# Electrical consequences of large-scale replacement of metal halide by LED luminaires

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Hermoso-Orzáez, MJ; Rojas-Sola, JI; Gago-Calderón, A. Electrical consequences of large-scale replacement of metal halide by LED luminaires. *Lighting Res. Technol.* 2018; **50:** 282–293. DOI: https://doi.org/10.1177/1477153516645

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Short title: Electrical impact of changing light sources

Received 25 February 2016; Revised 24 March 2016; Accepted 30 March 2016;

The recent trend for large scale replacement of luminaires using discharge light sources with LED luminaires without any significant adjustments to the electrical installation has generated controversy. This study examines the main electrical measures in a large outdoor lighting installation before and after the replacement of a large number of metal halide floodlights with LED luminaires. The electrical parameters of both technologies are discussed in detail and compared, with special attention given to the odd-numbered harmonics of voltage and current, the generated wave deformation, currents in the neutral conductor, the wattless reactive volt amps and the peak inrush currents. At cold start-up, the LED luminaires generate large power-on currents much larger than those generated by the metal halide lamps, despite requiring 36% less real installed power. This is a basic problem to be solved when planning a public lighting renovation with LED luminaires as the rest of electrical parameters are reduced. To address this problem, it is proposed to energise the luminaires using magneto-thermal protection circuits with slow trip curves that will tolerate the large short-term inrush currents.

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## 1. Introduction

Nearly 20% of the total electricity production worldwide is used for artificial lighting.[1] This energy consumption results in the production of approximately 1,900 Mt of $CO_2$ emissions per year, an amount equal to 70% of the emissions of all passenger vehicles and three times more than the emissions generated by the aviation sector.[2] A significant percentage of artificial lighting is outdoor lighting, which represents 2.3% of global electricity consumption[3] and may account for as much as 40% to 60% of the total electricity consumption of a municipality in a developed country according to various studies.[4-6]

Many outdoor lighting installations were constructed 30 to 40 years ago and therefore use inefficient and expensive illumination systems.[7] Currently, LED lighting - or solid state lighting (SSL)- is among the most energy-efficient and environmentally sustainable lighting technology available. De Almeida *et al* [2] show how SSL technology offers high luminous efficacy at increasingly lower costs as well as a lifetime that is several times greater than that of discharge lamps.

Attempts to reduce energy costs are driving the replacement of traditional discharge lamps in outdoor lighting installations, typically high pressure sodium (HPS) or metal-halide (MH), with LED technology. Numerous studies have analysed the energy efficiency of these new LED installations, comparing them with fluorescent lamps,[8] MH discharge lamps,[9] and other conventional technologies used in outdoor lighting.[10]

In addition, numerous projects to renovate street lighting installations with LEDs have been analysed and have shown potential average savings of more than 50%. For example, Valentova *et al* [11] analysed the status of 106 LED test cases from 17 European countries and found average energy savings of 55% compared with the original installations or reference energy consumption levels. Kinzey conducted a study for the U.S. Department of Energy of a project to replace 88,000 street lighting luminaires in the city of Detroit with LED technology. This project was reported to have reduced energy consumption by 60% compared with the existing HPS luminaires (assuming that all of the lights were in working order).[12]

Similar results were obtained in the city of Los Angeles, where more than 140,000 fixtures have been upgraded to LEDs. Energy consumption was reduced by 60%, carbon emissions were reduced by 40,500 tons/year, and costs were reduced by $7.5 million/year.[13] The City of Sydney, Australia has changed 6,150 conventional outdoor lights to LEDs since March 2012, resulting in a reduction in energy consumption of more than 51%. A survey conducted by the city government revealed that more than 90% of those who responded indicated that they found the new lights appealing and three-quarters of the respondents said that the LEDs have improved visibility.[14]

The rapid adaptation of LED technology has driven down the costs. This decrease in costs and the significant energy savings offered by LED lighting, which can be remotely controlled and managed, allows amortisation periods of less than 3 years for investments in renovations of conventional lighting installations.[15] The study of the Detroit lighting project calculated a "simple payback of less than 2.5 years from energy savings alone without any additional maintenance savings".[12] Research and consulting firms such as the Northeast Group have reported that global investment in LED street lighting is expected to total $53.7 billion between 2015 and 2025.[16]

However, the replacement of discharge lamps with LED lamps has created problems that have not been encountered previously in outdoor lighting installations. Blanco *et al* [17] showed that this new lighting equipment creates nonlinear electrical loads that may influence the power quality in low-voltage networks. These disturbances in electricity networks may be continuous or transient and may be of three types: Low-order harmonics, high-frequency emissions and start-up currents.

