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Keywords: Lamps, Efficiency, Perception, Flicker, Power Quality.

# Flicker Characteristics of Efficient Lighting Assessed by the IEC Flickermeter.

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## Abstract

We present an experimental study of the behavior of modern lighting technologies under supply voltage fluctuations. Some studies have reported that flicker severity measurements could exceed the compatibility levels without leading to flicker complaints when modern lighting is in use. Such conclusions have resulted in two main proposals regarding the assessment of flicker: to relax the flicker compatibility indexes and to adapt standardized procedures to assess flicker based on a new reference lamp instead of the current reference, the incandescent lamp. Our work presents alternative tools for analyzing the effect of efficient lighting on the assessment of flicker. Our main findings challenge the assumption that efficient modern lighting is not sensitive to voltage fluctuations, at least over a considerable frequency range. Furthermore, the results oppose the use of the standardized functional model of the incandescent lamp for assessing the flicker severity produced by modern lamps.

**Keywords**

Lamps, Efficiency, Perception, Flicker, Power Quality.

## 1. Introduction

International energy efficiency regulations have prompted the fast and definitive withdrawal of incandescent lamps, a change that has particular relevance to the assessment of the light flicker produced by voltage fluctuations. In terms of electromagnetic compatibility, flicker is defined as the annoyance induced by illuminance fluctuations caused by variations in the supply voltage of the lamp. The procedure for assessing this disturbance is defined in the IEC 61000-4-15 standard [1], which establishes the functional specifications for measuring the flicker severity value, $P_{\mathrm{st}}$, from the supply voltage. For this purpose, the 60 W incandescent bulb serves as the reference lamp.

The gradual replacement of incandescent lamps by more efficient lamps, such as halogen, compact fluorescent lamps (CFLs) and light emitting diode (LED) lamps [2] has promoted the research of new lighting technologies' sensitivity to voltage fluctuations. The main conclusions indicate that new lighting technologies seem to be less sensitive to voltage fluctuations than incandescent lamps [3]. Other recent studies have noted the absence of user complaints in sites where high flicker severity levels were measured, and suggest that this could be attributable to these new lighting technologies' lower sensitivity to voltage fluctuations [4, 5]. Based on these conclusions, international organizations for the standardization and improvement of electric power systems, such as the IEC and CIGRE/CIRED, are currently examining the possibility of modifying the established compatibility levels for voltage fluctuations and adapting the IEC 61000-4-15 standard to reflect the different sensitivity of modern lamps. Currently, CIGRE working group C4.111 is reviewing low voltage (LV) and medium voltage (MV) compatibility levels for voltage fluctuations, as well as analyzing possible alternatives to the concept of flicker severity for assessing voltage fluctuations [6].

However, other studies have warned against erroneous perceptions of modern lamps' insensitivity to voltage fluctuations. Some of these works have reported findings showing the sensitive behavior of CFLs and LED lamps in the presence of harmonic and interharmonic frequencies of higher values than the common frequency range established for flicker assessment [7, 8].

The present work provides new evidence that questions the lack of importance currently given to the light flicker produced by new lighting technologies. For this study, we selected some of the most common and efficient lamps on the commercial lighting market; models that are expected to replace the incandescent lamp. The present analysis was conducted in terms of flicker severity because the spectral characteristics of the illuminance of these lamps indicated that the frequency response of the lamp is not always the best tool for sensitivity analysis; to assist this, an illuminance flickermeter was designed. Furthermore, although a number of studies have proposed adapting the IEC flickermeter for modern lamps based on the linear model of the standard [5, 9], a linearity analysis of the illuminance raises doubts about the validity of this approach. Finally, for comparison with the objective results, we performed several subjective tests, in which a group of people were exposed to light flicker produced by test lamps.

The results of this work clearly question the effectiveness of modifying the established compatibility levels for voltage fluctuations, at least in relation to short- and medium-term trends in lighting technologies. Moreover, our results invalidate the possibility of directly adapting the IEC flickermeter for use with any modern lamp that could become the future reference lamp for flicker measurement.

