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MASTER EN ENERGÍAS RENOVABLES DISTRIBUIDAS

ANÁLISIS DE LA TEMPERATURA Y LA DISTORSIÓN DE LA TENSIÓN EN LÁMPARAS LED

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Trabajo para optar al

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Profesor Supervisor:

AURORA GIL DE CASTRO

Córdoba, junio, 2019

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ELENA GUTIÉRREZ BALLESTEROS

Tesis (Proyecto) presentada(o) a la Comisión integrada por los profesores:

AURORA GIL DE CASTRO

Para completar las exigencias del Master
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INFORME DEL DIRECTOR DEL TRABAJO FIN DE MASTER

La alumna Elena Gutiérrez Ballesteros viene realizando labores investigadoras desde su último curso del Grado con el Grupo de Investigación Instrumentación y Electrónica Industrial. Ha compaginado sus estudios de Máster con un contrato de investigación en el análisis de datos que servirá para solicitar un proyecto nacional, además de colaborar en el proyecto Galileo 'Edificio inteligente en Comunidades de Atención Residencial' concedido por la Universidad de Córdoba.

En su anterior TFG del Grado de Electrónica Industrial realizó una plataforma en la que interconectaba diferentes instrumentos de laboratorio con ayuda del software Labview NXG. Su trabajo supuso un importante hito en el grupo ya que dicho SW no había sido usado previamente, y carecíamos de conocimientos previos para su orientación. Por tanto, fue trabajo íntegramente propio de la alumna.

Como aplicación de dicha plataforma, en el previamente mencionado TFG midió una serie de lámparas LED para probar la plataforma. Sin embargo, no se llegó a profundizar en los resultados obtenidos por no ser objeto de estudio en aquel caso.

Tras haber cursado este máster de Energías Renovables Distribuidas, y con los conocimientos adquiridos durante el mismo, la alumna ha realizado un estudio pormenorizado de dichos resultados, teniendo en cuenta la metodología a seguir y analizando los resultados con mucha pulcritud. En estos resultados se ha trabajado con el grupo de investigación '*Electric Power Engineering*' de la Universidad técnica de Lulea, bajo la supervisión de la doctora Sarah Ronnberg.

La alumna ha trabajado de forma autónoma, analizando numerosos datos de diversas lámparas, e intentando obtener conclusiones de dicho análisis que puedan usarse en un artículo de revista. Es un estudio novedoso ya que incluso la metodología ha tenido que ser evaluada y verificada por no existir normativa al respecto de cómo realizar estas mediciones. Este estudio supondrá un importante hito en los comités reguladores ya que la estabilización térmica no había sido considerada hasta la fecha.

Resultado de este trabajo son los siguientes artículos en congresos:

- Gutiérrez Ballesteros, Elena; Gil de Castro, Aurora; Rönnberg, Sarah; Sakar, Selcuk. TEMPERATURE AND VOLTAGE DISTORTION ANALYSIS IN LED LAMPS. 25th International Conference on Electricity Distribution, Madrid 3-6 June 2019
- Gutiérrez Ballesteros, Elena; Gil de Castro, Aurora; Garrido Zafra, Joaquín; Medina Gracia, Ricardo; Rönnberg, Sarah; Moreno Muñoz, Antonio. STUDY OF LED LAMPS BEHAVIOR DUE TO VOLTAGE AND TEMPERATURE VARIATIONS. 26º Seminario Anual de Automática, Electrónica Industrial e Instrumentación, Córdoba 3-5 July 2019

Se encuentra actualmente trabajando en una versión casi definitiva del mismo para una revista de investigación de elevado impacto según JCR.

Además, ha publicado otros artículos de otra temática en la que la alumna también trabaja:

- Ronnberg, Sarah; Gutiérrez Ballesteros, Elena; Gil de Castro, Aurora; Westman, Malin; Brodin, Magnus. LONG-TERM POWER QUALITY MEASUREMENTS IN MEDIUM VOLTAGE NETWORKS. 25th International Conference on Electricity Distribution, Madrid 3-6 June 2019

Córdoba, a 15 de junio de 2019

El/la Directora/a	El/la Directora/a
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PROPUESTA DE TRIBUNAL PARA EL TRABAJO FIN DE MASTER

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Como tutor/a del Trabajo Fin de Máster especificado a continuación, se propone a la Comisión Académica del Máster los siguientes miembros para el Tribunal de dicho trabajo:

Título del TFM: ANÁLISIS DE LA TEMPERATURA Y LA DISTORSIÓN DE LA TENSIÓN EN LÁMPARAS LED

Autor: Elena Gutiérrez Ballesteros

Perfil: Investigador

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5	Eduardo Cañete Carmona

Córdoba, a 28 de junio de 2019 . El/la Tutor/a del TFM:

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Fdo: Aurora R. Gil de Castro

Normativa de referencia: Artículo 9 de la NORMATIVA ACADÉMICA BÁSICA PARA EL DESARROLLO DE LOS MÁSTERES OFICIALES Aprobada por Consejo de Gobierno de 2 de marzo de 2007 y modificaciones posteriores.
"*Los trabajos de fin de Máster serán expuestos y defendidos en acto público ante un tribunal para su evaluación y calificación. Este tribunal será aprobado por la Comisión de Estudios de Postgrado, a propuesta del Consejo Académico del Máster y estará compuesto por tres o cinco miembros doctores, de los que al menos uno de ellos será externo al Máster, no formando parte del mismo, los profesores que hayan dirigido los trabajos objeto de evaluación. Si por alguna causa debidamente justificada, un director de trabajo de fin de Máster debiera formar parte del tribunal de estos trabajos, será sustituido en el proceso de evaluación del trabajo dirigido. parte del tribunal de estos trabajos, será sustituido en el proceso de evaluación del trabajo dirigido*".

DEDICATORIA

A mi familia, amigos y profesores por todo el apoyo recibido estos años.

AGRADECIMIENTOS

Mi especial agradecimiento a Aurora, por confiar en mi trabajo, por todo el apoyo durante esta etapa tan importante y guiarme profesionalmente.

Al grupo de investigación Instrumentación y Electrónica Industrial (IEI) por todo el apoyo recibido, trabajo en equipo y compañerismo.

A Víctor, por su paciencia ayudándome tantas veces.

A Antonio por todo el apoyo recibido.

A mis compañeros de laboratorio, por toda la ayuda recibida y por todos los buenos momentos que han hecho las horas de trabajo más amenas.

Y por supuesto, a mi familia, amigos y compañeros que me han apoyado desde el comienzo.

¡Gracias a todos!

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RESUMEN

El objetivo del TFM es estudiar el comportamiento de la estabilización térmica en lámparas LED bajo diferentes condiciones de prueba y determinar un método y un parámetro adecuados para determinar el tiempo de estabilización. El artículo describe las diferencias entre las lámparas LED con respecto a parámetros como la iluminación, la potencia activa o la eficiencia, a diferentes temperaturas y voltajes de alimentación. Además, se ha medido la emisión de las lámparas LED, utilizando como parámetros el THD de la corriente y el valor RMS de la corriente a lo largo del tiempo de estabilización para analizar su tendencia, así como la inmunidad frente a perturbaciones en la red, centrando el estudio en el impacto de las variaciones de la tensión suministrada.

Palabras Claves: eficiencia, estabilización, iluminancia, lámpara LED, potencia activa, temperatura, tensión

ABSTRACT

The aim of the master project is to show that the thermal stabilization time varies between lamps and test condition and to determine a proper method (and which parameter to use) for finding at what point the lamps are considered stable. It is shown the differences in parameters like illuminance, active power or efficiency with different temperatures and supply voltages. In addition, it has been tested the emission of LED lamps, using as parameters the THD of the current and RMS current value along the stabilization time, as well as the immunity focusing in the impact from voltage fluctuation and from over and under voltage.

Keywords: active power, efficiency, illuminance, LED lamp, stabilization, supply voltage, temperature

1. INTRODUCCIÓN

Caracterizadas por su bajo consumo, una buena eficiencia lumínica y gran durabilidad, las lámparas LED están extendidas para uso doméstico y alumbrado público. Por el contrario, las características ópticas, fiabilidad y tiempo de vida tienen una gran dependencia con la temperatura de las lámparas LED [1], [2]. De hecho, el fabricante indica cómo varían los parámetros con la temperatura. Ha habido muchos informes sobre fallos tempranos en lámparas LED que han sido un impedimento para su aceptación pública [3]. Por lo tanto, la temperatura siempre es un tema crucial para el desarrollo de los productos LED. Cuando se realiza un ensayo sobre un dispositivo, independientemente de que el objetivo sea el momento del fallo, la calidad de la luz emitida o algún índice de calidad de suministro, es importante eliminar las incertidumbres que afecten a la reproducibilidad de los ensayos. Estas incertidumbres pueden ser por ejemplo variaciones en la tensión de alimentación de la lámpara o variaciones en la temperatura ambiente durante la realización de las medidas. Para lograr una mejor reproducibilidad al medir lámparas LED se recomienda encender la lámpara LED con antelación a la realización de medidas, dejándola el tiempo suficiente para que la lámpara se considere estable. Respecto al tiempo de estabilización de las lámparas LED, el estándar IEC 62612:2013 [4] solo considera la estabilización desde el punto de vista eléctrico fijándolo en 15 minutos, el estándar IEEE 1789-2015 [5] no establece un tiempo de estabilización a pesar de presentar muchos resultados de mediciones sobre lámparas LED, así como mediciones de la iluminación. Los estándares IEC 61000-4-13 [6] y 61000-4-15 [7] de inmunidad no contienen ninguna sugerencia para la estabilización de la iluminaria. Es por esto que cabe preguntarse cuánto tiempo tardan las lámparas LED en estabilizarse desde que son encendidas. Es sabido que medir en periodos de tiempo diferentes lleva a obtener diferentes resultados debido a la variación de temperatura, lo que es importante para la veracidad de los ensayos y para realizar estudios comparativos. En [8] se muestra que la temperatura de una lámpara LED de exterior de 80 W se estabiliza solo después de un tiempo de operación de varias horas. Se encontraron resultados similares en [3] con una lámpara LED de exterior de 114 W. Los estudios mencionados solo consideraron la característica térmica de las lámparas LED sin considerar la luz emitida ni las condiciones eléctricas.
En otro estudio [9], las lámparas fueron sometidas a variaciones moduladas rectangulares de tensión para pruebas de inmunidad. Aunque el enfoque de este estudio fue más bien la prueba de inmunidad, el tiempo de estabilización suficiente se indicó entre 10 min. y 15 min, dependiendo de la lámpara.

Además, el propósito de [10] fue analizar la variación en la intensidad de la luz durante la estabilización térmica de las lámparas LED, mostrando que disminuye con el tiempo, recomendando al menos 60 minutos de medición con lámparas LED residenciales. Sin embargo, solo se usó la iluminancia como parámetro para determinar la estabilización térmica de las lámparas.

En este TFM, esa investigación se extiende, definiéndose un método que utiliza también la iluminación, la potencia y la temperatura. En base a eso, la idea del documento actual es mostrar que el tiempo de estabilización térmica varía entre las lámparas y la condición de prueba, así como determinar un método y el parámetro apropiados que se utilizarán para encontrar en qué punto las lámparas se consideran estables desde esos puntos de vista. Además, después de alcanzar la estabilización térmica, se pretende caracterizar la emisión, la inmunidad y el rendimiento de las lámparas LED en función de la temperatura. Para hacer eso, las lámparas LED se han refrigerado con un ventilador externo, y se han estudiado diferentes parámetros en relación con la temperatura.

Por otro lado, la calidad de la energía está relacionada con las desviaciones en la tensión y la corriente de la forma de onda sinusoidal de amplitud y frecuencia constantes. El deterioro en la calidad de la energía se debe a eventos y perturbaciones en el estado estable, incluida la distorsión armónica entre otros [3]. Es necesario estudiar el impacto que la introducción a gran escala de las lámparas LED tendrá en la red en términos de la calidad de la energía desde el punto de vista de la distorsión armónica (con la consiguiente pérdida de calidad del suministro de electricidad) y de variaciones en la intensidad de la luz. Las lámparas LED actualmente en el mercado muestran una amplia variedad de contenido en la emisión de corriente armónica y el factor de potencia de desplazamiento, incluso cuando se alimentan con voltajes sinusoidales ideales [8].

2. ANTECEDENTES

Este trabajo es una continuación del estudio realizado en el TFG "Plataforma y estudio del comportamiento de lámparas LED frente a variaciones de tensión" realizado en la Universidad de Córdoba en el año 2018, el cual se enmarcaba dentro del proyecto titulado "Probability for disturbing light intensity variations of LED lighting – a pre-study" subvencionado por la Agencia de la Energía de Suecia (Swedish Energy Agency) (2017/09/01-2018/03/01) con número de proyecto LTU-1475-2017, en el cual participaba el grupo de Investigación TIC-240 Instrumentación y Electrónica Industrial de la Universidad de Córdoba.

Dentro de los antecedentes también se encuentran los citados en la introducción y que se referencian también a continuación:

- R. Lenk and C. Lenk, 2011, Practical Lighting Design with LEDs, 1st ed., New Jersey: Wiley, p. 62.
- Jaana Jahkonen, Marjukka Puolakka y Liisa Halonen, 2013, "Thermal Management of Outdoor LED Lighting Systems and Streetlights—Variation of Ambient Cooling Conditions", LEUKOS, 9:3, 155-176
- X. Luo, W. Xiong, T. Cheng y S. Liu, 2009, "Temperature estimation of high-power light emitting diode street lamp by a multi-chip analytical solution," in IET Optoelectronics, vol. 3, no. 5, 225232
- X. Luo, T. Cheng, W. Xiong, Z. Gan, y S. Liu, 2007, "Thermal analysis of an 80 W light-emitting diode street lamp," IET Optoelectronics, vol. 1, issue. 5, 191- 196
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- S. Sakar, S. Rönnberg y M. H. J. Bollen, 2018, "Light intensity behavior of LED lamps within the thermal stabilization period," 18th Int. Conf. on Harmonics and Quality of Power, ICHQP, 1-6.

3. OBJETIVO

El objetivo de este estudio es profundizar en el comportamiento de lámparas LED atendiendo a las características de la tensión de alimentación y temperatura medida en la lámpara, para ver el efecto sobre potencia activa, iluminancia y eficiencia a raíz de los resultados obtenidos en el TFG en el que este estudio se basa. Dicho TFG titulado "Plataforma y estudio del comportamiento de lámparas LED frente a variaciones de tensión" se defendió por la misma autora que este TFM para la obtención del título de Graduada en Ingeniería Electrónica Industrial (2018).

Para ello, ante la falta de normativa al respecto de la medida de temperatura en la lámpara, en primer lugar, es objeto de estudio la metodología apropiada a seguir para obtener conclusiones relevantes acerca de la temperatura. La línea del estudio es en relación con la variación de la temperatura de la lámpara respecto a la temperatura ambiente, teniendo en cuenta la relación que puedan presentar con las variaciones de la iluminancia y de la potencia activa. Estos estudios se realizan contemplando diversas formas de onda de la tensión de alimentaciones, es por ello que se estudia la inmunidad de las lámparas alimentándolas con tensiones de amplitudes mayores y menores que la nominal de red y con fluctuaciones en la amplitud con una frecuencia de modulación de 5 Hz.

4. METODOLOGIA

En la metodología se definen las condiciones de los ensayos realizados: ensayos con y sin ventilador para estudiar el comportamiento de las lámparas LED cuando se encuentran sometidas a diferentes temperaturas y alimentadas con diferentes tensiones de alimentación, con el fin de estudiar la inmunidad de dichas lámparas frente a fluctuaciones en la tensión, así como a valores de tensión mayores y menores al de la red.

Además, se estudian las curvas de temperatura obtenidas a partir de las matrices de temperatura tomadas con la cámara térmica durante 60 o 90 minutos con un periodo de muestreo de 10 minutos, según se ha considerado necesario para el estudio de la estabilización de las lámparas. Se comparan las curvas de la temperatura ambiente con la temperatura en el cuerpo de la lámpara LED para ver si siguen el mismo patrón.

También se incluye un estudio de la reproducibilidad de las medidas, comparando las distintas medidas con y sin fluctuación en la tensión de la alimentación, y con y sin ventilador, refrigerando las lámparas y variando el tiempo entre la toma de medidas para verificar la exactitud de los valores obtenidos. Es decir, se ha estudiado la reproducibilidad para medidas tomadas en días distintos próximos entre sí en el periodo de verano del año 2018 y 2019 y también se ha comprobado la reproducibilidad de las medidas en el transcurso del año comparando las medidas en verano de 2018 con las de 2019. Como resultado de esto se han obtenido unos valores muy similares cuando la diferencia es de pocos días y una variación de valor constante para la iluminancia y en la temperatura al refrigerar con el ventilador cuando el tiempo entre mediciones es de un año, lo que se podría explicar parcialmente por la degradación de la iluminancia emitida por las lámparas LED y por las variaciones y desajustes que el ventilador haya podido sufrir a lo largo de un año.