Specifically, these problems are caused mainly by the integrated power management circuits required for LED lighting. LED lights require constant output current control to drive the LEDs without reducing their longevity. Buck-boost and flyback converters are typically used for power management because they offer wide input and output ranges, high capacity and high efficiency. However, these converters are characterised by high start-up, or inrush, currents, long start-up times and voltage overshoots during start-up, which can affect power management systems, possibly causing damage.[18]

The bulk capacitors required for these drivers cause a high inrush current when an input voltage is applied because the capacitors act as a short circuit in the discharged state, and only weak current-limiting measures are typically included in power supplies to suppress this current surge. This inrush current can be up to 100 times greater than the nominal current, although the duration of this surge is less than one millisecond (for a Philips Xitanium 150W 0.70$A_{DC}$ 230$V_{AC}$ LED driver datasheet -Full product code: 871829115008400- the inrush current is stated as 130$A_{AC}$ for 165 us and for the Meanwell HLG-150-H LED driver datasheet with a nominal input values of 0.75$A_{AC}$/230$V_{AC}$ has a cold start inrush current of 65$A_{AC}$ for 425 us). This current spike is one of the major challenges in lighting installations, where a single power line connected to several luminaires must support the sum of all of the inrush currents. This surge can trigger protection circuits. Thus, the limiting factor for the number of power supplies connected to a single power line is not the rated power but the inrush current.[19] Several studies have shown that these same electronic drivers that cause inrush currents are responsible for other negative electrical effects such as harmonic distortion and high neutral-conductor currents in the network.[20]

This study seeks to characterise and establish the electrical conditions that optimise the energy efficiency of outdoor LED lighting. To that end, the electrical parameters of power supply circuits in six electric panels were analysed before and after 63 MH lighting fixtures, i.e., floodlights, were replaced with 189 LED floodlights.

## 2. Installation

The floodlight installation that was the subject of this study is located along the coast side of the town of Fuengirola (Málaga, Spain, Latitude: 36.53564 and Longitude: -4.62139) (Figure 1).

Specifically, this study is based on the lighting of the beach along the main promenade of the city and examined 63 poles 12 m in height and separated by an average distance of 35 m (a distance of more than 2 Km). The objective of the installation is to obtain approximately an average illuminance of 10 lx (Em) and a illuminance uniformity greater than 0.3 (Em/Emin) on a 50 m wide sand beach. Discomfort glare measures are not taken into account as this is a lighting installation over a non-driving zone. Previously, a single MH discharge floodlight was mounted on each pole using a quartz metal halide lamps with clear outer bulb. The rated power of each lamp given by the manufacturer is 985 W and the luminaire uses an electromagnetic ballast unit to power the light source (Core: FeV 400-50HA and Coil base: Polyamide with F.G. 30%) with a 100 uF power factor correction capacitor. The real total power consumption of each floodlight will be described and analysed in the result and discussion section of this study according to field measures taken.

The original 63 MH floodlights were replaced with 189 new LED luminaires, each of them with a reference power consumption of 180 W. These new luminaires were chosen to provide an equivalent illuminance to the MH lamps and to improve the uniformity thanks to a better light distribution capability achieved through having a bigger number of luminaires per pole. The number and the power of the LED luminaires were selected based on computer simulations to obtain the specified desired illuminances and they were corroborated with field measures after their installation. The power supplied to the floodlights is distributed through six electrical panels. Each panel contains one or more circuits that have copper cables with a cross-sectional area of 6 mm$^2$ to feed a certain number of poles and a variable number of floodlights; this configuration was used for both the MH and LED luminaires. The configuration of these electrical panels and the theoretical power installed, is given in Table 1. We consider this is an appropriate public lighting installation to compare electrical parameters for conventional and LED luminaires. It has several electrical panels with identical luminaires and similar and a significant power connected to each of them.