## 2. Experimental Setup

All the experiments in this study were based on illuminance signals obtained from the various lamps tested. In this section, we describe the set of lamps under test (LUTs) and the process applied to obtain the illuminance signals.

### 2.1. Set of Lamps Under Test

We selected a set of commercially available lamps from different high- and low-end manufacturers, in order to test samples of different lighting technologies, including the halogen lamps, fluorescent lamps using electronic or electromagnetic ballast and LED lamps. The lamps selected for testing also include a variety of the energy efficient behaviors represented by European Union energy labeling, which uses classes from A to G, where A is the most energy efficient and G the least.

Some studies have proved that the sensitivity behavior of some lamps changes when different illumination levels are applied, for two main reasons. First, at low illuminance levels, the eye is less saturated with light and therefore is more sensitive to light flicker. Second, the interaction between dimmer technologies and brightness-control methods applied in self-ballasted lamps generates alternative paths for the voltage fluctuations [10]. Hence, several dimmable lamps were included in the set of LUTs using the Leading Edge (LE) dimmer Busch-Jaeger 2247U.

The main characteristics of the LUTs are given in Table 1.

### 2.2. Generation and Acquisition Process

Fig. 1 depicts the experimental setup used to acquire and store the illuminance signals of the LUTs. First, an analytical signal is converted into an analog signal by a D/A converter (National Instruments USB-6211) at a rate of 100 kHz. The analog signal is then amplified to 230 V by a 7500 Krohn-Hite Amplifier (75 W, from DC to 1 MHz) and a 120/230 V transformer. This signal is applied to the lamp, which is enclosed in a white box, in which the light sensor is also located. This sensor is connected to a luxmeter (E4-X Hagner Digital Luxmeter, with an accuracy better than ±3%) which provides an analog output signal, $l(t)$, representing the illuminance, that is digitized by the A/D converter (National Instruments USB-6211) at a sampling rate of $f_s = 10$ kHz and 16 bits per sample, and finally stored.

## 3. LUT Frequency Response to Voltage Fluctuations

Traditionally, the frequency response of the lamps, namely gain factor, is used to analyze lamps' sensitivity to voltage fluctuations [3, 7, 11]. The main conclusions drawn from previous studies regarding this particular issue are summarized in this section.

The gain factor characterizes the relationship between the relative amplitudes of illuminance and voltage fluctuation, $\frac{\Delta L}{L}$ and $\frac{\Delta V}{V}$, respectively, for a given sinusoidal fluctuation frequency, $f_{\mathrm{m}}$:

$$G(f_{\mathrm{m}}) = \frac{\Delta L/L}{\Delta V/V}. \tag{1}$$

Previous research has reported different results from the analysis of the gain factors obtained for a set of lamps, selected from different lighting technologies and manufacturers. Some of these results indicate that new lighting technologies clearly exhibit greater insensitivity to voltage fluctuations than the incandescent lamp [3]. However, the results obtained in other studies raise doubts about this insensitivity. Some of these works show that the sensitivity of some lamps with external electromagnetic ballast and halogen lamps is close to and even higher than the incandescent lamp in a wide frequency range [7, 11]. Furthermore, some CFLs and LFLs can be very sensitive to high interharmonic frequencies as it is proved in [8].

Moreover, the study performed in [7] also includes the gain factor of some dimmable lamps working at 100%, 75%, 50% and 15% of their nominal illuminance. The results obtained when the 100% of the nominal illuminance was applied, show that dimmable lamps exhibit lower sensitivity than the reference lamp. Nevertheless, the sensitivity to voltage fluctuations of some of the CFLs and LEDs dimmable lamps increase as the illuminance decrease, reaching sensitivity values which are clearly above the sensitivity of the incandescent lamp over the entire frequency range.

Therefore, these works clearly question the insensitivity to voltage fluctuations of modern lamps, being the results dependent on the technology development.