5. RESULTADOS

Los resultados se dividen en dos secciones, la primera de ellas contiene propiamente los resultados, y es en la que se muestran las variaciones de la temperatura, iluminancia y potencia activa respecto al instante anterior. Se obtiene así, el tiempo de estabilización requerido para cada parámetro, el cuál ha sido fijado como el instante para el cual la variación de los parámetros es menor o igual al 1%.
La segunda sección es una discusión en la que se abordan los puntos que se indican a continuación:

- La emisión de las lámparas LED desde el punto de vista del THD *(Total Harmonic Distortion)* de la corriente y el valor RMS de la corriente. La topología de las lámparas parece explicar los tres tipos de comportamientos que se observan atendiendo a estos dos parámetros.

- La inmunidad de las lámparas LED frente a fluctuaciones en la tensión de alimentación y huecos y sobretensiones. Los parámetros estudiados han sido la iluminancia, potencia activa y eficiencia.

- El comportamiento de las lámparas LED con la temperatura comparando las variaciones entre los parámetros estudiados para todas las lámparas. Los resultados muestran que la iluminancia, potencia activa y eficiencia se mantienen dentro de un rango cuando las lámparas LED están sometidas a diferentes condiciones ambientales, las cuales han sido simuladas usando la refrigeración por ventilador y sin utilizar la refrigeración, sin importar la diferencia de temperatura de la lámpara LED.

6. CONCLUSIONES

Se han obtenido conclusiones del estudio de la curva de temperatura y la reproducibilidad de la metodología, así como de los resultados, tanto de la parte de estabilización de la lámpara LED como la parte de discusión sobre la emisión, inmunidad y comportamiento de los parámetros frente a la temperatura y condiciones ambientales.

En esta memoria queda recogida una breve exposición de lo que ha resultado en un texto para un artículo escrito para su publicación en una revista científica. Dicho texto se adjunta en el Anexo A en el cual queda explicado detalladamente todo el estudio realizado, con todas las consideraciones realizadas y todas las conclusiones obtenidas a raíz de los resultados obtenidos.

7. ESTUDIOS FUTUROS

En base a este estudio, profundizar en la topología de las lámparas resultaría de gran interés para poder hacer una clasificación más exhaustiva del comportamiento observado en la iluminancia, potencia activa y eficiencia, así como en la variación en la temperatura debido a los componentes que integran las lámparas LED.

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[8] X. Luo, T. Cheng, W. Xiong, Z. Gan, and S. Liu, 2007, "Thermal analysis of an 80 W light-emitting diode street lamp," *IET Optoelectronics*, vol. 1, issue. 5, 191- 196

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A N E X O S

ANEXO A: TEXTO DEL ARTÍCULO PARA REVISTA

Abstract

The aim of the paper is to study the thermal stabilization behaviour in LED lamps under different test conditions and to determine a proper method and parameter for finding the stabilization time. The paper describes the differences between LED lamps regarding parameters like illuminance, active power or efficiency, under different temperatures and supply voltages. In addition, the emission of LED lamps has been considered along the stabilization time, using as parameters the THD of the current and RMS current value. Finally, the immunity study has also been included with the impact over LED lamps subjected to voltage fluctuation and over and under voltage.

Introduction

Characterized by their low consumption, good illumination efficiency and high durability, LED lamps are currently extended for many applications in domestic use as well as in street lighting. However, optical characteristics, reliability, and lifetime strongly depend on temperature in LED lamps [1], [2]. In fact, the manufacture indicates how the parameters are affected by the temperature variation. There have been many reports about early failures of lamps that have been seen as a barrier in the public acceptance of LED lamps [3]. Therefore, temperature is always a crucial issue for LED product development. When testing a device, regardless of the aim being time of failure, light output quality or some power quality index, it is important to eliminate uncertainties affecting the reproducibility of the tests. These uncertainties can be e.g. variations in voltage feeding the lamp or variations in the ambient temperature during the measurement. To achieve better reproducibility when measure LED lamps it is recommended to allow the lamp to burn for a certain amount of time, i.e. until it is considered stable. However, standards only consider the stabilization from the electrical point of view but the thermal stabilization has not been considered yet, as 15 minutes stated in IEC 62612:2013 [4], while IEEE standard 1789-2015 [5] does not stablish a stabilization time though presents lighting metrics among many other LED lamps measurements. Neither immunity standards 61000-4-13 [6] nor 61000-4-15 [7] give information about stabilization time for lighting devices. So that, it is claimed to wonder and to investigate how long LED lamps take to reach the stabilization of the different parameters, not only from an electrical but also from a thermal point of view. Stating a right thermal stabilization time is imperative according to make true tests and true benchmarking since different temperatures can lead to different measurements results. In [8] it is showed that the temperature of an 80 W LED street lamp is stabilized only after an operation time of several hours. Similar results were found in [3] with a 114 W LED street lamp. The aforementioned studies only considered the thermal characteristic of the LED lamps without considering neither light output nor electrical quantities.

Moreover, the purpose of [9] was to analyze the variation in the light intensity during thermal stabilization of the LED lamps, showing that it decreases with time, recommending at least 60 minutes measurement with residential LED lamps. However, only the illuminance was used as a parameter to determine the thermal stabilization of the lamps.

On the other hand, power quality is related to the deviations in the voltage and current of the sinusoidal waveform of constant amplitude and frequency. The deterioration in the power quality is due to events and disturbances in the steady state, including harmonic distortion among others [3]. As it is said in [10], an electric device by itself adds a distortion in the grid which affects all the connected devices, so that, it is difficult to know in what device the distortion started.

In another study [11], the lamps were subjected to rectangular modulated voltage variations for immunity testing. Although the focus of this study was rather immunity testing, the sufficient stabilization time was indicated between 10 min and 15 min depending on the lamp.

The novelty of this study is that here is extended to give a method not only using illuminance but also active power and temperature. Based on that, the idea of the current paper is to show that the thermal stabilization time varies between lamps and test condition, as well as to determine a proper method with an appropriated parameter to be used for finding at what point the lamps are considered stable from those points of view. Moreover, another aspect considered in this paper is the study of emission, immunity and performance of LED lamps after reaching the thermal stabilization. To do that, LED lamps have been cooled down with an external fan, and different parameters have been studied in relation to the temperature.

The remaining sections of the paper are structured as follow:
Firstly, Measurement setup gives information about the devices and LED lamps used for measuring, as well as the communications between devices to synchronize the data acquisition, Methodology explains the process carried out to be able to check the behaviour of LED lamps with different supply voltages and ambient conditions, to have knowledge of the acquired data as its reproducibility and to find a good method to analyze the illuminance and temperature parameters. Results shows the evolution of the parameters along time to evaluate the stabilization time of the LED lamps and which parameter stablishes it. Discussion section shows the emission in LED lamps with parameters like THD of current and curent RMS value, moreover in this section the immunity of LED lamps due to voltage fluctuation, over and under voltage are checked and also includes a global knowledge from all the lamps tested about the influence of ambient conditions in active power, illuminance and efficiency. Finally, the conclusions are stated.

Measurement setup

Test Platform

The platform is composed by a wooden base where a cap has been set to keep constant distance between the studied lamp and the other devices, and a paperboard box which encloses the LED lamps to avoid light disturbances during the measurements. The platform contains the sensor of the luxmeter E4-X from Hagner (Resolution: 1 lux/mV), the thermal camera Ti45FT from Fluke (emissivity: 0.95, lens: 20 mm, focal relation (F): 0.8) and the fan 3610KL-05W-B50 from Minebea Mitsumi (Source: 20 V CC).
The Yokogawa DL850E oscilloscope measures, with three channels, voltage (analog module 701267: speed 100kS/s and 16-Bit), current (measurements from the Pearson current probe and acquired with the voltage analog input module 701251: high speed of 1MS/s and 16-Bit) and light output (another channel from the module 701251), all synchronized. The thermal camera records the temperature. The distribution of the devices is shown in Figure 1.

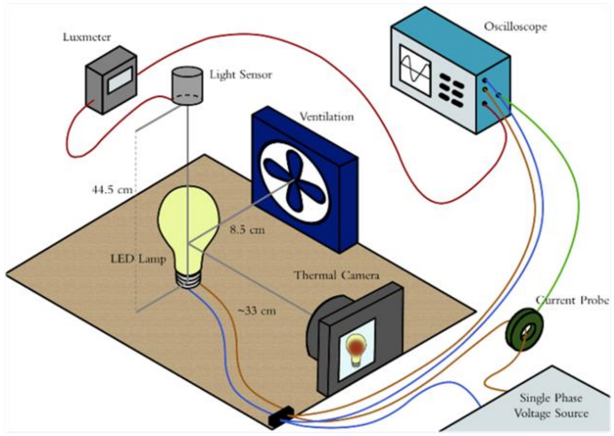


Figure 1. Test Platform overview.

Communications

To synchronise the data acquisition of the light output, voltage and current, the Yokogawa DL850E oscilloscope and Keysight Technologies Programmable Single phase Voltage Source 6811B have been connected by Ethernet and GPIB command respectively, controlling both instruments trough LabVIEW NXG 1.0.2 and VISA ports as Figure 2 shows.

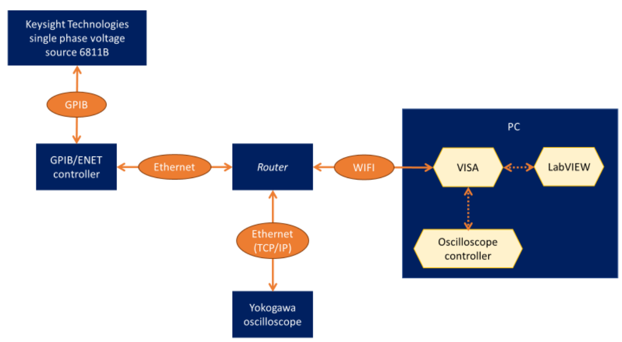


Figure 2. Connections and communications implemented in the platform.

LED lamps tested

The list of LED lamps tested is given in Table 1. LED lamps currently available in the Spanish market have been tested during 90 minutes. Four different brands have been chosen, the power varies from 5 W to 12 W. The illuminance emitted by the lamps varies from 350 lm to 1055 lm.

Table 1. Data of Tested Lamps, provided by the manufacturer

LED number	Power (W)	Lumens (lm)	Colour temperature (K)
LED 1	6	470	2700
LED 2	9	806	2700
LED 3	7	470	2700
LED 4	8	806	3000
LED 5	8	470	2700

LED 6	12	806	2700
LED 7	10	1055	4000
LED 8	9	-	6000
LED 9	5	350	4000
LED 10	6	400	3000

The waveform of the current for each LED lamp tested with sinusoidal 230 V waveform as supply voltage is shown in Figure 3. According to [12], most of the lamps do not have power factor correction circuit.

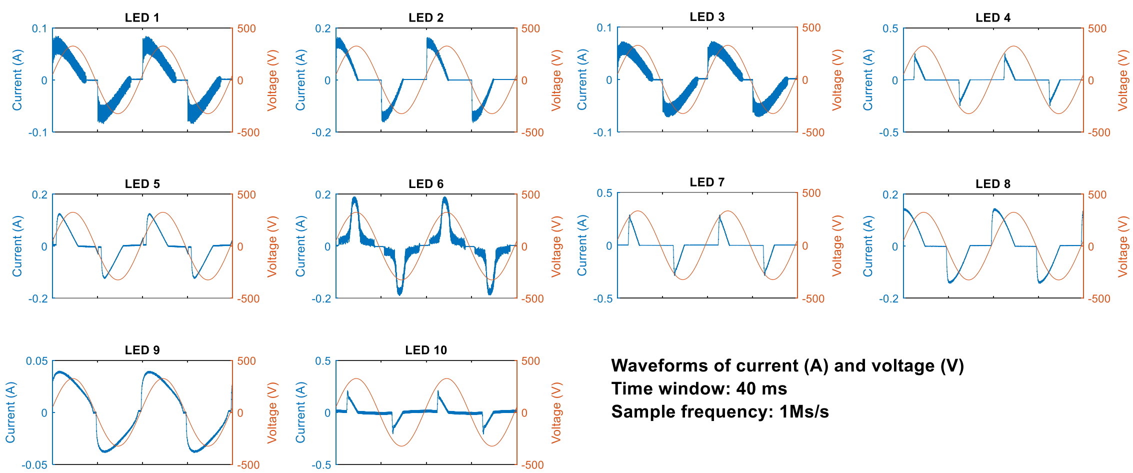


Figure 3. Waveforms of the current and voltage of tested LED lamps connected to pure sinusoidal 230 V RMS.

In LED 2 and LED 8 the current pulse finishes when the voltage peak takes place, unlike LED 1 and LED 3, and also, because the current peak starts when the voltage zero crossing, both differ from LED 4, LED 7 and LED 10. LED 5 waveform looks similar to LED 2 and LED 8 except for some distortion before the current peak.

On the other hand, all LED lamps seem to have a capacitive power supply, except LED 6 and LED 9 which are the only ones in which the waveform seems sinusoidal, voltage and current are in phase and have a high frequency ripple which seem to lead to an active PFC (Power Factor Correction) in their topology.

Methodology

Tests conditions

The temperature in the laboratory has been kept at 24ºC. The acquisition frequency of the oscilloscope was set to 1 MS/s with a 0.2 s window as recommended by IEC 61000-4-30 standard. Supply voltage frequency has been 50 Hz.

The following measurements have been made with different purposes:

To test the immunity of LED lamps:

- Sinusoidal voltage waveform, 207 V RMS (-10%).
- Sinusoidal voltage waveform, 253 V RMS (+10%).

To observe the impact of the supply voltage distortion with the thermal stabilization of the lamps:

- Sinusoidal voltage waveform, 230 V RMS.
- Distortion of the supply voltage with a modulation frequency of 5 Hz with an amplitude of 3% of the fundamental voltage (230 V RMS) as indicated in Figure 4.

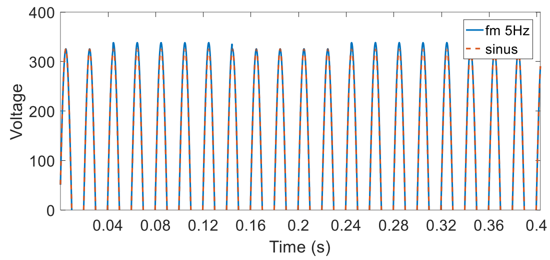


Figure 4. Supplied voltage considered as distortion.

These measurements have been made, with the fan on and off to see the ambient temperature influence on the illuminance and on the active power, two factors that define the efficiency of the lamps.

Voltage, current, temperature and light output have been measured from t=0 to t=60 min, taking one sample every 10 minute and the time and temperature dependencies have been studied, so that, some LED lamps have been measured until t=90. Data has been taken every 10 minutes as the temperature has a slow dynamic.

Illuminance

As the illuminance is a waveform, the average value has been computed over the 200 ms window to obtain a single value at each instant and get the illuminance pattern. As Figure 5 shows, the average value is similar to 90 percentile and maximum values.

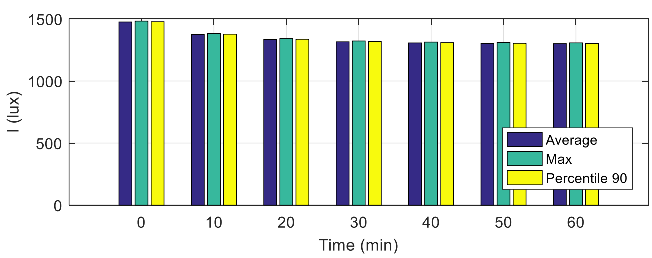


Figure 5. Illuminance average, percentile 90 and maximum value from captured windows for each instant with 5 Hz sinusoidal voltage fluctuation without fan cooling the lamps.