**Figure 1.** General view of the study area and floodlights along the seafront promenades of Fuengirola (Málaga, Spain)

# 3. Materials and methods

## 3.1 Instrumentation

### *3.1.1 Clamp ammeters*

High-precision clamp ammeters (Kyoritsu. Model: K2413R) with a very wide measurement range (5mA – 1,000A) and a sample rate of three values per second were used to measure the peak current in each phase at the input of the electrical panel and also to measure the steady-state phases and neutral conductor currents.

### *3.1.2 Network analyser*

A network analyser (Circutor. Model: AR6. Measurement and recording according to EN 50160. Class 0.5) was used to measure the electrical parameters and harmonics in the supply lines: Voltage, current, active power, reactive volt amps, phase voltage and phase and neutral conductor current harmonics.

## 3.2 Method

The process followed in the investigation was as follows:

1. Different procedures were used for the two types of instrumentation: First, using the clamp ammeters, the peak phase currents at start-up, the nominal phase currents and the neutral conductor current in each of the lines of the six electrical panels were measured. These measurements were first taken with the MH luminaires and again with the LED luminaires installed. For both types, the parameters at start-up were measured by individually and sequentially connecting each of the lines in the electric panels. Additionally, the average nominal values were measured thirty minutes after start-up of the luminaires, which ensured that the operating temperature and any other parameters that affect the operation and the energy consumption of the luminaires had reached a steady state. Second, the aforementioned measurements were supplemented by recording the power in the six electrical panels using a network analyser. All of

the characteristic electrical parameters of the network and the harmonics were measured with the analyser installed at the input to the lighting equipment. These measurements were taken first with the MH luminaires and subsequently with the LED luminaires.

2. The collected data were used to study the electrical characteristics of the two types of lighting using various connection configurations (multiple distributions and total installed power on one line) in isolation for each electrical panel. The results for the two types of luminaires were compared. With these results, it was possible to evaluate the reductions in power consumption and compare the following significant values in the electrical supply lines: The peak currents at cold start-up, the current in the neutral conductor, the phase voltages, the power factor, the harmonics and the active power and reactive volt amps in the circuit. The results were evaluated, and conclusions regarding the electrical operating characteristics of the installation under study with the two types of lighting were reached.

## 4. Results and discussion

Initially, to simplify and as a reference, we show the specific data of only one out of the six electrical panels involved in the study as all of them are similar and later on we analyse the overall result of all the luminaires installed. Table 2 shows the values obtained with the clamp ammeters for the peak currents at cold start-up, the nominal phase currents and the neutral conductor current for the MH and LED luminaires powered from the electric panel CM-005. The peak current measured cannot be considered as an absolute value but used as a comparison element between the two technologies as the sample rate of the measure equipment is not fast enough as to accurately capture the exact peak value of the inrush current.

The installation was initially planned to be as balanced as possible between the three power phases, but there is in both cases a significant amount of current in the neutral cable. Many reasons can be suggested for this finding:

- The electrical installation is designed so that only one phase is available to power all the luminaires placed on each pole. As the number of poles connected to a line of an electrical panel are not always multiples of three, not all the phases power the same number of luminaires and they are not balanced.
- The loads connected on each phase may have changed with the time: Ageing of the ballast, cable, connectors and fuses; partial substitution of elements (mixing old and new devices), and remodelling and changes in the electrical installation due to requirements for temporary or special installations by the maintenance department of the city for holidays etc., installation mistakes in the lines' development and connections etc

Some of these problems have been solved with the substitution of all the old luminaires with new devices but the rest of elements are not addressed. Consequently the current in the neutral conductor is lowered due to the reduction of power installed, but it also changes from a 56.04% of the average currents of the phases with the MH luminaires to a 47.28% with the LED luminaires.

If we consider the inrush peak current we have to capture as values as large as 59.0 A in phase 1 for MH or a 60.6 A for phase 3 for LED. They, as a global value, are similar. However, if we compare the ratio between these values and the steady current measured on the same phase afterwards, for the MH the peak value found is 2.63 times the steady current but for the LED that ratio increases to 7.3.

Table 3 shows the results obtained with the network analyser for the following electrical parameters in the steady state: Power values (active and reactive, including both capacitive and inductive and the power factor), current, voltage and the harmonics of the phase voltages and currents and in the neutral conductor from the same CM-005 panel. Similar data were obtained for both the MH and LED floodlight configurations for the rest of the electrical panels involved. Figure 2 includes all the power triangles of the phases of this electrical panel with MH and LED luminaires showing watts, VARs and overall volt amps and the different lagging and leading nature of the power factor (PF) obtained.