## 4. Spectral Analysis of the LUTs' Illuminance

The gain factor assumes that the illuminance fluctuation is concentrated around the fluctuation frequency of the supply voltage. This fact is true for the case of the incandescent lamp. However, given the electronic complexity of the brightness-control methods applied in some of the LUTs, distortion can be expected, which could have influence on the sensitivity and, hence, on the annoyance. Therefore, a spectral analysis of the illuminance signals was conducted. To obtain the spectrum for each of the LUTs, a set of sinusoidal voltage fluctuations was applied, each of them having the following form:

$$u(t) = A_0 \sqrt{2}[1 + \frac{\Delta V}{V} cos(w_{\mathrm{m}} t)] cos(w_0 t), \tag{2}$$

where $A_0$ =230 V, $w_0 = 2\pi \cdot 50$ rad/s and $w_{\mathrm{m}} = 2\pi \cdot f_{\mathrm{m}}$ rad/s.

For this experiment, a relative voltage amplitude of $\frac{\Delta V}{V} = 1\%$ and fluctuation frequencies from 1 to 35 Hz in steps of 1 Hz were used.

The illuminance, $l(t)$, was registered according to the process described in Fig. 1 in order to calculate $\frac{\Delta L}{L}$ for a given fluctuation frequency, $f_{\mathrm{m}}$.

The results of the analysis demonstrate that the illuminance spectrum of some LUTs is not concentrated around the $f_{\mathrm{m}}$ component, but is scattered across other frequency bands. Fig. 2 shows an example of the spectrum obtained from the Fourier transform of the illuminance envelope for $f_{\mathrm{m}} = 27$ Hz. The curves represent the values of $\frac{\Delta L}{L}$ integrated in 2 Hz frequency bands, normalized to the corresponding value of the main frequency component of the fluctuation, $f_{\mathrm{m}}$, highlighted in boldface.

As seen, the LFL 18 W lamp (F1) and the CFL 12 W lamp (C4) present a dispersed spectrum outside the band of the fluctuation frequency $f_{\mathrm{m}} = 27$ Hz, which is clearly different from the spectrum of the incandescent lamp. This occurs at any $f_{\mathrm{m}}$ in the range of 0–35 Hz.

This observation raises two issues. First, it questions the absolute validity of the gain factor as a tool for analyzing lamps' sensitivity to voltage fluctuations. It seems appropriate to study the influence of such lamp sensitivity on the flicker severity, considering all the frecuency components present in the range of 0–35 Hz. Second, the existing spectral dispersion points to a nonlinear behavior, which suggest the need for a linearity analysis of the LUTs in terms of voltage fluctuation frequency.

## 5. Analysis of LUT Influence on the Flicker Severity

Observations in the previous section indicate a need to analyze the sensitivity of the LUTs considering all the frequency components of the illuminance, $l(t)$, in the range of 0–35 Hz. In fact, this is the procedure established by the IEC 61000-4-15 standard [1] to measure flicker severity using a model which represents the linear characteristics of the incandescent lamp.

To consider the real characteristics of the LUTs, it is necessary to use a tool that operates with an illuminance input signal, i.e. an illuminance flickermeter [12]. The IEC 61000-4-15 standard defines the design specifications for a flickermeter based on the voltage supply, according to a physiological model of the lamp–eye–brain chain. Some of the blocks of the model include the performance characteristics of the 60 W incandescent lamp [1]. The illuminance flickermeter provides the flicker severity value based on the illuminance signal. Consequently, designing an illuminance flickermeter requires that the blocks of the IEC voltage flickermeter related to the lamps' response be adapted. This implies that the quadratic demodulation (Block 2 of the IEC standard) must be eliminated, and the weighting filter (the lamp–eye response in Block 3 of the IEC standard) must be modified, so that the frequency characteristics of the human eye are only reflected [13].

The validation of the implemented illuminance flickermeter was performed by means of the functional tests defined in the IEC 61000-4-15 standard, which are used for assessing the performance of a flickermeter and the accuracy of its results [13]. This validation procedure can also be used to classify the flickermeter. The maximum deviation obtained in our implementation reaches a value of 2.1% for any test-point, thus verifying its accuracy and linearity characteristics. Therefore, the new tool could be classified as highly accurate class F1 meter.