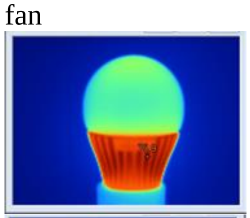
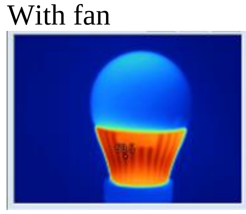
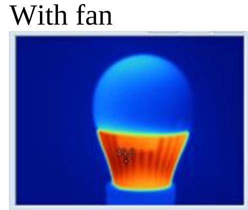
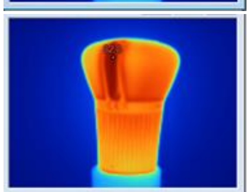
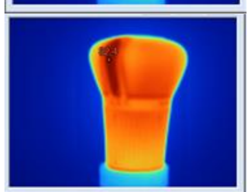
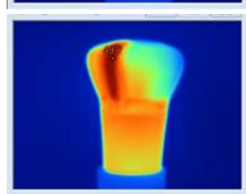
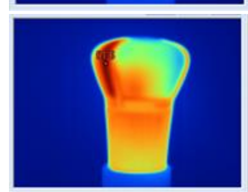
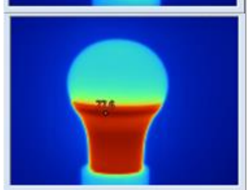
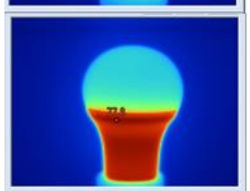
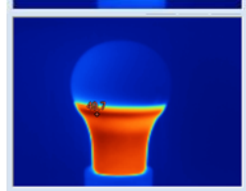
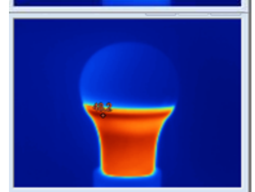
Temperature pattern

The temperature pattern has been obtained through thermal pictures based on the hottest temperature recorded at the last measurement (t=60 or t=90 min), this means that the temperature at this point has been taken in the other previous instants.

Table 2Table 2. Hottest temperature at t=90 min for LED 5 and LED 6 and t=60 for LED 7 shows the hottest temperature and its position (shown with a cross) for three different LED lamps (each row) at the last instant recorded. LED lamps were connected to pure sinusoidal and distorted voltage in the two first columns (without the fan connected) and the same voltages but cooling down the temperature in the last two columns.

LED 5 (first row in Table 2) slightly changes the position of the hottest point when the lamp is cooling down compared to ambient temperature.

Table 2. Hottest temperature at t=90 min for LED 5 and LED 6 and t=60 for LED 7

	Pure sine voltage waveform. Without fan	Distorted voltage waveform. Without fan	Pure sine voltage waveform. With fan	Distorted voltage waveform. With fan
LED 5				
LED 6				
LED 7				

As the hottest point at the last instant captured has been chosen to obtain the temperature evolution with time, it has been studied if the position of the hottest temperature keeps at the same point along time.

The positions of the hottest temperature have been represented for each recorded instant. Except for the first instant (t=0 min), when the temperature is not relevant for the thermal stabilization study as will be later shown, hottest point positions keep rather at the same position. So that, hottest point is considered to be consistent along time. Figure 6 shows two examples feeding LED lamps with sinusoidal waveform of 230 V, refrigerating the lamp (with fan).

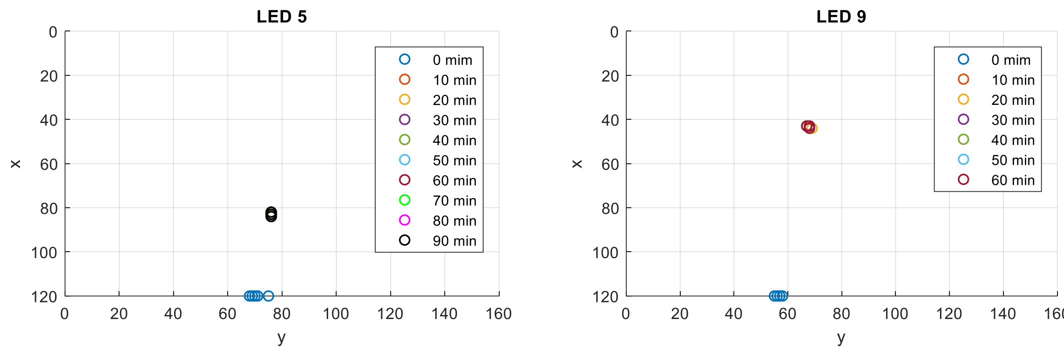


Figure 6. Positions of hottest temperature along time for LED 5 (left) and LED 9 (right), both connected to sinusoidal 230 V RMS with fan cooling the lamps.

Because only at the initial instant the hottest point does not keep in the same position, it has been studied how the initial temperature of the lamp impacts in the stabilization of the LED lamp. The initial temperature has been reduced 33.15 ºC (from 27.9 ºC to -5.25 ºC) for LED 5 and 26.9 ºC (from 26.4 ºC to -0.5 ºC) for LED 9 cooling them down in a freezer. With these new cooler initial conditions, the illuminance, the active power and the LED lamp temperature have been measured, without fan, along the LED lamp stabilization time and then compared with the measurement starting from a warmer ambient LED lamp temperature as initial condition. As Figure 7 shows, comparing both graphs at t=90 min for LED 5, the illuminance variation is 1.44% (11.9 Lux), the active power variation 0.0358 % (0.003 W) and the temperature variation -2.45 % (1.85ºC). Figure 8 shows for LED 9 at t=60 that variations are -0.4575 % (41 Lux), 0.246 % (0.014 W) and 0.352 % (0.3ºC), respectively for illuminance, active power and LED temperature. Due to the low percentages of variation, the impact of the initial temperature is not considered significant and once the stabilization time is achieved, the values in the parameters studied are rather similar.

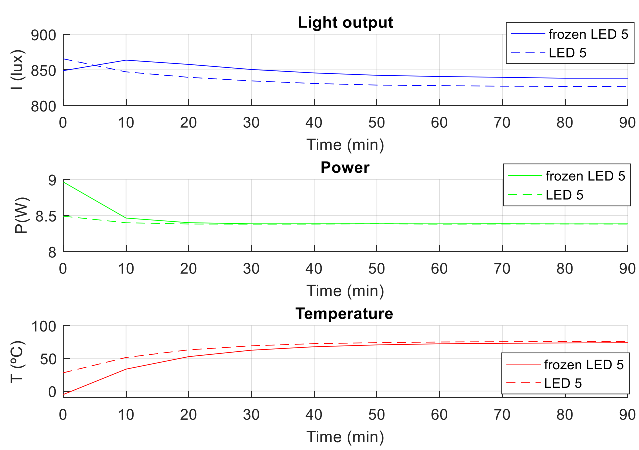


Figure 7. LED 5 measured for two different temperature initial points without fan connected to a 230 V sinusoidal supply voltage

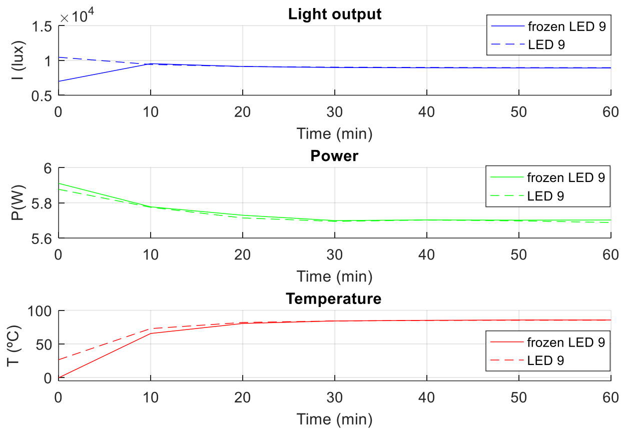


Figure 8. LED 9 measured for two different temperature initial points without fan with 5 Hz sinusoidal voltage fluctuation

In addition, the hottest point at last instant captured evolution with time has been compared with temperature evolution at other points of the thermal picture, not only points located inside the LED lamp have been represented, but also points from the ambient temperature surrounding the lamp at the left and the right side of the LED lamps because the position of the fan (Figure 1, right area in Figure 11) could lead to differences in ambient temperature between both sides. The case studied has been for a sine supply voltage with fan, as the effect of the fan is what can add some temperature variation.

LED 5 is shown as a sample and the points positions chosen from the thermal picture are represented in Figure 9. Positions around the hottest point recorded by the camera have been chosen, including points inside the sink, and outside, covering both sides of the lamps. As the fan is located in the right hand, the influence by this device must be studied. As it can be observed in Figure 10, ambient temperature curves (points located outside the sink) follow the same pattern in the same range of temperatures, within 27ºC and 30ºC for both sides of the LED lamp.

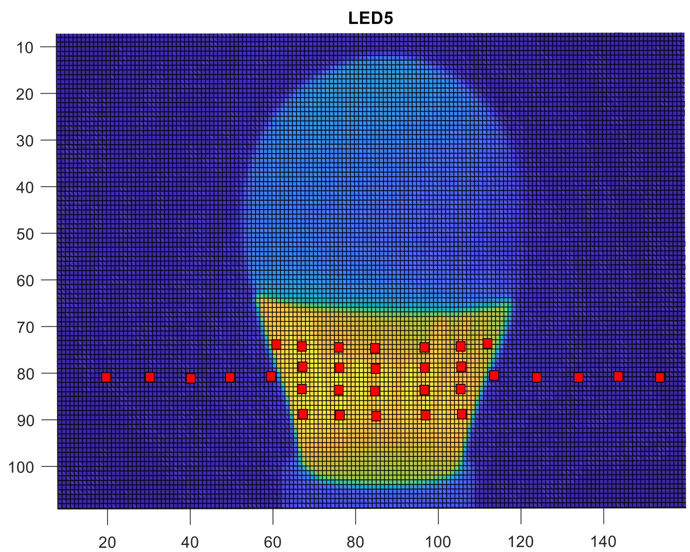


Figure 9. Selected points position in the thermal picture from LED 5 at t=90 min to compare curves of temperature.

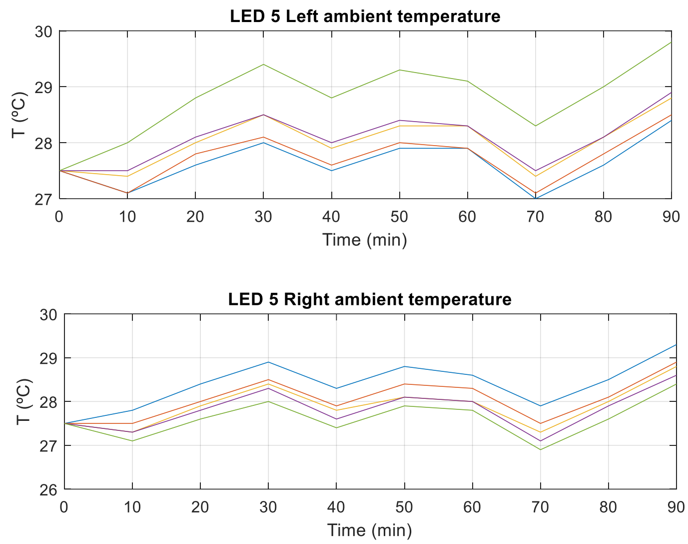


Figure 10. Temperature curves obtained from five ambient temperature points at the left and right sides of the hottest point in LED 5 with fan connected.

Furthermore, in order to check if the ambient temperature is affected by the fan position, the area around the lamp (excluding the lamp itself) has been considered as ambient temperature, taking right and left areas shown in Figure 11. From those areas, the average has been calculated and shown in Figure 12.

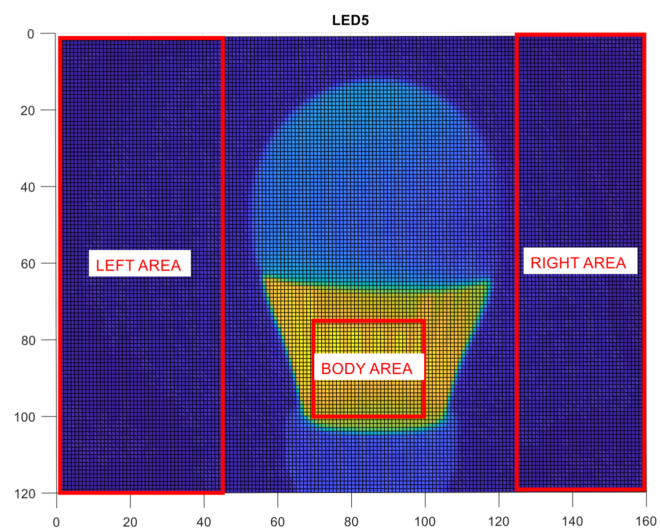


Figure 11. Temperature areas analysed from a thermal picture of LED 5 at t=90 min.

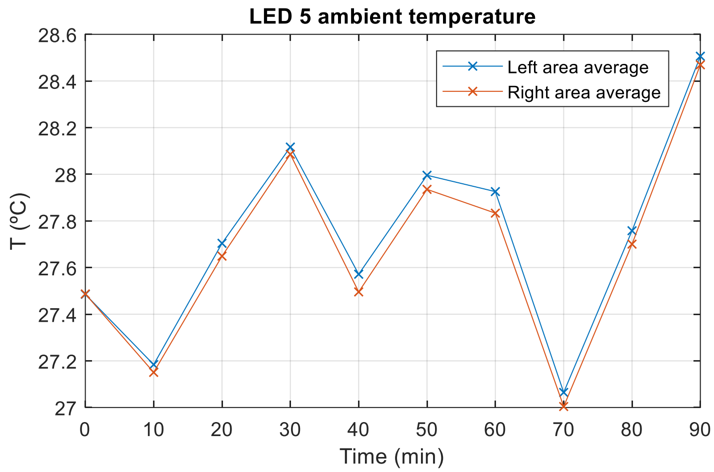


Figure 12. Average ambient temperature in the left and right area.

The results in Figure 12 state that the ambient temperature change evenly around the LED lamp independently of the position of the fan, being 0.1 ºC at t=60 min the maximum difference between both sides. So that, the average of the right area has been taken as ambient temperature.

On the other hand, curves from the LED body follow the same pattern but different from ambient temperature pattern as it is seen if Figure 10 and Figure 13 are compared, for this reason it has been studied the relationship between ambient temperature variations and the hottest point at last instant temperature evolution.

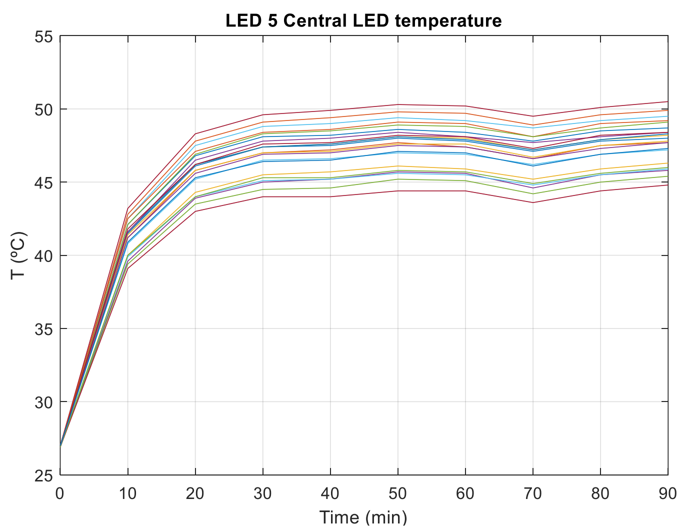


Figure 13.Temperature curves obtained from LED 5 body

The average value within these areas is representative as indicated in Figure 14, where average, 90 percentile and maximum values are represented.

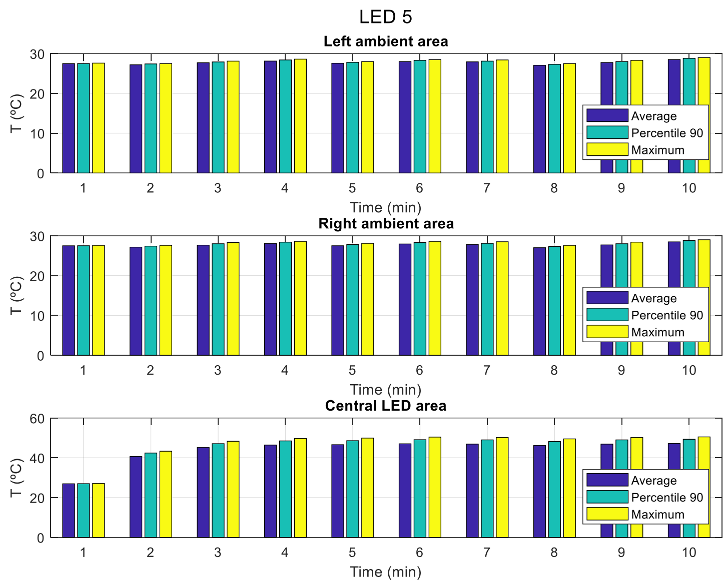


Figure 14. Average, 90 percentile and maximum value from the analysed areas of LED 5 for each instant.