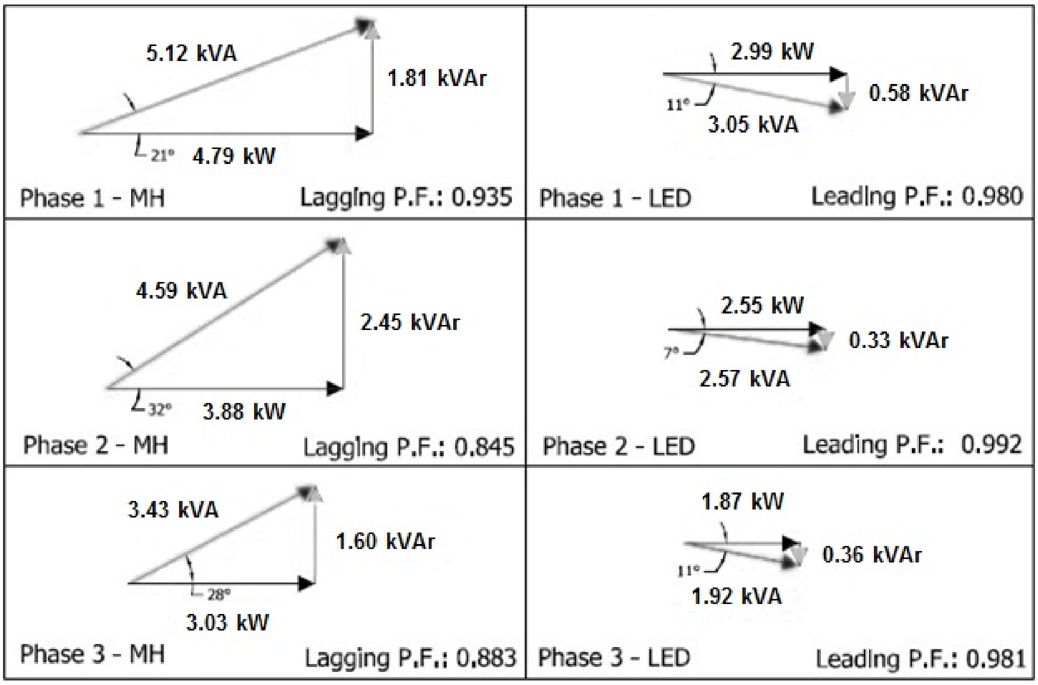
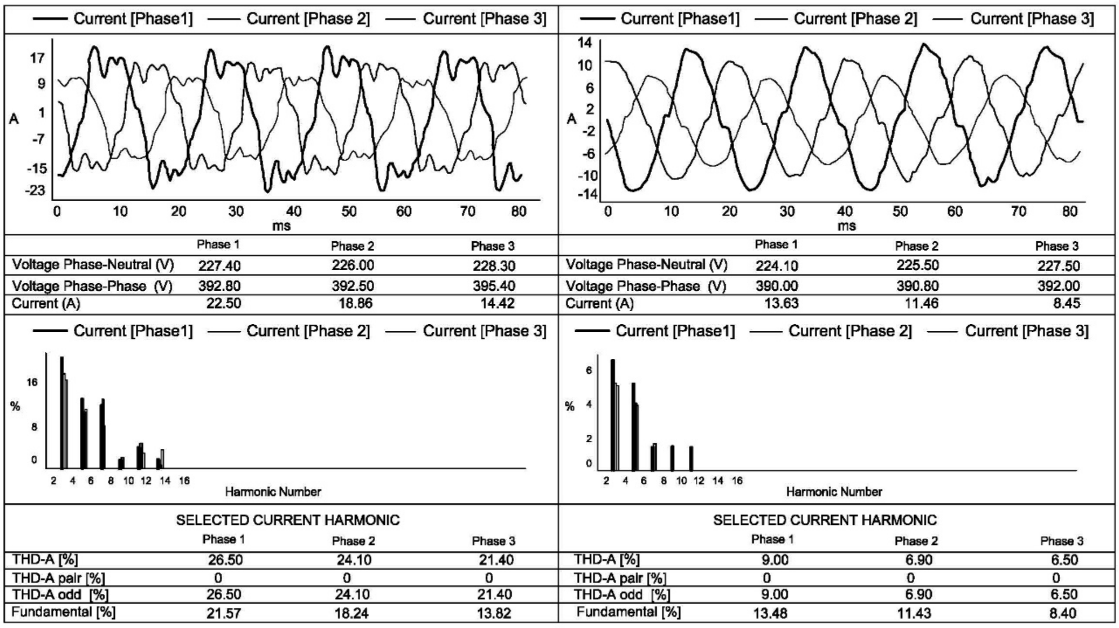