### *5.1. Sensitivity Analysis using an Illuminance Flickermeter*

For this analysis, various sinusoidal voltage fluctuations (Eq. (2)) with $f_\mathrm{m}$ from 1 to 35 Hz were generated. The relative amplitude values were those producing $P_\mathrm{st} = 1$ when applied to the incandescent lamp, $\frac{\Delta V}{V}\big|_{P_{\mathrm{st,I1}}=1}$.

Using the generation and acquisition process depicted in Fig. 1, illuminance signals of 10 min were registered for each voltage fluctuation. Finally, using the illuminance flickermeter, the $P_\mathrm{st}$ values were calculated.

Fig. 3 shows the results of the analysis for the nondimmable and dimmable lamps (at 100% and 15% of their nominal illuminance). This figure shows the $P_\mathrm{st}$ values associated with each

LUT, normalized to the flicker severity of the incandescent lamp, in terms of voltage fluctuation frequency.

For nondimmable lamps (Fig. 3(a)), the results are quite similar to those for the gain curves [7]. The only remarkable difference is the slight increase in the sensitivity of the LFL 18 W (F1) for frequencies approximately below 10 Hz. This is consistent with the additional frequency components observed in the spectral analysis, which are expected to produce flicker severity values that are different from the case of a single $f_{\mathrm{m}}$ component.

Noticeable differences can also be seen in the results for dimmable lamps at 100% of the nominal illuminance value, shown in Fig. 3(b). In particular, while the CFL 12 W lamp (C4) provides high sensitivity values at low fluctuation frequencies, as also observed in its gain curve [7], here it provides, in terms of $P_{\mathrm{st}}$, high sensitivity values at high fluctuation frequencies also ($f_{\mathrm{m}} > 23$ Hz approximately). This effect is also appreciable at a low illuminance level (15% of the nominal illuminance), shown in Fig. 3(c). Similarly, at 15% of the nominal illuminance, the CFL 11 W lamp (C5) exhibits higher sensitivity compared with that represented by its gain curve [7] over the entire frequency range, reaching the same sensitivity values as the incandescent lamp. In contrast, the LED 8 W lamp (L2) exhibits lower sensitivity at 15% of the illuminance compared with that represented by its gain curve [7]; nevertheless, this is clearly above the sensitivity of the incandescent lamp.

### *5.2. Subjective Tests*

To complete the evaluation of the LUTs' sensitivity to voltage fluctuations, we assessed the LUTs in terms of annoyance by conducting a set of subjective tests with a group of 10 people. These tests, which applied the same philosophy as the objective tests, involved a comparison of the extent of disturbance produced by some LUTs and the incandescent lamp, at the same $P_{\mathrm{st}}$ level. Because of difficulties in perceiving a value of $P_{\mathrm{st}} = 1$ with the incandescent lamp at some frequencies, $P_{\mathrm{st}} = 2$ was selected as the reference value for the comparison.

The test procedure consisted of simultaneously applying to the LUTs and the incandescent lamp the $\frac{\Delta V}{V}$ values that, according to the experimental results from the illuminance flickermeter, generated a $P_{\mathrm{st}} = 2$ value for each lamp. The lamps were located in optically isolated rooms. Each subject was instructed to compare the perceived light flicker produced by the LUTs with that from the incandescent lamp, using the rating scale detailed in Table 2.

The experiment was repeated for the voltage fluctuation frequencies of $f_{\mathrm{m}}$ =1, 10, 15, 20, 30, 35 Hz and for H1, C1, C3, F1, L1, C4 and L2 lamps. In the case of dimmable lamps, the experiment was performed at 100% of their nominal illuminance. Table 3 presents the results, for each $f_{\mathrm{m}}$, based on the rating awarded by at least 50% of the subjects.

Most of the test points demonstrate that the sensitivity values obtained in the objective experiments correspond to the subjective perceptions ($P_{\mathrm{LUT}} = P_{\mathrm{I1}}$). Positive deviations of one step of the rating scale can be observed for some test points. The vast majority of these deviations point to a level of discomfort that is slightly higher than the expected $P_{\mathrm{st}} = 2$ value. This indicates that, at those frequencies, the LUTs show higher sensitivity than the objective values derived from the illuminance flickermeter. However, the LFL 18 W lamp (F1) presents a negative deviation, which could indicate a sensitivity slightly lower than the expected value.