The percentage temperature variation between instants have been represented in Figure 15 according to equation (1). Positive values represent temperature increase and negative values temperature decrease. As it can be seen, when the thermal stabilization is reached, in general, a variation in ambient temperature produces a smaller variation in LED lamp temperature following the same trend (increment or decrement). For all lamps, Figure 16 represents the LED lamps temperature variation (hottest point curve) due to the ambient temperature variation (average of the right ambient temperature area) since the variation between t=30 min and t=40 min also according equation (1), in this figure is shown how, for the 83.33% of the values represented, both temperatures decrease or increase. Within this percentage, the 10% of the LED lamps temperature variations are higher than the ambient temperature variation, with a difference within -0.0194% and -0.1495% between both temperatures which can be explained by the error of the average of right area ambient temperature showed in Figure 14. 3.0490% is the maximum variation difference between both temperature variations. The lamps which do not behave following this trend for all the instants are LED 5, LED 6 and LED 8.

$$\Delta X\ (t_n) = \frac{X(t_n) - X(t_{n-1})}{X(t_{n-1})} * 100 \qquad (1)$$

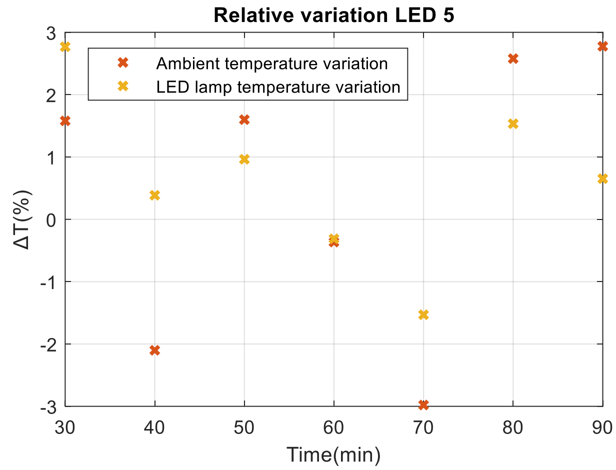


Figure 15.Variation in the LED lamp 5 temperature taken from the average of the LED sink area and right side ambient temperature area.

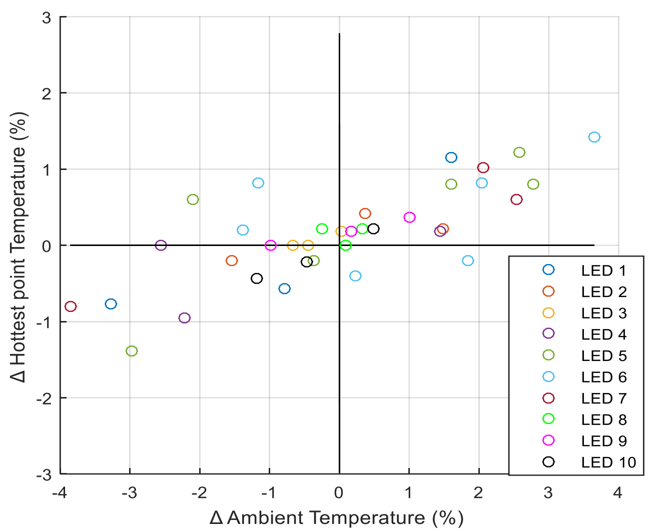


Figure 16. Variation of the hottest point temperature with the changes in ambient temperature for all the LED lamps.

Reproducibility

To check the reproducibility of measurements, the stabilization time from LED lamps has been measured not only with a difference of some days between measurements but also with a difference of a year (measurements done during summer in 2018 and in 2019). The first instant is not considered in this section since the initial conditions do not define the stabilization values as have been explained before. The percentage of change is written in absolute values since the purpose in this section is to verify if there is variation between measurements, not to study the tendency of the parameters over time.

In summer 2018, measuring in different days, with a 5 Hz modulation frequency supply voltage and without cooling the lamp with the fan, gave the results shown in Figure 17, where the temperature error keeps almost constant in 2% which is a difference of 1.8ºC at the worst case. The illuminance and active power error decreases along the stabilization, reaching errors below 0.25%.

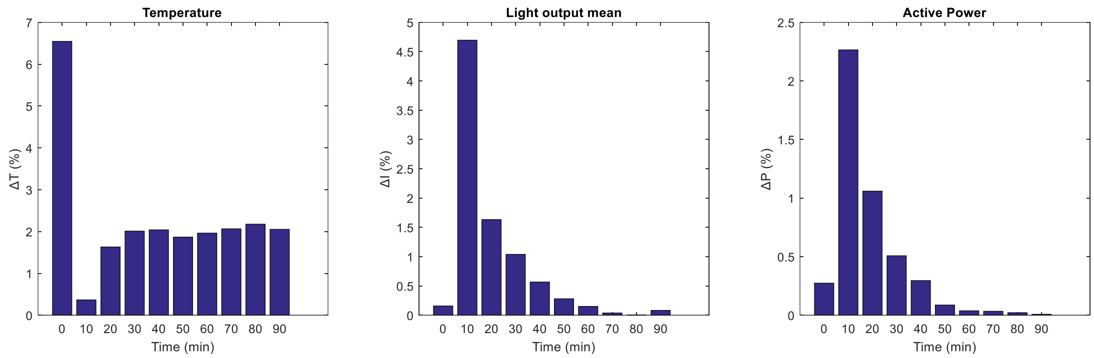


Figure 17. Comparison between two measurements in LED 6, both in July 2018, with 5 Hz sinusoidal voltage fluctuation without fan cooling the lamps.

The same test was done in summer 2019, measuring with a difference of few days feeding lamps with sinusoidal voltage. As it is seen in Figure 18 for LED 4, in the case without fan cooling, the temperature difference keeps below 0.3378% since t=10 min and the difference in illuminance and active power below 0.04%.

The test was repeated with fan cooling the LED lamps, and the resulting temperature is around 3% of variation for LED 4 and LED 5. There is some difference in the illuminance and active power variation for both LED lamps. While illuminance variation keeps constant around 0.65% and active power is below 0.18% of variation for LED 4, for LED 5 these parameters have almost no variation, 0.07% as maximum for illuminance and below 0.04% for active power.

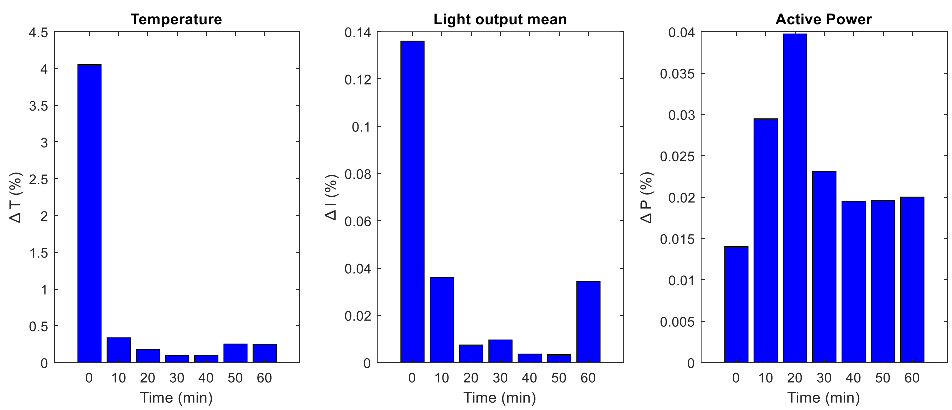


Figure 18. Comparison between two measurements in LED 4, both in summer 2019 with sinusoidal voltage without fan cooling the lamps.

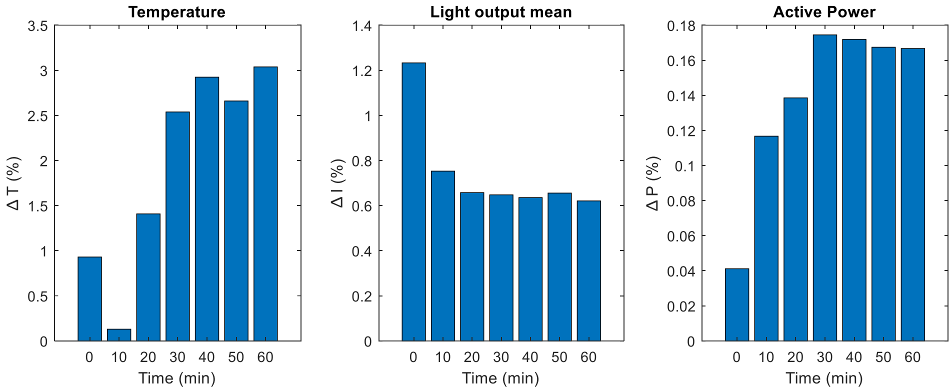


Figure 19. Comparison between two measurements in LED 4, both in May 2019 with sinusoidal voltage with fan cooling the lamps.

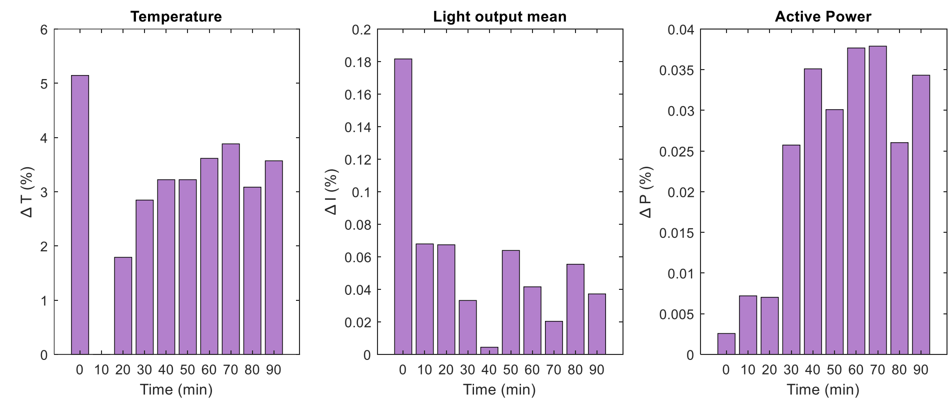


Figure 20. Comparison between two measurements in LED 5, one in May 2019 and the other one in June 2019, with sinusoidal voltage with fan cooling the lamps.

The measurements with sinusoidal voltage and without fan cooling the lamps have been also compared between years (summer 2018 and 2019). The difference in temperature is below 0.6% after t=30 min for both LED lamps and active power almost keeps without variation. However, there is a constant error in illuminance, a variation around 3% and 3.5% for LED 5 and LED 4 respectively. The illuminance degradation of the LED lamps over time could partially explain this error as it has been studied in [13].

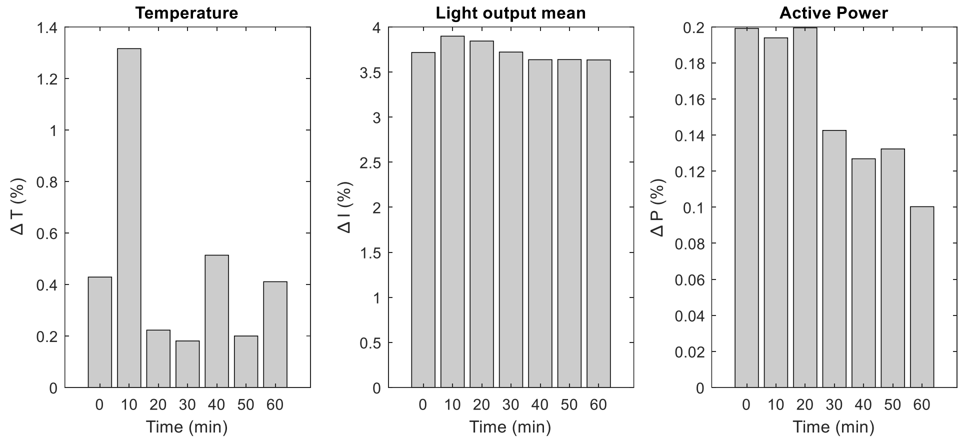


Figure 21. Comparison between two measurements in LED 4, one in July 2018 and the other one in May 2019, with sinusoidal voltage and without fan cooling the lamps.

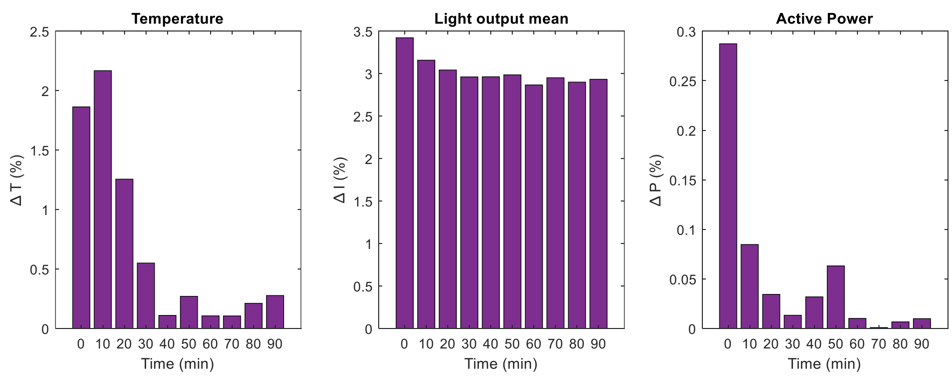


Figure 22. Comparison between two measurements in LED 5, one in July 2018 and the other one in May 2019, with sinusoidal voltage and without fan cooling the lamps.

As for Figure 21 and Figure 22, also when the measurement with fan is done, there is a constant error in illuminance similar to the one explained before around 1.6% for LED 4 and 1.75% for LED 5. Also, adding the fan, which is sensitive to suffer changes over time, there is a constant error around 6.5% for LED 4 and LED 5 in temperature, as can be seen in Figure 23 and Figure 24.

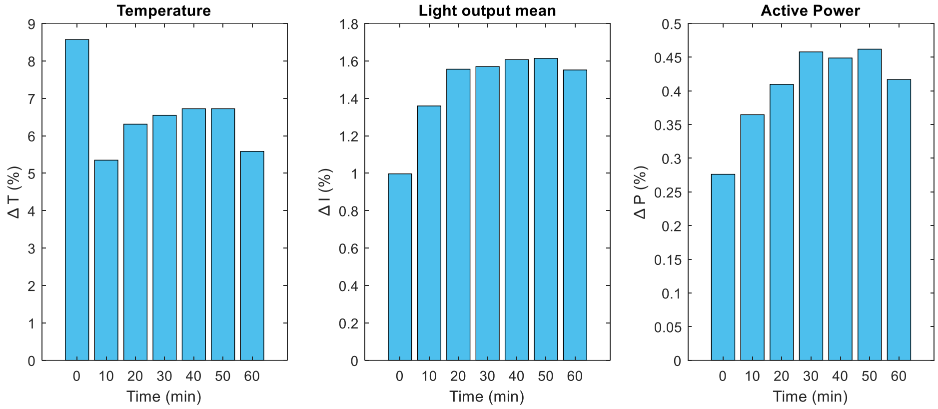


Figure 23. Comparison between two measurements in LED 4, one in July 2018 and the other one in May 2019, with sinusoidal voltage with fan cooling the lamps.

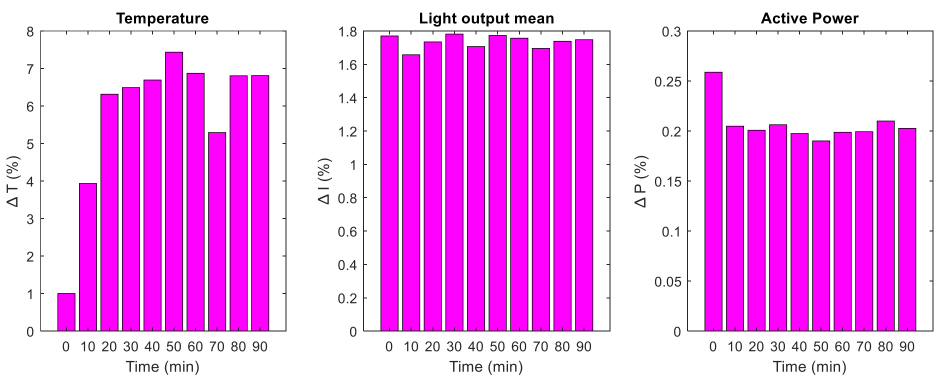


Figure 24. Comparison between two measurements in LED 5, one in July 2018 and the other one in May 2019, with sinusoidal voltage with fan cooling the lamps.

The standard IEC 61000-3-2 [14] indicates that the repeatability of the measurements shall be better than ±5%, so that, attending to the worst cases observed, the variation between years in illuminance can be accepted as good. For the temperature comparing between years in the case with fan, the variation is close to this reference, around 6.5%. Active power is far from reaching that limit.

Results

Temperature, active power and illuminance evolution over time has been considered in this section with the aim of studying the stabilization of LED lamps. This trend has been plotted not only in absolute values but also as a percentage of variation between two consecutive instances according to equation (1), where X is temperature (ºC), active power (W) and illuminance (lux) respectively in every case study. Positive values indicate that the value of the variable has increased from one instant to another and its absolute value indicates the percentage of variation.