**Figure 2.** Phase triangle power diagrams of all the phases of the CM-005 electrical panel for MH and LED luminaires

Figure 3 shows comparisons of the distortions of the waveforms of the phase and the neutral conductor currents due to harmonics in the CM-005 electrical panel analysed for both the MH and the LED luminaires. The number of significant frequency harmonics is similar in both cases (6 in MH and 5 in LED) but their relevance (in %) is much bigger for the MH luminaires. The greater harmonics generated by the MH luminaires causes a more deformed waveform from the original sine shape in the powerline.



|  | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Voltage Phase-Neutral (V) | 227.40 | 226.00 | 228.30 |
| Voltage Phase-Phase (V) | 392.80 | 392.50 | 395.40 |
| Current (A) | 22.50 | 18.86 | 14.42 |

|  | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Voltage Phase-Neutral (V) | 224.10 | 225.50 | 227.50 |
| Voltage Phase-Phase (V) | 390.00 | 390.80 | 392.00 |
| Current (A) | 13.63 | 11.46 | 8.45 |

SELECTED CURRENT HARMONIC

|  | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| THD-A [%] | 26.50 | 24.10 | 21.40 |
| THD-A pair [%] | 0 | 0 | 0 |
| THD-A odd [%] | 26.50 | 24.10 | 21.40 |
| Fundamental [%] | 21.57 | 18.24 | 13.82 |

SELECTED CURRENT HARMONIC

|  | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| THD-A [%] | 9.00 | 6.90 | 6.50 |
| THD-A pair [%] | 0 | 0 | 0 |
| THD-A odd [%] | 9.00 | 6.90 | 6.50 |
| Fundamental [%] | 13.48 | 11.43 | 8.40 |

**Figure 3.** Waveform distortions of the phase currents and the neutral conductor current due to the harmonic currents in electrical panel CM-005 with MH and LED luminaires (THD-A: Current Total Harmonic Distortion) (MH: Left and LED: Right)

The measures obtained in all the 6 electrical panels with the two types of lighting technologies (MH & LEDs) are summarized and compared in Tables 4 to 7. Table 4 shows how the reactive volt amps measured have been reduced by slightly more than 35% with the LED luminaires, that the nature of the load changed from inductive to capacitive and that the real power values found show a real power reduction obtained of only 32%. That is much lower than the expected 46% shown in Table 1 as the power consumption of the MH luminaire (lamp + ballast) is a little less than expected and that of the LED luminaire is bigger than the declared by the manufacturer. Considering that the two technologies use the same electrical installation, this overconsumption can only be generated by the LED luminaires and, consequently, their declared nominal values are not exact on our field installation.

The economic saving obtained by the change of luminaires is proportional to the active power reductions. However, in some cases, this cost reduction can be increased by changing the total power contracted on each electrical panel and taking advantage of the lower amount of powerless reactive current generated by the improvement of the power factor from averages values of 0.91 (MH) to 0.97 (LED).

Table 5 shows that the ratio in percentage of current in the neutral conductor in each electrical panel relative to their average nominal phase currents decreased by 24% for the LED luminaires compared with that of the MH luminaires. This reduction is similar to the reduction in power in each electrical panel.

In addition, to measuring the peak currents at start-up and the currents in the neutral conductor for each of the six electrical panels, the voltage and current harmonics in the panels were analysed for both the MH and LED luminaires (Table 6). With the LEDs, the percentage of harmonics in the phase voltages was lower, typically by 27%. However, this reduction was not uniform; an increase of 6.25% in the percentage of odd harmonics was measured in panel CM-017. Table 6 also shows a substantial decrease in these phase current harmonics, with an average reduction of 63.16%. The reduction in odd harmonic currents in the neutral conductor was less consistent: An average reduction of 11.13% was observed in three of the electrical panels, whereas in panels CM-017, CM-062 and CM-145, increases of 11.67%, 58.74% and 22.54%, respectively, were observed.