The results of the subjective tests point to the objectives results obtained from the illuminance flickermeter in the previous experiments.

## 6. Study of the IEC Lamp Model for the LUT

The lamp model defined in the IEC standard assumes a linear behavior of the illuminance and, hence, of flicker severity in the presence of voltage fluctuations. This linearity is modeled by means of the quadratic demodulator defined in Block 2, combined with the weighting filter in Block 3 [1]. Previous studies have recommended modifying the IEC flickermeter by simply adapting the weighting filter to a new reference lamp [5, 9]. However, this proposed approach assumes a linear real behavior of all the lamps.

The results we obtained for some of the LUTs from the spectral analysis of the illuminance envelope showed a relevant dispersion outside the expected fluctuation frequency $f_{\mathrm{m}}$, which could indicate a nonlinear response to voltage fluctuations. This finding suggests the need for a linearity analysis of the LUTs.

### 6.1. *Linearity Analysis of the LUT Frequency Response*

To date, it has been universally accepted that the illuminance response of incandescent lamps is linear with regard to voltage fluctuations, and hence that flicker severity is too. In fact, for this type of lamp, linearity means proportionality, i.e., a linear increase in $\frac{\Delta V}{V}$ means a proportional increase in $\frac{\Delta L}{L}$ and consequently in the flicker severity [1].

We analyzed the linearity of the LUTs for different levels of $\frac{\Delta V}{V}$. For this purpose, the LUTs were supplied with sinusoidal voltage fluctuations of $f_\mathrm{m}$ from 1 to 35 Hz and $\frac{\Delta V}{V}$ values corresponding to a $P_\mathrm{st} = 1$ for the incandescent lamp, $\left.\frac{\Delta V}{V}\right|_{P_\mathrm{st,I1}=1}$. Then, the $P_\mathrm{st}$ values of the illuminance signals for each lamp were obtained using the illuminance flickermeter. These $P_\mathrm{st}$ values were used as the reference values, $P_\mathrm{st,init}(f_\mathrm{m})$. This experiment was repeated for a proportional set of values of the relative amplitude:

$$\left(\frac{\Delta V}{V}\right)_{exp} = k \cdot \left.\frac{\Delta V}{V}\right|_{P_\mathrm{st,I1}=1} \quad \text{with } k = 1 : 0.5 : 5. \tag{3}$$

According to the IEC standard specifications, for a given $f_m$, a linear relationship should exist between the obtained $P_\mathrm{st}$ values and the relative amplitudes, $(\frac{\Delta V}{V})_{exp}$, presenting a slope $m_\mathrm{ref}(f_\mathrm{m}) = P_\mathrm{st,\ init}(f_\mathrm{m})$.

The regression line that best fits the experimental flicker severity values obtained for the relative amplitude values $(\frac{\Delta V}{V})_{exp}$ was calculated. After obtaining the slope of each of these regression lines, $m_\mathrm{exp}(f_\mathrm{m})$, the percentage deviation regarding the ideal slope, $m_\mathrm{ref}(f_\mathrm{m})$, was also calculated:

$$\frac{\Delta m}{m}\left(f_\mathrm{m}\right) = \frac{m_\mathrm{exp}(f_\mathrm{m}) - m_\mathrm{ref}(f_\mathrm{m})}{m_\mathrm{ref}(f_\mathrm{m})} \cdot 100 \tag{4}$$

The deviations were clearly below 5% for the entire frequency range for almost all the LUTs. However, some of the LUTs presented higher deviations, which merited detailed analysis. The deviation values of these lamps as a function of $f_\mathrm{m}$ are presented in Fig. 4.