Temperature variation

As it was shown in [9], the light intensity in LED lamps decreases with time until a level that can be considered as steady state after switching on, in the same way, LED lamps temperature increases with time until they reach a stable temperature. Stabilization temperature is different for each LED lamp and depends on the ambient conditions as can be observed in Figure 25 comparing the temperature reached with and without fan in each LED lamp.

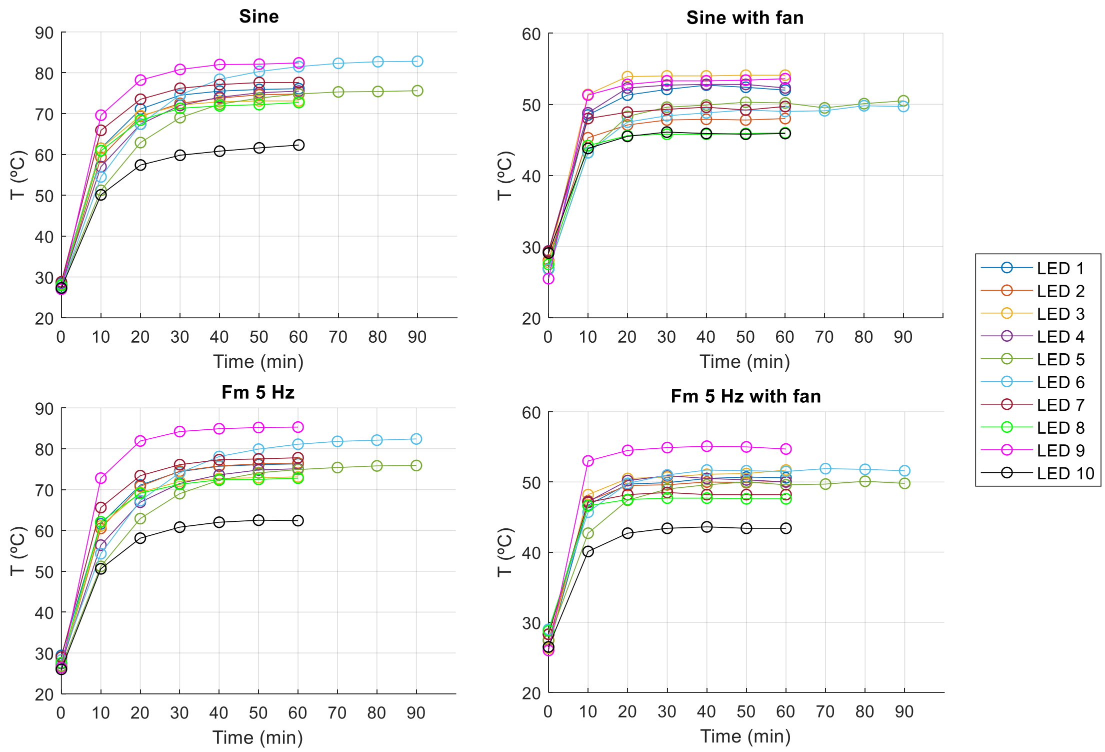


Figure 25. Absolute temperature for different LED lamps connected to sinusoidal and to 5 Hz sinusoidal fluctuation voltage with and without fan cooling the lamps.

The thermal stabilization time t_s is defined as the lowest value of t_n for which the following inequality holds:

$$\Delta T(t_n) \leq 1\% \qquad (2)$$

To the aim of this study, the threshold for the temperature variation has been set to 1% as it implies 1ºC variation.

To start with, the LED lamp samples were connected to pure sinusoidal voltage waveform without a fan and the results are shown in Figure 26. Again, it is shown that all LED lamps increase in temperature with time (seen as a positive percentage of variation), however the difference in temperature varies between lamps. The percentage of variation between 20 to 10 min (first sample shown in Figure 26) varies between 23.7% (LED 6) and 11.5% (LED 7). This difference in variation between lamps decreases, reaching 2% after 50 min.

As it was previously defined, the thermal stabilization time t_s is defined as the time when the temperature variation is lower than 1% (red dotted lines). The variation at minute 60 is 1% or below for 70% of the lamps tested (the other reaching 1.5% variation as maximum). The thermal stabilization time from this temperature study is similar to the one found in [9] measured over light intensity.
Only LED 5 and 6 did not reach strictly 1% at minute 60, so that, they were measured longer time. In these cases, the difference between temperature at minute 70 compared to minute 60 was 0.98% and 0.66% respectively, so that, both lamps are considered to be below 1% from minute 60 to 70.

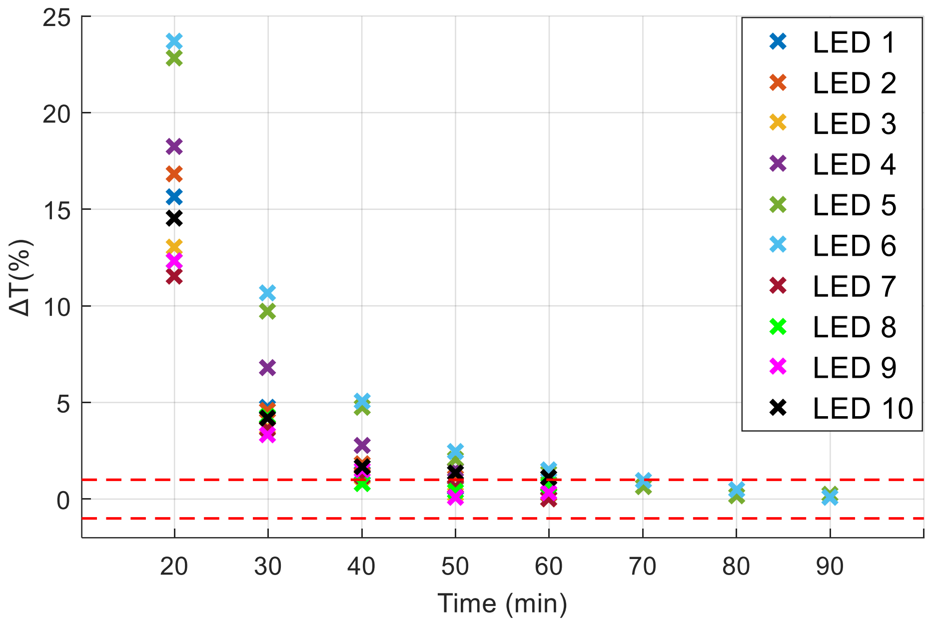


Figure 26. Temperature variation (%) of different LED lamps connected to pure sinusoidal 230 V RMS without fan cooling the lamps.

In order to know how external temperature influences the thermal evolution in the LED lamps (i.e. when LED lamps are subjected to cooler ambient temperatures where they are located), the same test was repeated (pure sinusoidal voltage waveform) with a fan cooling the lamps, reducing the temperature with approximately 25 to 40%, and the results are shown in Figure 27.

In the second sample (from 20 to 10 min), the variation in temperature varies between 11.8% (LED 5) and 1.9% (LED 7). This difference between lamps decreases even more leading to a shorter thermal stabilization time (ts=30 min, except for LED 1 in which ts=40 min) compared to the previous case without fan.

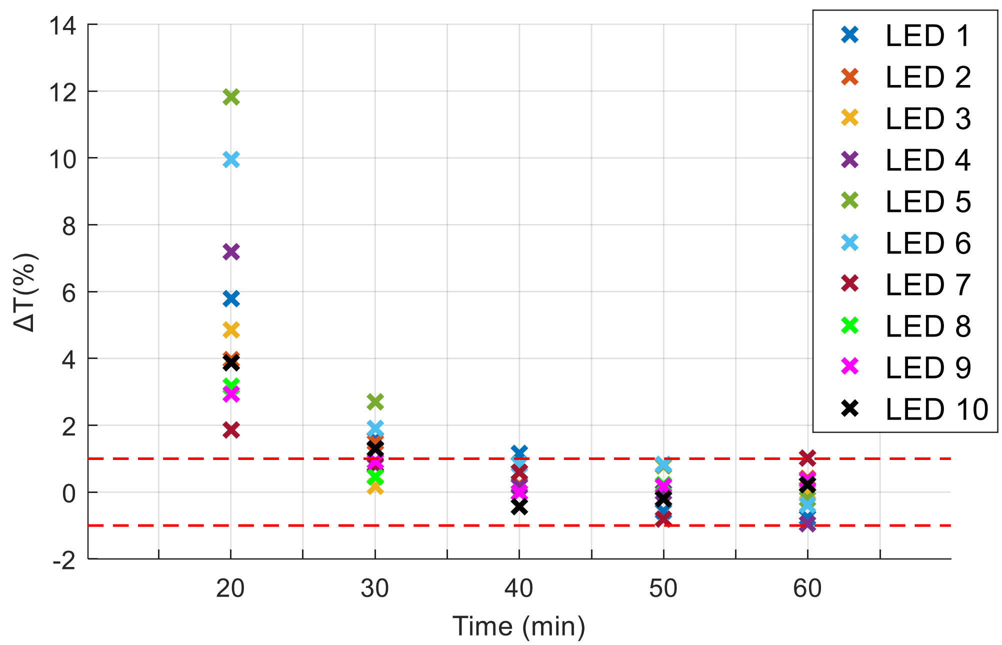


Figure 27. Temperature variation (%) of different LED lamps connected to pure sinusoidal 230 V RMS with fan cooling the lamps.

The other effect considered is the temperature stabilization study when lamps are connected to a distorted voltage waveform (as shown in Figure 4). With this test, the temperature dependency with the voltage fluctuation will be studied without (Figure 28) and with (Figure 29) a fan cooling the lamps.

In the case shown in Figure 28, the temperature variation with modulation frequency is similar to the result obtained when lamps were connected to pure sinusoidal voltage waveform (Figure 26) both without fan cooling the lamps, and the stabilization time can also be considered to be 60 min from this study. The distortion in the voltage waveform has no significant effect in the thermal stabilization, as it also takes 60 min to be stable in this case.

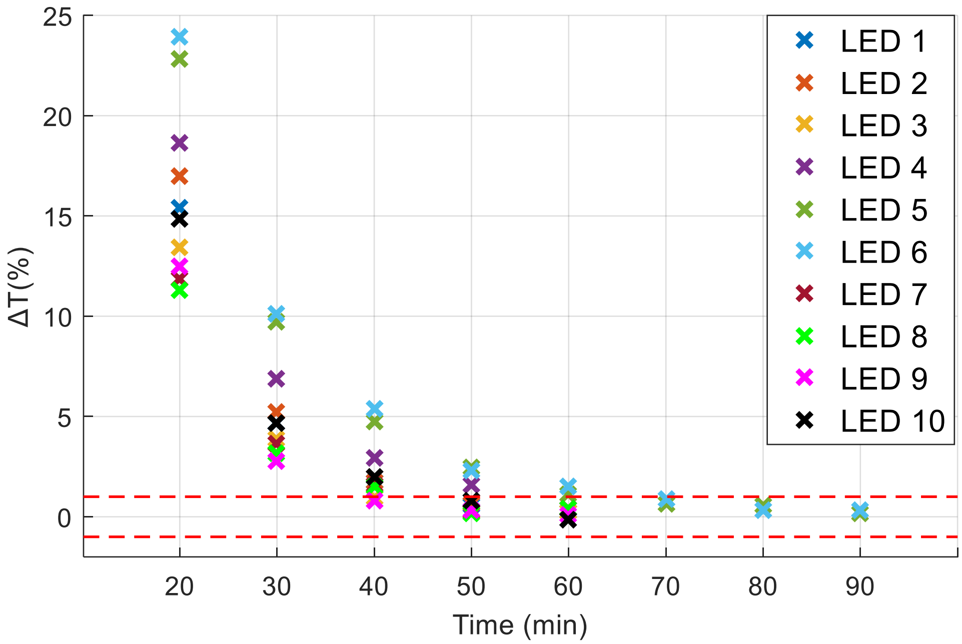


Figure 28. Temperature variation (%) of different LED lamps connected to 5 Hz sinusoidal voltage fluctuation without fan cooling the lamps.

The effect on cooling the lamps when they are connected to a distorted voltage waveform is shown in Figure 29. This case shows some similarities with the case of the lamps connected to a sinusoidal waveform and cooled by the fan (cf. Figure 27). In the second sample (from 20 to 10 min), the variation in temperature varies between 11% (LED 5) and 1.9% (LED 8). At this instant, most of the lamps have the same increase in temperature independently of the supplied voltage, but LED 10, as it increases in temperature more with distorted voltage (6.5%) than with pure sinusoidal (3.9%). Similar behaviour takes place in the other instants.

The difference between lamps decreases even more during the following samples leading to the same thermal stabilization time (30 min for almost all lamps and 40 min for all lamps) compared to the previous case (pure sine) without fan.

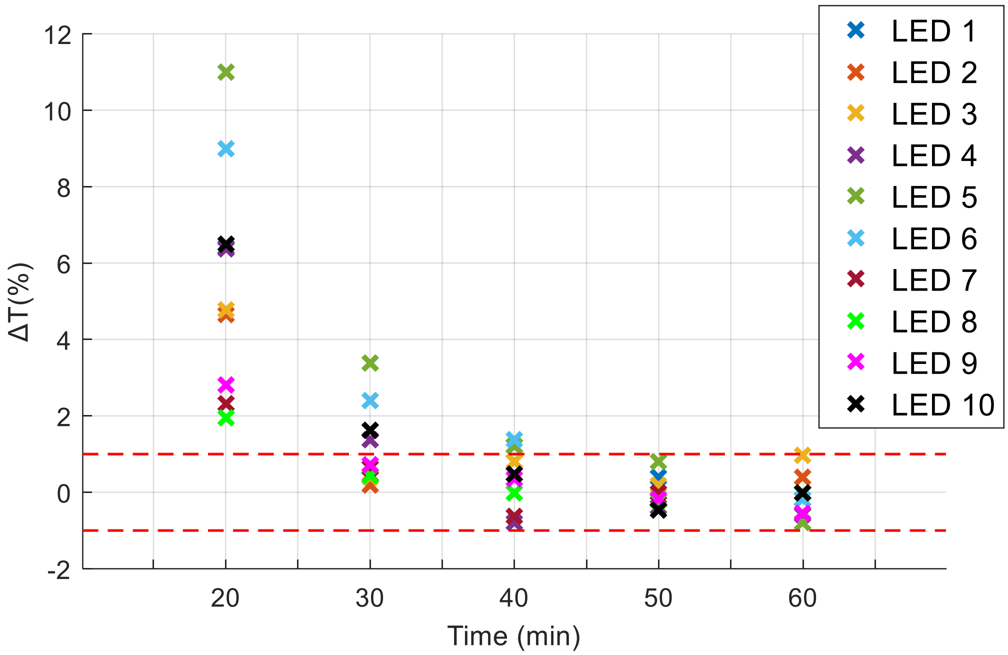


Figure 29. Temperature variation (%) of different LED lamps connected to 5 Hz sinusoidal voltage fluctuation with fan cooling the lamps.

Due to the initial conditions of the LED lamp are not relevant for the stabilization and the resolution of the vertical scale between the first sample and the following, the first sample (t_1-t_0) at all the thermal stabilization patterns has been removed from Figure 26 to Figure 29 and showed in Figure 30, in which it can be seen that during the first 10 minutes, the variation in temperature reaches the highest values, ranging between the values in Table 3, being the maximum variation 175.8% (LED 9) with 5 Hz modulation frequency supply voltage without fan and the minimum 50,52% (LED 10) with sine supply voltage with fan, as with fan the temperature variation is lower than without fan for both supply voltage because the absolute temperature reached is also lower (Figure 25).

Table 3. Maximum and minimum percentage variation between 0 and 10 min according to equation (1) for all cases studied.

Supply voltage and ambient condition	LED (maximum variation)	Maximum variation (%)	LED (minimum variation)	Minimum variation (%)
Sine	LED 9	157.8	LED 5 y 10	83.5
Sine with fan	LED 9	101.2	LED 10	50.52
Fm 5 Hz	LED 9	175.8	LED 5	91.04
Fm 5 Hz with fan	LED 9	103.8	LED 10	51.32

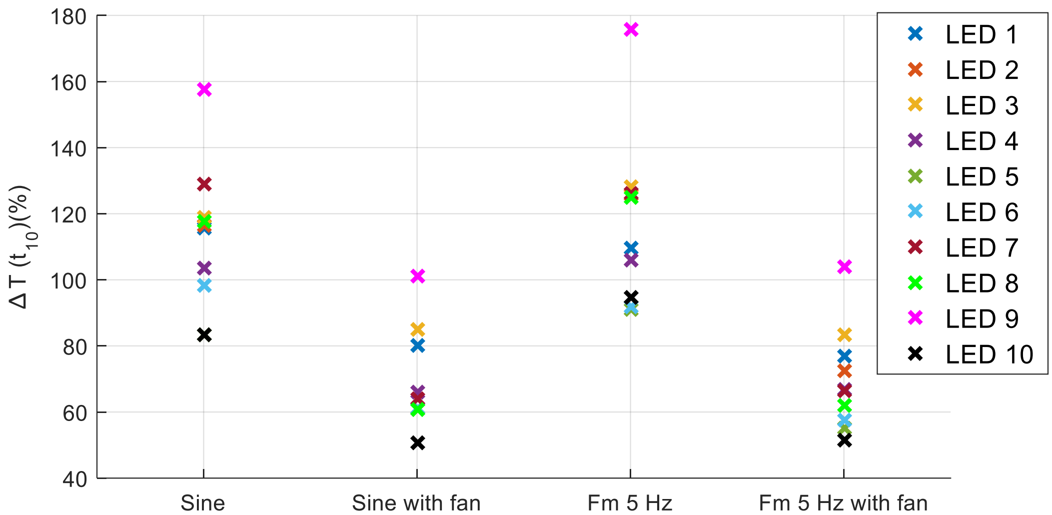


Figure 30. Temperature variation (%) for different LED lamps at t=10 in all the cases studied.