Table 7 shows the ratio between the cold start inrush currents found and the steady phase current measured. As a comparison value, the ratio found with MH luminaires is less than 2 but the same ratio with LEDs is larger than 6. This difference emphasizes that the peaks are much bigger with the LED technology although the nominal current with the LED is a 32% less as shown in Table 4. To obtain a more accurate measure a different type of equipment has to be used.

Conventional household circuit breakers (B type) trip in a range of 3-5 times the nominal current of the equipment. Public lighting protection systems (C type) trip at 5-10 times that current. This second range covers the measured inrush peaks of MH luminaires but the indicated and measured peak for LED can randomly overpass that limit as was initially observed on our study set. The consequence of this random process was that almost every time that the installation was powered on in a cold start one or two line protections (out of the total of 18 in the test installation) had to be rearmed after an initial trip. This failure was found in all the circuits several times. Consequently a bigger transitory hysteresis is required for this new installations and circuit breakers designed for engines and power transformers can be used as they have a transitory trip range of 10-15 times of their nominal current (D type) (Figure 4). Once these new protections were installed the cold start tripping problem totally disappeared in our installation.

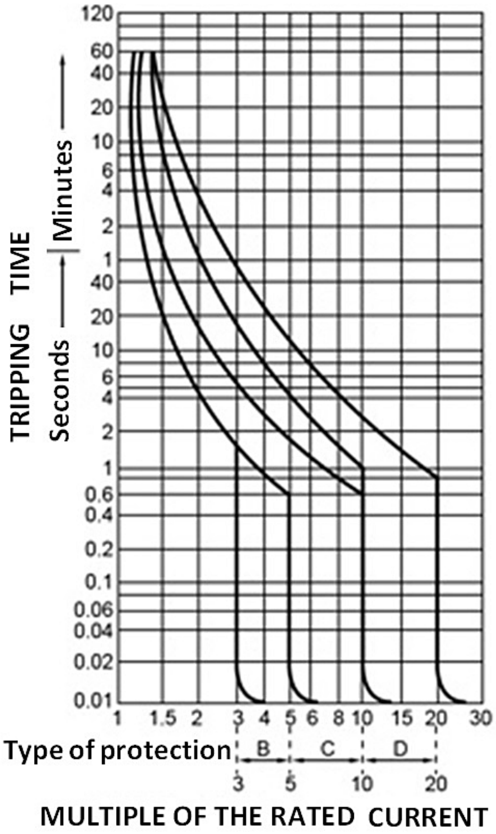


**Figure 4.** Tripping range specification for class B, C and D type of commercial circuit breakers

## 5. Conclusions

This study compared types of lighting technology used in a large outdoor lighting installation and the concerns that should be taken into account when replacing conventional luminaires with new LED equipment using the same electrical and mechanical infrastructure. The LED luminaires have produced significant energy savings over their MH equivalents as the light emitted by the LEDs is more directional.

Moreover, the electronic drivers of the LED light sources significantly reduced the power factor of the installation, which changes from inductive to capacitive. Considering the electrical values of the lighting installation:

- Our new LED luminaires require, overall, 32% less nominal installed power and 35% less reactive volt amps. That is almost 25% less power saving than expected because the LED luminaire consumed more energy than their nominal specification. We consider that the power consumption of any new LED luminaire should be verified with several test samples before accomplishing a large modification of any lighting installation to avoid this type of problem.
- The power factor is improved from an average of lagging 0.91 for the MH installation due to leading 0.97 for the LED luminaires generated by the capacitors of their drivers.
- In the steady state, it was observed that the current in the neutral conductor was reduced proportionally to the reduction in power. However, the short-term peak currents at cold start-up of the LED luminaires were more than twice those of the MH luminaires. This has been found to be a mayor drawback when planning this type of large technology renovation.
- A reduction of slightly more than 60% was observed in the odd harmonics in the circuit currents. The harmonics in the phase voltages and the current in the neutral conductor were generally reduced, averaging nearly 25% and 10%, respectively. It has been observed that this reduction in harmonics caused less distortion in both the current and voltage waveforms.