Among the nondimmable lamps, the LFL 18 W (F1) presented large deviations at all $f_\mathrm{m}$, reaching values between 15% and 30% at low frequencies (1–10 Hz) and around 15% and 20% for frequencies close to 35 Hz. Among the dimmable lamps, the LED 8 W lamp (L2) presented deviations around 30% in the frequency range of 20–25 Hz. The CFL 12 W lamp (C4) presented deviation values greater than 5% at low frequencies ($f_\mathrm{m} < 5$ Hz) and in the range of 20–25 Hz.

These results confirm that some LUTs have a nonlinear frequency response under voltage fluctuations, a finding that indicates a possible mismatch between the real behavior of these LUTs and the functional lamp model specified by the standard.

### *6.2. LUT–adapted IEC Flickermeter*

To identify the origin of the nonlinearity of certain LUTs, we compared the results generated by two different tools: (1) the illuminance flickermeter, which used the real characteristics of each LUT; and (2) a flickermeter adapted to each LUT, but using the quadratic demodulation specified in the IEC standard, considering the hypothesis of a linear behavior of the LUTs.

The main characteristics of this second tool, called the LUT–adapted IEC flickermeter, are as follows:

1. The input is an analytical voltage fluctuation according to Eq. (2).
2. It must be implemented in the frequency domain, taking advantage of the band-limited components of the sinusoidal voltage fluctuations. Because of the complexity involved in obtaining a weighting transfer function adapted to every nonlinear LUT, the adapted IEC flickermeter used the experimental frequency responses obtained from the gain curves of the LUT [7], $|H_\mathrm{lamp}(f)|$, combined with the eye response [13], $|H_\mathrm{eye}(f)|$.

$$|H(f)_\text{lamp-eye}| = |H(f)_\mathrm{eye}| \cdot |H(f)_\mathrm{lamp}| \qquad (5)$$

3. The functional model of the lamp is represented by a squaring multiplier (as it is specified in Block 2 of the IEC standard) combined with the LUT frequency response, in contrast to the illuminance flickermeter, which works with the lamps' real characteristics.

The working principle of this LUT–adapted flickermeter is as follows. When the input voltage signal (Eq. (2)) is modulated by a sinusoidal fluctuation, $f_\mathrm{m}$, the quadratic demodulation established by the IEC standard (Block 2) generates only a single relevant component, of frequency $f_\mathrm{m}$ and amplitude $2 \cdot A_0^2 \cdot \frac{\Delta V}{V}$, at the output of the demodulation filters (Block 3 of the IEC standard). Consequently, the amplitude of this component can be weighted by the corresponding known value of the module of the frequency response (Eq. (5)). Hence, for every LUT, it is possible to obtain the instantaneous flicker sensation (output of Block 4 of the IEC standard), $P_{\mathrm{inst}}$, and therefore its corresponding $P_{\mathrm{st}}$ for any weighted sinusoidal voltage fluctuation of a given $f_{\mathrm{m}}$ and $\frac{\Delta V}{V}$.

The LUT–adapted flickermeter was validated using the values provided for Test 1 of the IEC standard, defined for sinusoidal voltage fluctuations, with the 230 V/50 Hz incandescent lamp [1]. All the test points reported deviations below 1%.

Following this procedure, we obtained the $P_{\mathrm{st}}$ values for the same voltage fluctuations used for the linearity analysis described in Subsection 6.1, i.e., $f_m$ from 1 to 35 Hz and $\frac{\Delta V}{V} = k \cdot \frac{\Delta V}{V}\Big|_{P_{\mathrm{st,I1}}=1}$, where $k = 1$ and 5.

Fig. 5(a) and 5(b) show the percentage deviations of the LUT–adapted IEC flickermeter results in relation to the values obtained using the illuminance flickermeter for $k = 1$ and 5, respectively, in terms of the fluctuation frequency. Results are shown only for lamps that presented high non-linearity values in the previous analysis of Subsection 6.1.