Active power variation

The active power evolution with time is represented. As it is observed in Figure 31 the slope of the curves are softer than the ones for the temperature, what means that the active power does not change as much as temperature along time.

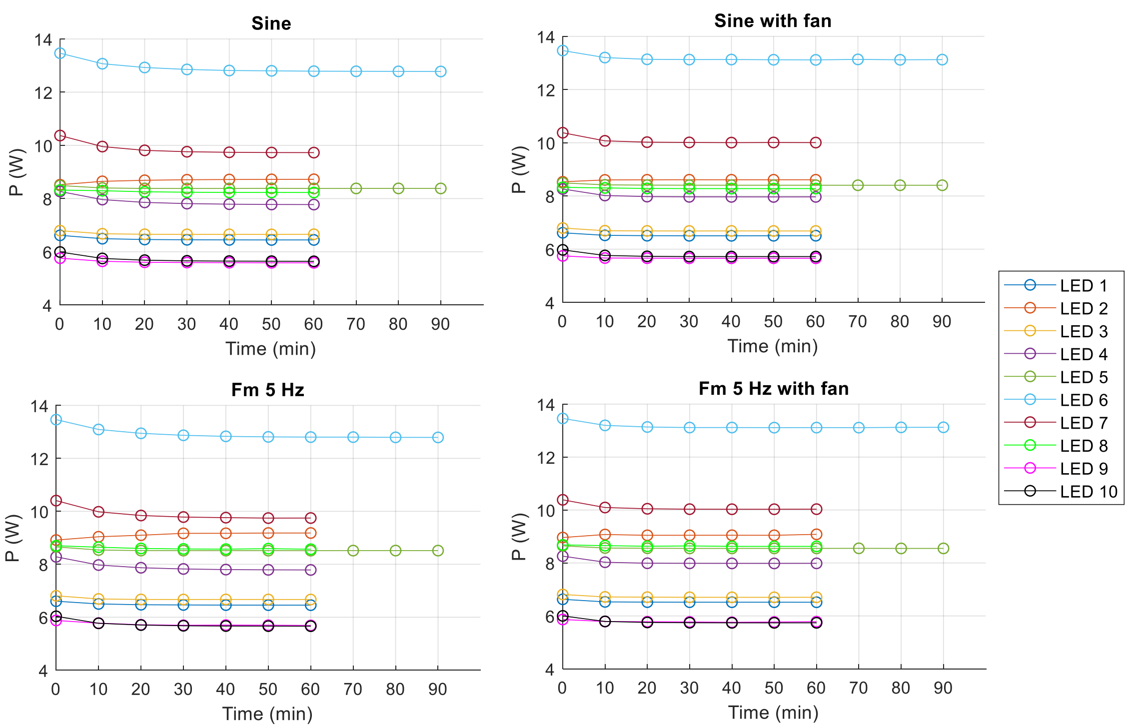


Figure 31. Absolute active power for different LED lamps in all the cases studied.

As it was stated at the beginning of this section, the active power evolution with time has been plotted as a percentage of variation between two consecutive instances according to equation (1). As it can be seen from Figure 32, the results are very similar, all the lamps (except LED 2) decreases in active power with time (negative percentage of variation) as was already shown in [9] and [15] until minute 30 (minute 20 for LED 8 feeding with distortion), from this minute, active power has slightly variations, either increase or decrease. To know the stabilization time according to active power, the variation in active power might be considered ≥-1% in the inequation (2). According to that, the stabilization time is 20 min for this set of lamps either with or without distortion and without refrigeration. When refrigeration with fan is applied, the stabilization time becomes shorter (10 min) as it also happens with temperature stabilization time.

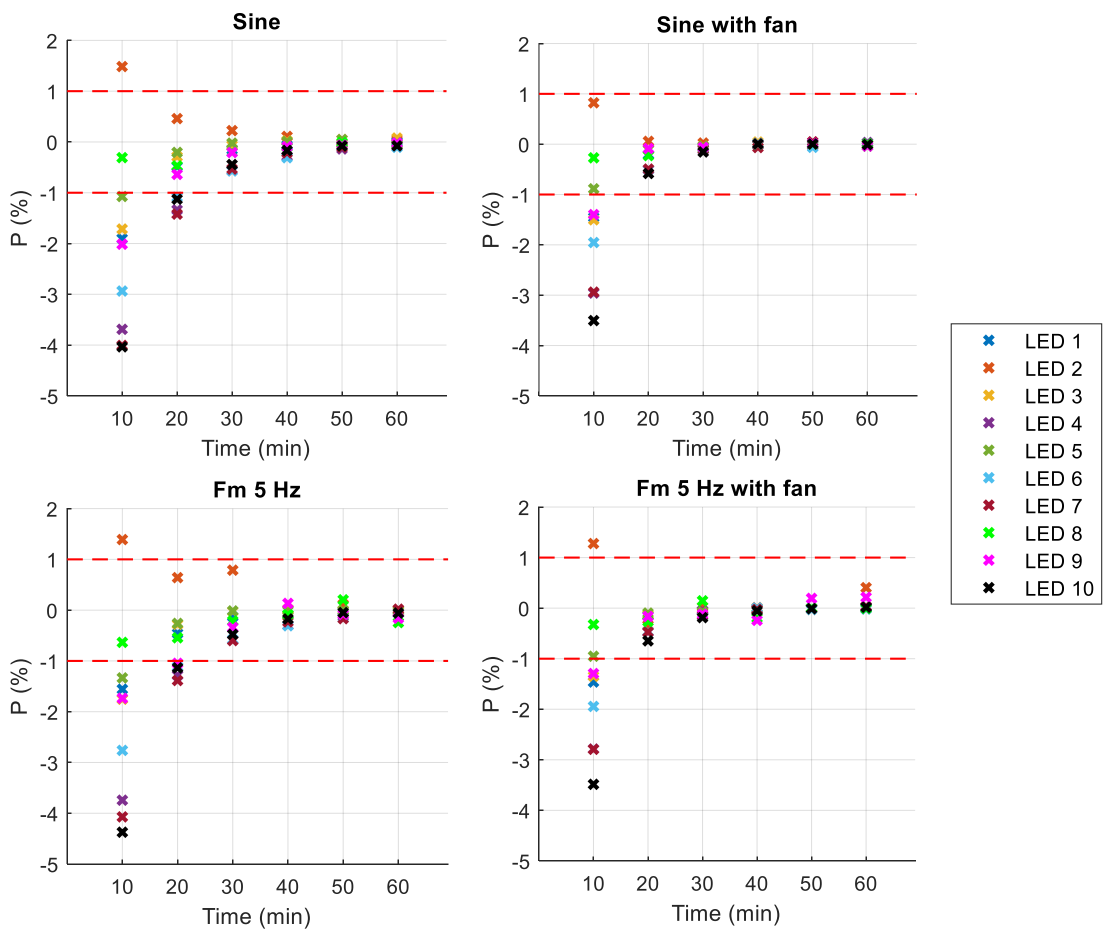


Figure 32. Active power variation (%) of different LED lamps for all the cases studied.

Illuminance variation

Figure 33 shows the evolution along time in absolute values which slope is similar to the one from the active power.

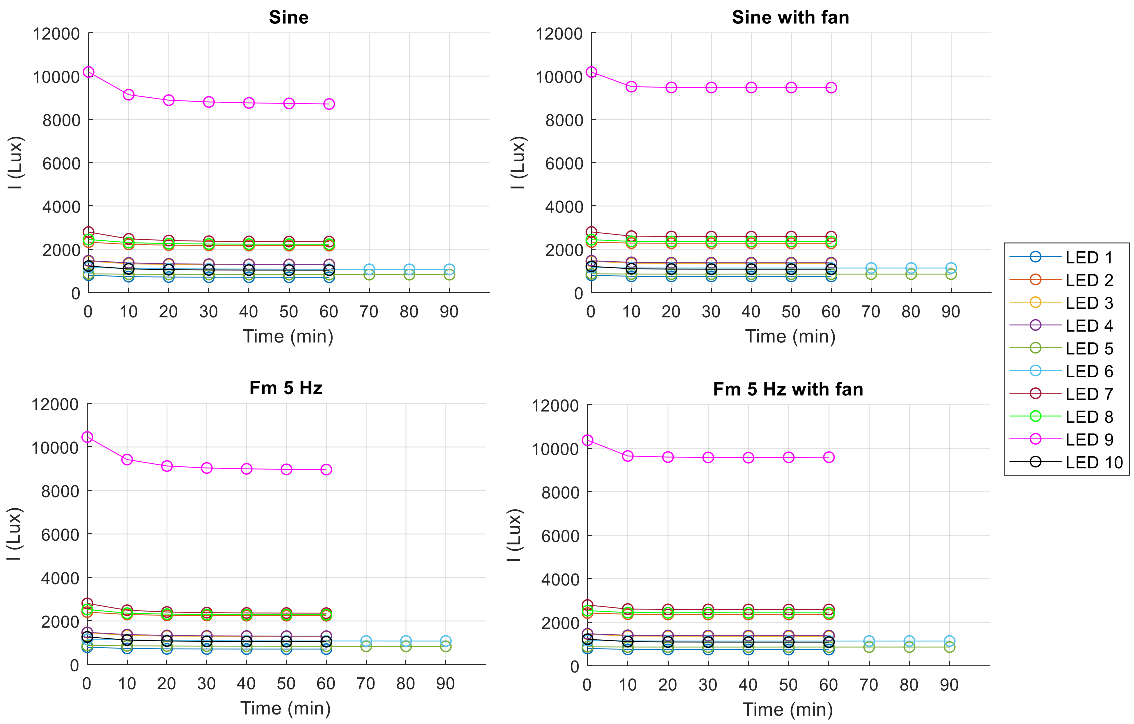


Figure 33. Absolute illuminance for different LED lamps in all the cases studied.

Similar to previous cases, the LED lamps illuminance evolution with time has been plotted as a percentage of variation between two consecutive instances according to equation (1) (Figure 34).
As with active power, all the LED lamps decrease in illuminance with time, as shown in [9] and for the cases refrigerating with fan, as for active power, there are some slight increases after minute 20, when stabilization is reached. To know the stabilization time according to illuminance, the variation in illuminance might be considered $\geq$-1% in inequation (2). According to that, the stabilization time for these lamps is 30 min without fan and 20 min with fan.

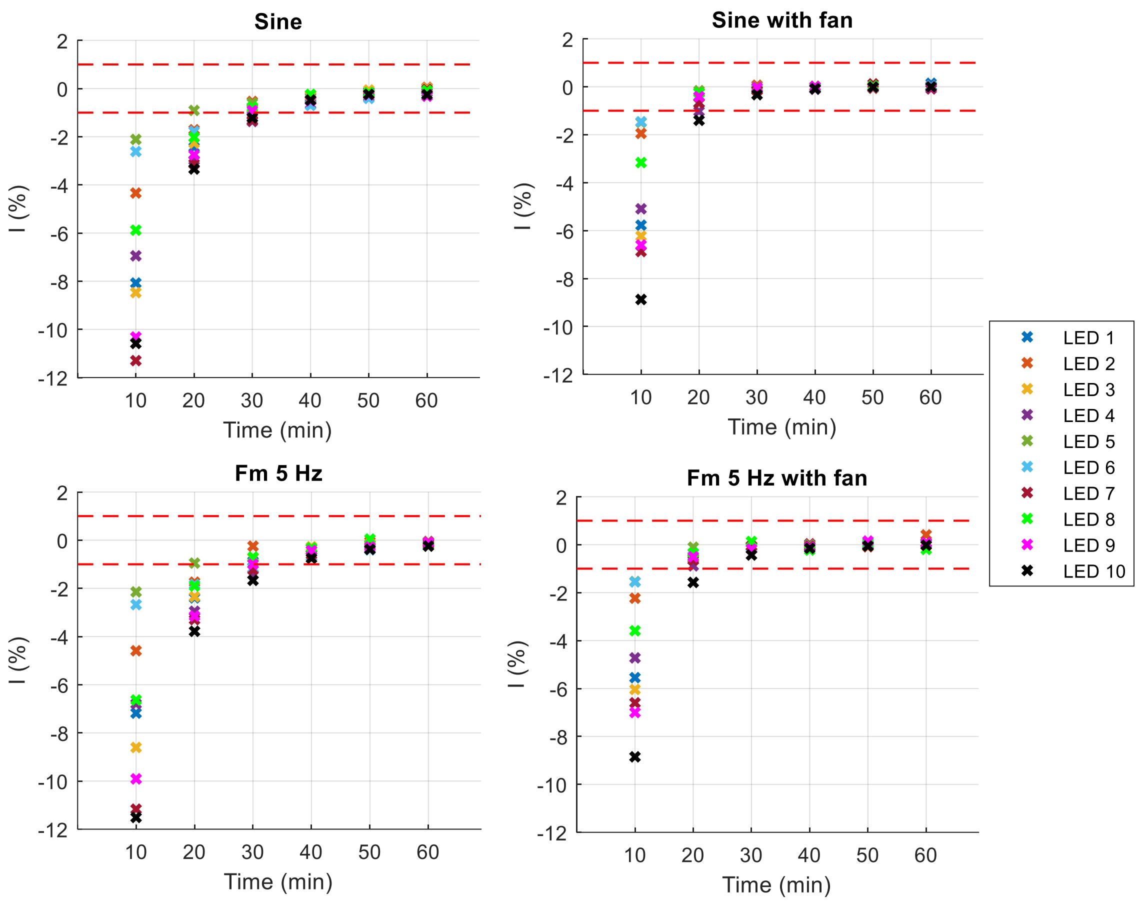


Figure 34. Illuminance variation (%) of different LED lamps for all the cases studied.

Harmonics variation

Figure 35 represents how current harmonics have almost no variation over time and therefore with temperature. For all the cases studied the results have been similar to this one.

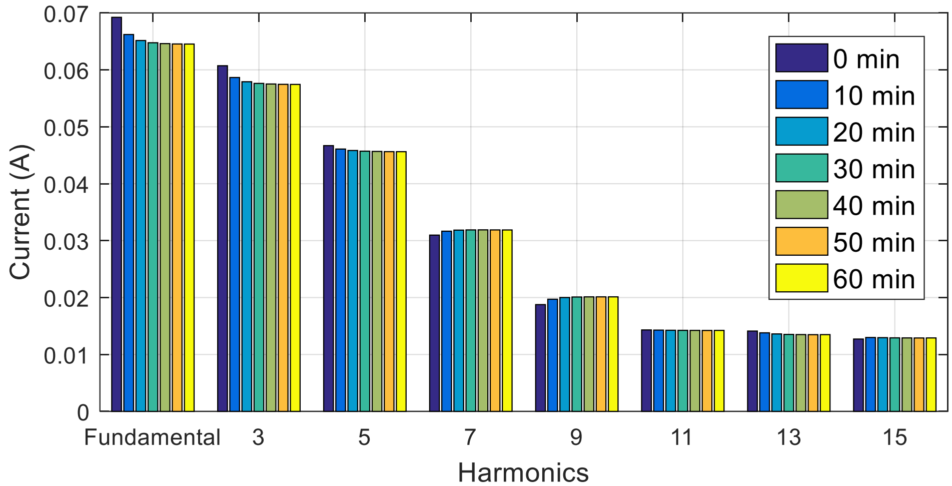


Figure 35. Current harmonics amplitude evolution with time in LED 7 (supply with sinusoidal waveform)

Discussion

In this section, three studies are done based on the previous results, but combining different parameters in order to obtain new conclusions. First, emission is considered, where different power quality parameters are studied for LED lamps when connected to pure sinusoidal voltage waveform. Then, immunity is considered, where those PQ parameters are studied when LED lamps are connected to distorted voltage. To end with, the performance of LED lamps is studied to see the effect on LED lamps in terms of temperature.