From the aforementioned results, it can be concluded that the change from MH to LED luminaires improves significantly all the electric parameters studied except for the peak currents at cold start-up. It was verified that these surges may randomly trip the surge protectors placed in the electrical panels, cutting off power to the installation and requiring a second starting procedure. For this reason, converting a lighting installation from a conventional MH technology to LEDs can be done without any type of concern about the electrical and mechanical installation that is already being used other than installing new magneto-thermal circuit breakers adapted to the new power demand with slow trip curves. These must be used to optimize the protection and to tolerate the short term peak currents that occur when the LED luminaires are first energised.[21]

**Funding**

The authors received no financial support for the research, authorship, and/or publication of this article.

**Acknowledgement**

The authors wish to express their sincere appreciation to the Technical Lighting Service of the municipality of Fuengirola (Málaga, Spain).

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## Figure captions

**Figure 1.** General view of the study area, location and distribution of electrical panels and floodlights along the seafront promenades of Fuengirola (Málaga, Spain)

**Figure 2.** Phase triangle power diagrams of all the phases of the CM-005 electrical panel for MH and LED luminaires

**Figure 3.** Waveform distortions of the phase currents and the neutral conductor current due to the harmonic currents in electrical panel CM-005 with MH and LED luminaires (MH: Left and LED: Right)

**Figure 4.** Tripping range specification for class B, C and D types of commercial circuit breakers

**Table 1.** Electrical panels and theoretical installed power per panel with metal halide (MH) and LED luminaires

| Electrical Panel | Number of poles | Number of MH floodlights | Total Power MH (kW) | Number of LED floodlights | Total Power LED (kW) |
|---|---|---|---|---|---|
| CM-005 | 12 | 12 | 12.00 | 36 | 6.48 |
| CM-017 | 16 | 16 | 16.00 | 48 | 8.64 |
| CM-022 | 10 | 10 | 10.00 | 30 | 5.40 |
| CM-062 | 8 | 8 | 8.00 | 24 | 4.32 |
| CM-107 | 9 | 9 | 9.00 | 27 | 4.86 |
| CM-145 | 8 | 8 | 8.00 | 24 | 4.32 |
| **Total** | **63** | **63** | **63.00** | **189** | **34.02** |

**Table 2**. Steady and inrush cold start peak currents (A) for the CM-005 electrical panel considering all the harmonics (wide) and filtered to the main network frequency (50Hz)

| | **METAL HALIDE**<br>12 poles and one 1000W luminaires per pole | | **LED**<br>12 poles and three 180W LED luminaires per pole | |
|---|---|---|---|---|
| | **PEAK CURRENTS AT START-UP (A)** | | **PEAK CURRENTS AT START-UP (A)** | |
| | **Current (wide)** | | **Current (wide) (A)** | |
| **Phase 1** | 59.0 | | 14.6 | |
| **Phase 2** | 43.6 | | 19.1 | |
| **Phase 3** | 30.0 | | 60.6 | |
| | **NOMINAL STEADY CURRENTS (A)** | | **NOMINAL STEADY CURRENTS (A)** | |
| | **Current (wide)** | **Current (50 Hz)** | **Current (wide)** | **Current (50 Hz)** |
| **Phase 1** | 22.5 | 21.6 | 14.1 | 13.9 |
| **Phase 2** | 28.0 | 17.5 | 11.3 | 11.3 |
| **Phase 3** | 13.2 | 12.8 | 8.3 | 8.2 |
| **Neutral** | 11.9 | 8.1 | 5.3 | 4.9 |

