing to electronic ballasts.

Measurements on small LED lamps for domestic applications, presented in the literature, show a wide range in emission levels. It is therefore important to perform regular measurements of the harmonic emission of LED street lamps so as to prevent power quality problems in the future.

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