Emission in LED lamps

Three types of behaviour relative to THD and I RMS can be distinguished due to a temperature increase:

- **Type 1:** THD increases and I RMS decreases **(**most of the LED lamps).
- **Type 2:** THD decreases and I RMS increases **(**LED 2 and LED 8)
- **Type 3:** THD decreases and I RMS decreases **(**LED 6 and LED 9)

LED 2 and LED 8 show a type 2 behaviour, as well as LED 6 and LED 9 show a type 3, both types differ from behaviour of the majority (Type 1). It could be explained regarding the topology of these LED lamps, as it was shown in Figure 3.

This classification corresponds to both cases, with and without fan.

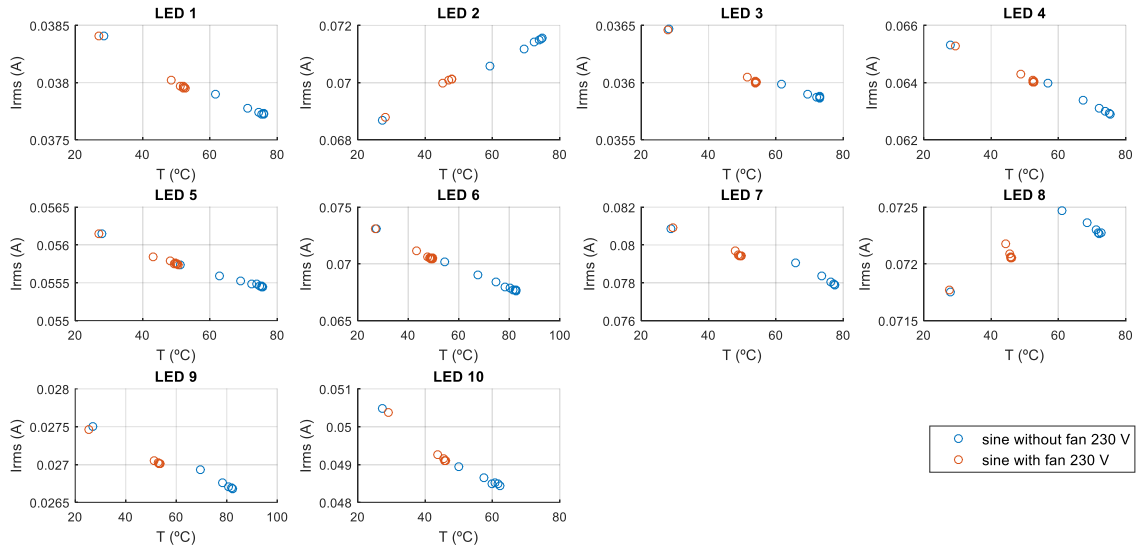


Figure 36. I RMS evolution over temperature with LED lamps connected to sinusoidal voltage waveform with (orange) and without (blue) fan.

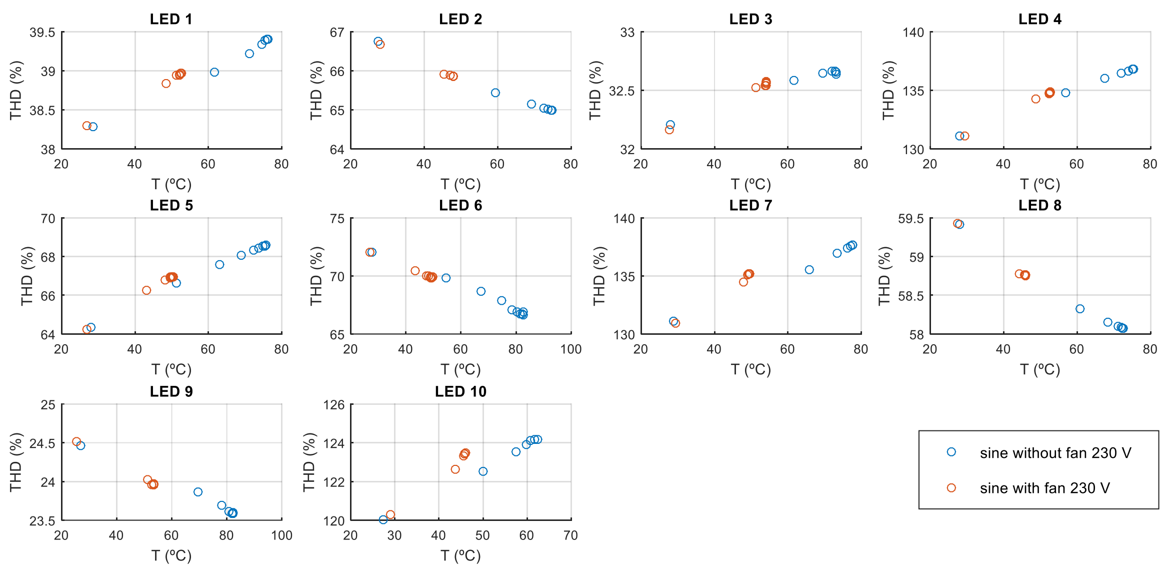


Figure 37. Current THD evolution over temperature with LED lamps connected to sinusoidal voltage waveform with (orange) and without (blue) fan.

Immunity in LED lamps

Impact from voltage fluctuation

Figure 38 represents the variation in the active power, temperature and illuminance when the LED lamps were connected to 5 Hz sinusoidal voltage fluctuation compared to sinusoidal voltage waveform following equation (3), where X is active power (W), temperature (ºC) and illuminance (lux).

$$\Delta X = \frac{X_{fm} - X_{sine}}{X_{sine}} * 100 \qquad (3)$$

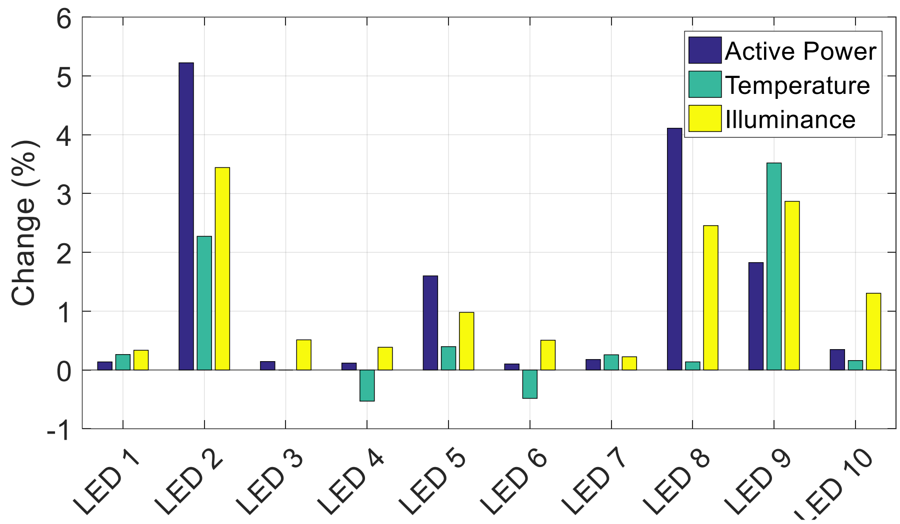


Figure 38. Active power, temperature and illuminance variation when LED lamps are connected to 5 Hz sinusoidal voltage fluctuation compared to sinusoidal voltage waveform.

All the lamps show a small increase in active power and illuminance when connected to 5 Hz sinusoidal voltage modulation compared to pure sinusoidal, but the difference varies between lamps (reaching 5.3% maximum) even more than the effect seen when cooling the lamps.

Impact from over and under voltages

To study the immunity, and to get rid of the temperature as possible, the measurement comparison has been done using the fan to cool the LED lamps so that they reach the thermal stabilization faster and to keep as constant as possible the stabilization temperature between tests. However, the variations between measurements with and without fan have been checked.

The under and over voltage has been tested through a variation of ±10% of 230 V, which corresponds to 207 V and 253 V respectively with a sinusoidal waveform. Also, the modulation of 5 Hz waveform has been compared. It has been taken as a reference the values obtained with the 230 V sinusoidal supply voltage.

Active Power

The supply voltage variations do not change the active power in a significant way. As it is shown in Figure 39.a with LED 4, the maximum variation between different supply voltages is 0.03 W. However, LED 5 in Figure 39.b shows that there is a decrease of 10% in active power when undervoltage is applied, almost the same behaviour is seen for overvoltage, which increases the active power by 8%. Also, with voltage modulation of 5 Hz, the active power is 0.4 W higher than with 230 V. For this reason, it can be stated that a variation in supply voltage amplitude causes a variation in the active power in almost the same proportion. Therefore, those LED lamps show two different behaviours in the active power for different supply voltage amplitude, even though the active power variation in absolute values is small for both cases due to the low consumption of LED lamps.

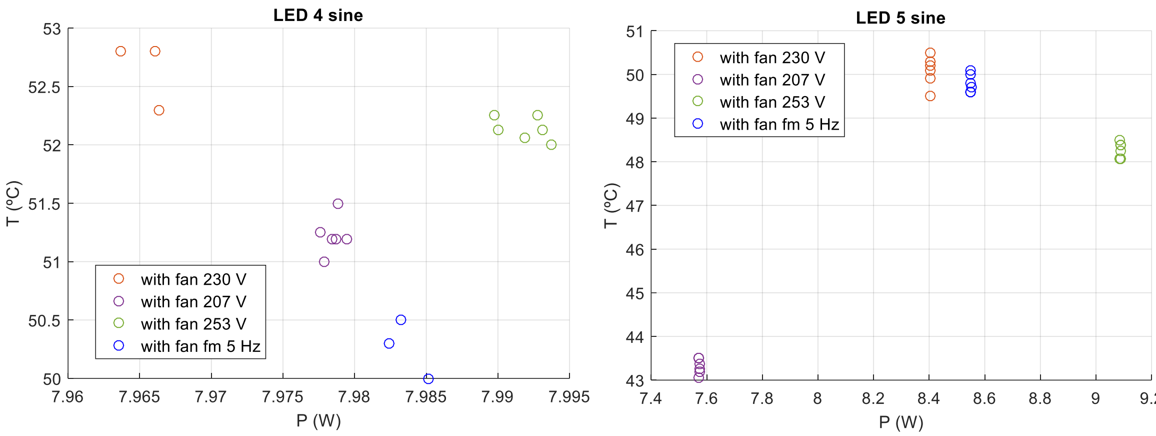


Figure 39. Active power with temperature cooling with fan a) the LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage.

Comparing with the measurements without fan in Figure 40, for LED 5 the biggest active power variation takes place comparing the measurements with fed with overvoltage (0.12 W), for the rest of supply voltages, the variation between LED lamps with fan and without fan takes place in the second decimal. For LED 4 this difference is within 0.191 W (230 V) and 0.228 (207 V). Therefore, it does not matter if the measurements are with or without fan to compare the active power immunity from under and over voltage because the variation between both cases is almost constant for all the supply voltages.

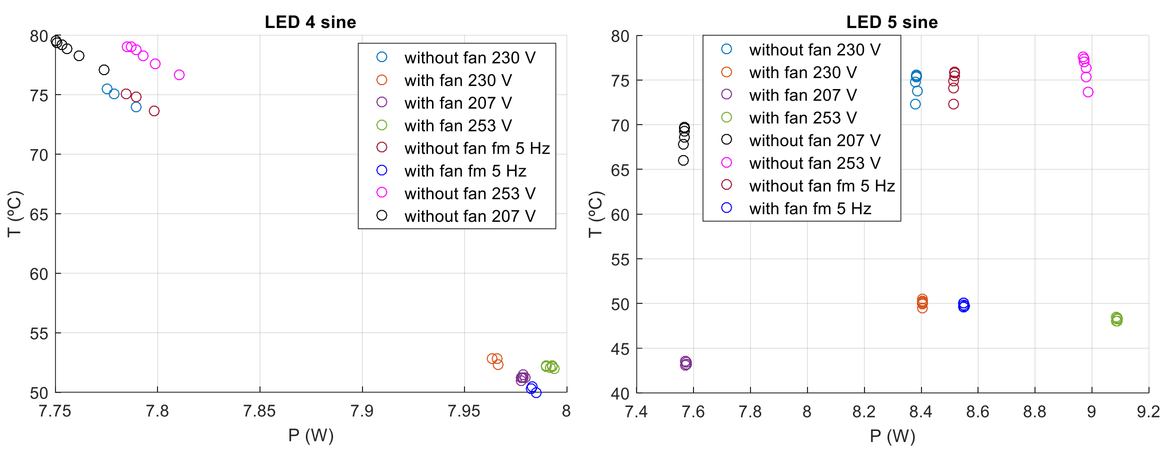


Figure 40. Active power cooling and without cooling the lamp with fan. a) LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage

Illuminance

The behaviour of the illuminance is similar to the one from the active power for both LED lamps shown in Figure 41.

As Figure 41.a represents, for the different supply voltages applied to LED 4, the maximum illuminance variation between them is 2.25% (31 lux) taking as reference the measurement with a supply voltage of 230 V.

On the other hand, for LED 5, the variations for under and over voltage are 6.8% and 7.7% respectively. As with active power, the illuminance variation for the modulation of fm5 Hz is not as big as the one for the under and over voltage, just 1.12%, as it is shown in Figure 41.b.

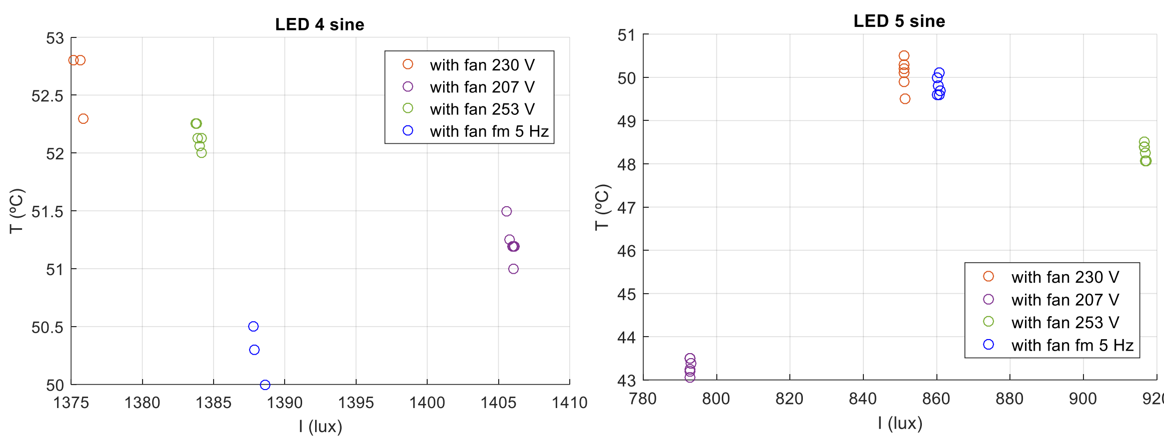


Figure 41. Illuminance with temperature cooling with fan a) the LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage

If the results for each supply voltage is compared with the measurement without fan following equation (4), it is seen that, for LED 5, the illuminance variation is within 2.75% (207 V) and 3.13% (fm 5 Hz modulation), except when the LED lamp is fed with 253 V which variation is 4.87% for LED 5 in Figure 42 which means less impact in illuminance for over voltage. In the case of LED 4 illuminance the results without fan do not keep such a similar variation with the measurements with fan, the range of variation is within 3.982% (253 V) and 6.687% (with modulation of 5 Hz). Despite of this, if the results without fan are used for studying the illuminance immunity, the maximum variation in illuminance between different voltage supplies is 2.7% (35 lux), close to the result obtained with fan, taking again 230 V measurement as reference.

$$\Delta X = \frac{X_{fan} - X}{X} * 100 \quad (4)$$

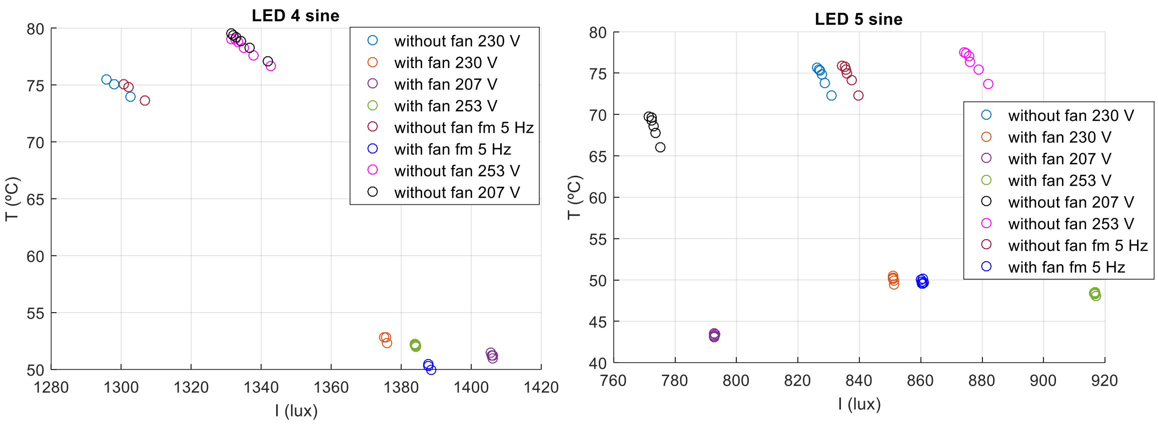


Figure 42. Illuminance against temperature without and with cooling with fan a) the LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage

It has been shown that under and over voltage has bigger impact in active power than in illuminance for LED 5 and the opposite for LED 4. Comparing both LED lamps, LED 4 has better immunity from under and over voltage according to its smaller variations described above. So that, in this paper has been shown two differnet behaviour from under and over voltage of LED lamps.