**Table 3.** Electrical parameters and harmonics obtained with the network analyser for panel CM-005 (THD-V: Voltage Total Harmonic Distortion / THD-A: Current Total Harmonic Distortion)

| | **METAL HALIDE**<br>12 poles and one 1000 W luminaires per pole | | | | **LED**<br>12 poles and three 180 W luminaires per pole | | | |
|---|---|---|---|---|---|---|---|---|
| | **Active Power (KW)** | **Reactive Power (KVAR)** | **Apparent Power (KVA)** | **Power Factor** | **Active Power (KW)** | **Reactive Power (KVAR)** | **Apparent Power (KVA)** | **Power Factor** |
| **Phase 1** | 4.79 | 1.81 | 5.12 | 0.935 | 2.99 | - 0.58 | 3.05 | 0.980 |
| **Phase 2** | 3.88 | 2.45 | 4.59 | 0.845 | 2.55 | - 0.33 | 2.57 | 0.992 |
| **Phase 3** | 3.03 | 1.60 | 3.43 | 0.883 | 1.87 | - 0.36 | 1.92 | 0.981 |
| | **Voltage phase-neutral** | **THD-V odd (%)** | **Current (A)** | **THD-A odd (%)** | **Voltage phase-neutral** | **THD-V odd (%)** | **Current (A)** | **THD-A odd (%)** |
| **Phase 1** | 227.10 | 2.40 | 22.50 | 26.50 | 223.40 | 1.30 | 13.75 | 9.00 |
| **Phase 2** | 225.80 | 2.20 | 20.35 | 24.10 | 225.60 | 1.30 | 11.46 | 6.90 |
| **Phase 3** | 227.90 | 1.80 | 15.05 | 21.40 | 227.10 | 1.20 | 8.46 | 6.50 |
| **Neutral** | --- | --- | 20.86 | 82.60 | --- | --- | 5.58 | 42.40 |

**Table 4.** Active power, apparent power and power factor obtained with the network analyser for all the electrical panels

| **ACTIVE POWER / APPARENT POWER / POWER FACTOR** | | | | | | |
|---|---|---|---|---|---|---|
| **METAL HALIDE** | | | | **LED** | | |
| **Electrical Panel** | **KW** | **KVA** | **Power Factor** | **KW** | **KVA** | **Power Factor** |
| **CM-005** | 11.71 | 13.15 | 0.89 | 7.41 | 7.59 | 0.98 |
| **CM-017** | 11.10 | 12.22 | 0.91 | 9.95 | 10.21 | 0.97 |
| **CM-022** | 10.39 | 11.43 | 0.91 | 5.79 | 6.08 | 0.95 |
| **CM-062** | 8.51 | 9.45 | 0.90 | 5.61 | 5.80 | 0.97 |
| **CM-107** | 8.29 | 8.62 | 0.96 | 4.91 | 5.08 | 0.97 |
| **CM-145** | 7.85 | 8.16 | 0.96 | 5.68 | 5.83 | 0.97 |
| TOTAL | **57.85** | **63.03** | **---** | **39.35** | **40.59** | **---** |

**Table 5.** Ratio (%) between the current in the neutral conductor versus their average nominal phase currents for the MH and LED luminaires on each electrical panel.

| **Electrical Panel** | **MH (%)** | **LED (%)** |
|---|---|---|
| CM-005 | 56.04 | 47.26 |
| CM-017 | 64.33 | 24.63 |
| CM-022 | 113.23 | 136.31 |
| CM-062 | 100.27 | 59.83 |
| CM-107 | 71.05 | 41.57 |
| CM-145 | 68.18 | 18.93 |
| **Average** | **78.85** | **54.76** |

**Table 6.** Reductions in the percentage of harmonics in the phase-neutral voltages and in the phase and neutral currents

| **Electrical Panel** | **Phase-Neutral Voltage (%)** | **Phases Current (%)** | **Neutral Current (%)** |
|---|---|---|---|
| CM-005 | 40.63 | 68.89 | 48.67 |
| CM-017 | -6.25 | 50.28 | -11.67 |
| CM-022 | 61.90 | 54.83 | 69.85 |
| CM-062 | 24.44 | 54.10 | -58.74 |
| CM-107 | 7.84 | 78.31 | 41.21 |
| CM-145 | 34.78 | 77.35 | -22.54 |
| **Average** | **27.22** | **63.96** | **11.13** |

**Table 7.** Ratio of cold start inrush current to the maximum phase current for MH and LED luminaires.

| **Electrical Panel** | **MH** | **LED** |
|---|---|---|
| CM-005 | 2.63 | 7.33 |
| CM-017 | 1.49 | 3.57 |
| CM-022 | 3.38 | 5.29 |
| CM-062 | 2.05 | 7.50 |
| CM-107 | 1.97 | 3.35 |
| CM-145 | 2.48 | 4.59 |
| **Average** | **2.33** | **6.18** |