Efficiency

In terms of efficiency, the maximum difference between the different voltage supplies in LED 4 is 3.5 lux/W and in LED 5 4.1 lux/W as it is represented in Figure 43. The difference observed without refrigeration is close to this one, being the maximum 5.1 lux/W for LED 4 and 4.46 lux/W for LED 5 as Figure 44 shows. For both LED lamps and for both ambient conditions, the best efficiency in the tested LED lamps takes place feeding with 207 V while for the other voltage supplies, a similar pattern of the efficiency change can not be described.

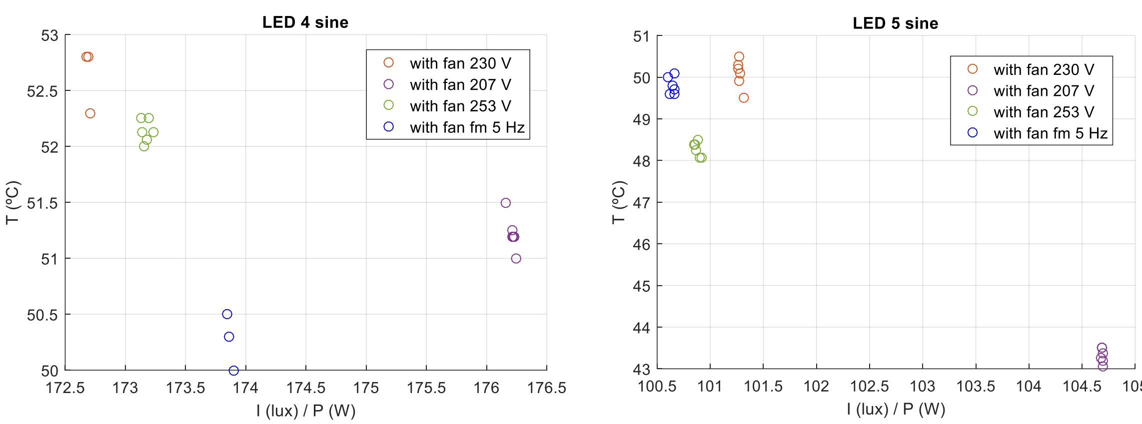


Figure 43. Efficiency against temperature cooling with fan a) the LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage

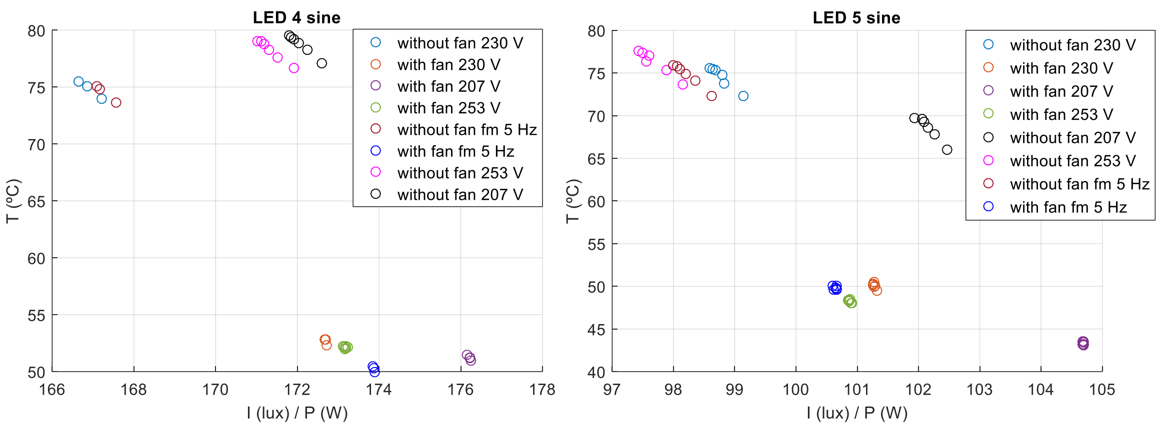


Figure 44. Efficiency against temperature without fan and cooling with fan a) the LED 4 at left and b) LED 5 at right. Differences with under and over voltage and fluctuation in the supply voltage

Performance change in terms of temperature

All the comparisons in this section have been done when the LED lamps were stable (after stabilization time) and connected to pure sinusoidal voltage waveform.

Figure 45 represents the change in illuminance and active power when the LED lamps are cooled with an external fan. It follows equation (4), where X is active power (W) or illuminance (lux) accordingly. The temperature reached with and without fan change depending on the LED, being the difference between both cases from 19ºC (25.99%) to 33.1ºC (39.98%), LED 3 and LED 6 respectively.

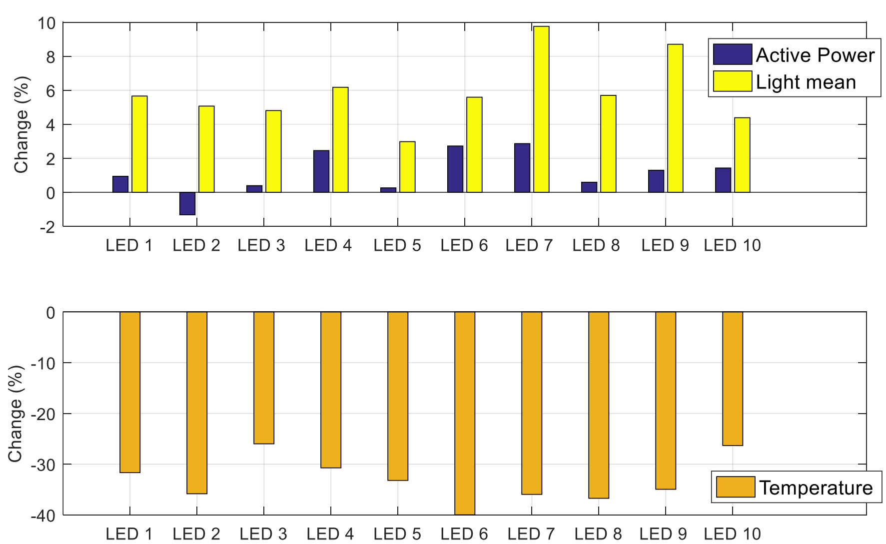


Figure 45. Active power, temperature and illuminance variation when LED lamps are connected to pure sinusoidal voltage with and without fan.

The biggest impact is seen for LED 7, the absolute temperature difference between the two cases is 35.95%, and this gives a change in active power of 3% and a change in illuminance of 9.8%.
Cooling the lamps leads to an increase in illuminance for all the lamps. The variation in the illuminance varies between 3% and 10%. Moreover, cooling the lamps leads to an increase in active power for all the lamps (except LED 2). The variation in active power is lower, between 0.3% and 3%, so that, the active power is less sensitive to cooling the lamps than the illuminance.

Active power

For 70% of the LED lamps, the active power variation between the measurements with fan and without fan is less than 1.5%. The maximum change is 2.864 % in LED 7, which is 0.2786 W. It is also shown in Figure 46 that the variation in temperature it is different depending on the lamp.

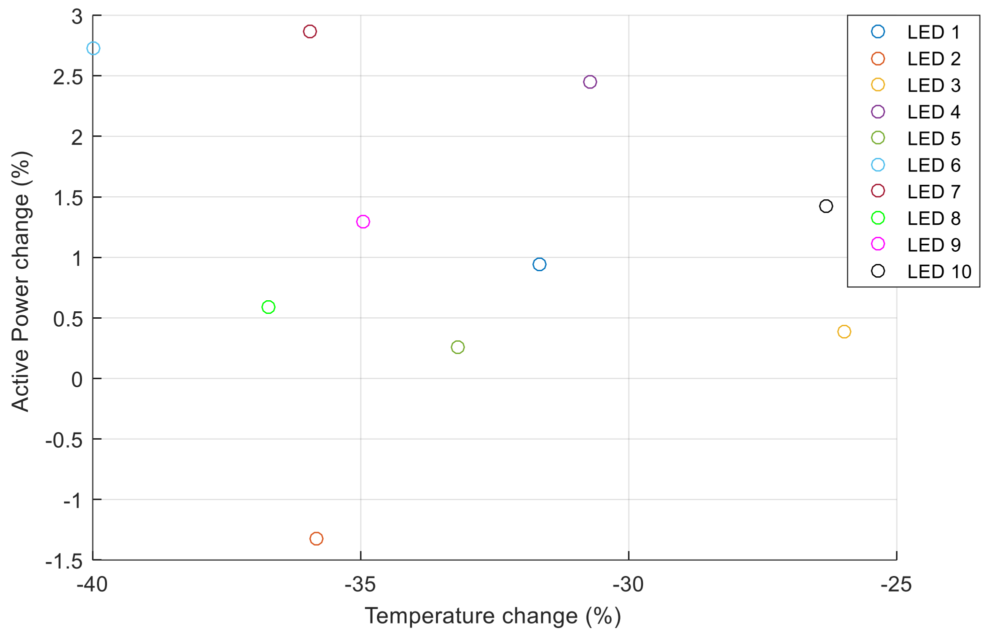


Figure 46. Percentage of active power difference between the measurement with and without fan against the percentage of LED lamp temperature for all the LED lamps tested.

Illuminance

The illuminance percentage of change is within 6.176% (LED 4) and 4.387% (LED 10) for 70% of the LED lamps tested, in Figure 47 it is shown how the difference of the variation between lamps keeps around this 2% independently of the temperature variation.

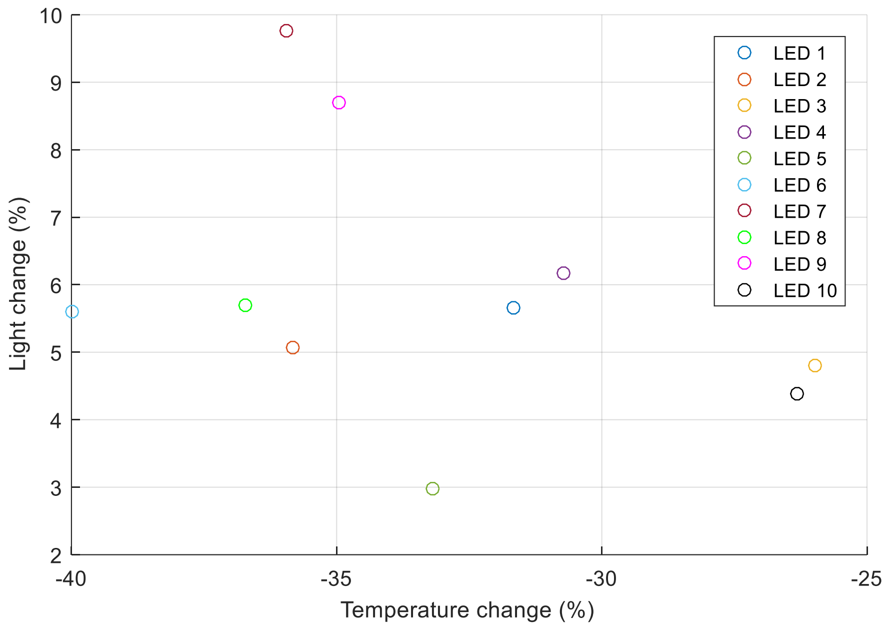


Figure 47. Percentage of illuminance difference between the measurement with and without fan against the percentage of LED lamp temperature for all the LED lamps tested.

Efficiency

The efficiency also keeps within a variation around 2% being the range from 2.711% (LED 5) to 5.078% (LED 8). LED 2, LED 7 and LED 9 have better efficiency, but it has been seen that some parameters of these LED lamps are outliers.

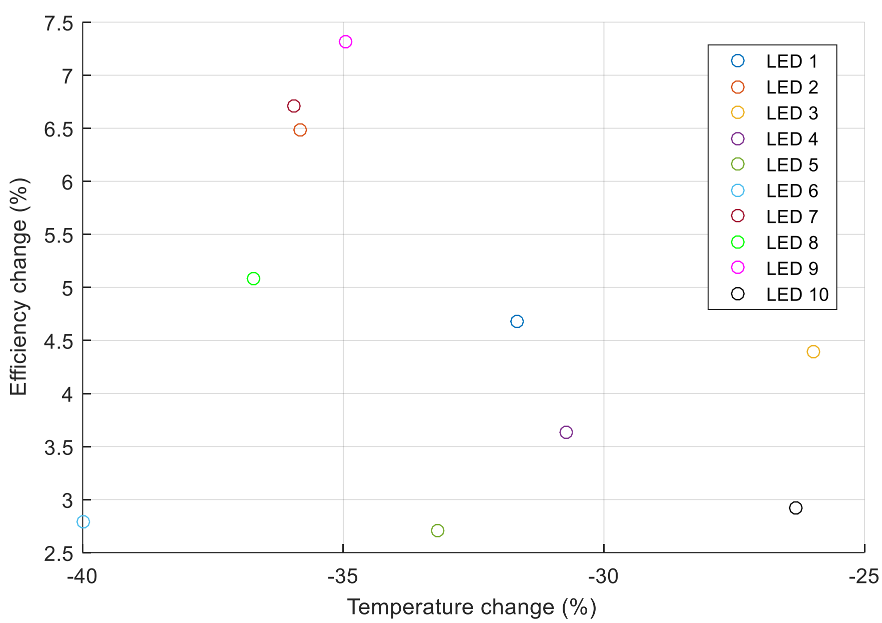


Figure 48. Percentage of efficiency difference between the measurement with and without fan against the percentage of LED lamp temperature for all the LED lamps tested.

Conclusion

The stabilization time according to temperature evolution presents the longest time (60 min), while according to light output and the active power the lamps reach before the stabilization time (30 and 20 min respectively). For this reason, thermal stabilization is considered the reference to know when the LED lamp is stable before doing more measurements. It is also shown that the stabilization time differs for different ambient temperatures. As the LED lamps were sensitive to changes in ambient temperature, this parameter should be kept constant during comparative tests.

As the illuminance increases more than the active power when the LED lamps are cooler, it is concluded that the LED lamps are more efficient at low temperatures. So that, efficiency in LED lamps changes depending on the weather conditions, as seasonal changes or the geographical area.

As results show, a variation in the sinusoidal waveform has different effects depending on the LED lamp studied. However, in all of them there are a slight increase in the active power and illuminance. More measurements over different voltage distortions at different frequencies will be included in further research.

To know the influence of voltage distortion (immunity) or emission, we are using a fan as it stabilizes the lamp from a temperature point of view.

Temperature and voltage do matter in LED lamps efficiency. From active power point of view, temperature does not impact. The lamps do not get warmer due to voltage distortions.

For standardized tests, it is needed to stablish the point to be studied (or compared), if it is the hottest point or ambient temperature of the room where the lamp is connected. It is moreover important for reproducibility, to indicate which point has been taken for temperature point of view.
From electrical parameters point of view, taking the hottest point or ambient temperature is not determinant, as the same relationships has been observed in both cases.

The initial temperature does not define the stabilization temperature, it is defined by the ambient temperature and the LED lamps' electrical features.

The ambient conditions change the temperature of the LED lamp due to the electronic components inside the lamps. So that, in Figure 46 and Figure 47 it can be seen how the variation in active power and in illuminance keeps within a range for most of the LED lamps even though the temperature difference with and without fan is very different for each lamp (being under the same conditions). It means that ambient conditions set a value for illuminance and active power, but not for the temperature of the components of the LED lamps. The temperature of each LED lamp changes in a way that all of them under the same ambient condition reach a similar illuminance and active power percentage variation.

Has been shown two different behaviours in illuminance and active power from over and under voltage, however, the efficiency has not such a different behaviour.

Even though three different types of behaviour according to THD of current and current RMS against temperature are found, these do not explain the differences in the illuminance, active power and efficiency variations between the measurements done with and without fan cooling the LED lamps.

On the other hand, the topology of the LED lamps studied seems do explain the mentioned three types classification.

Regarding the reproducibility, from measurements done with a difference of few days it is obtained similar values. However, there is a constant error in illuminance comparing summer 2018 and 2019, which could be partially explained by the illuminance degradation along time of use. Also, there is a constant error in temperature measuring with fan, which could be explained by a possible change over a year in this device.

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