The LFL 18 W (F1) and CFL 12 W lamp (C4) exhibited substantial deviations over the entire frequency range for both ranges of $P_{\mathrm{st}}$, i.e., flicker severity values corresponding to $k = 1$ and 5. The F1 lamp presented deviations between 15% and 20% for frequencies $f_{\mathrm{m}} > 15$ Hz in the case of $k = 1$ and between 10% and 30% over the entire frequency range for $k = 5$. The C4 lamp presented deviations around 15%–20% for frequencies $f_{\mathrm{m}} < 20$ Hz and very high deviations for frequencies above 25 Hz, being almost independent of the $P_{\mathrm{st}}$ range. However, the LED 8 W (L2) lamp presented small deviations (always below 8%) for the low range of $P_{\mathrm{st}}$ ($k = 1$), but the deviation became relevant (around 15%–20%) in the frequency range of 20–25 Hz and around 10% at 5–10 Hz and 25–30 Hz as the flicker severity range increased ($k = 5$).

The results confirm that the nonlinear behavior of some of the LUTs in the presence of voltage fluctuations implies a completely different behavior from that of the incandescent lamp. Given this observation, the IEC lamp functional model is not appropriate for measuring light flicker produced by lamps other than the incandescent lamp.

## 7. Conclusions

We presented a rigorous and extensive experimental work analyzing the effect of modern and energy-efficient lighting technologies on perceptions of the light flicker caused by supply voltage fluctuations.

Current approaches tend to be focused on the widespread use of modern lamps as the explanation of the lack of correlation between high measured values of flicker severity and the absence of complaints. Consequently, proposals for modifying the assessment of flicker severity tend to be oriented along two main lines: to increase the flicker compatibility threshold; to carry out a basic adaptation of the standardized procedure for flicker assessment to a new reference lamp. The results of our work contradict these assumptions.

Our experimental work involved several lamps, chosen from among the various lighting technologies currently in use. All of the lamps tested are more efficient than the incandescent lamp, which is still used in the IEC standard as the reference for flicker assessment.

The first set of results warns against using the gain factor to characterize the behavior of modern lighting technologies when subjected to supply voltage fluctuations: some of these lamps have complex and dispersed illuminance frequency distributions.

Based on this initial finding, we analyzed sensitivity to voltage fluctuations in terms of flicker severity. The results of this analysis demonstrate that the sensitivity of some modern lamps, which have a high level of current and medium-term market penetration, is heavily frequency dependent. Some of the lamps, namely the halogen lamp, the linear fluorescent lamp (LFL) and some types of CFL, were clearly more sensitive than the incandescent lamp in a wide frequency range, depending on the test conditions. In addition, under low illuminance conditions, the flicker severity level of some of the lamps, such as the CFL and LED types, increased, greatly exceeding the reference value of the incandescent lamp. Furthermore, subjective tests performed with a group of 10 people, confirmed the sensitivity inferred from the experimental objective tests. Interpreted conservatively, these results should encourage not so much the relaxation of the quality standards, but rather the control of lamps' immunity to voltage fluctuations.

The work also examined the convenience of applying the IEC functional model to assess the flicker severity produced by modern lamps. This analysis revealed that some of the lamps exhibited significant nonlinear behavior, in particular the LFL and CFL types controlled by external electromagnetic ballasts and one type of dimmable LED lamp that is controlled by internal electronics. Given this finding, the standardized lamp model based on a quadratic demodulation should not be used for flicker assessment if a new reference lamp were introduced. Adapting the standardized procedure would be more complex than simply replacing the eye–lamp weighting characteristic; that is, defining a new functional model for a new reference lamp will require more in-depth work [14–16].

In sum, the association reported by some studies [4, 5] between the absence of complaints in sites with high measured values of flicker severity and the widespread use of modern lighting technologies should be challenged. The measurements in these studies were performed using the current IEC flickermeter, which uses the functional model of the incandescent lamp. However, when consumers are exposed to other types of lamp, the flicker measurement will not be correlated with consumer perception, because the correct assessment of flicker severity will require a different strategy and model.

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# Figure Legends

| | |
|---|---|
| Figure 1 | Scheme of the generation and acquisition process. |
| Figure 2 | Example of the spectrum (in logarithmic scale) of the LUTs' illuminance of a sinusoidal fluctuation of $f_\mathrm{m} = 27$ Hz. Values of $\frac{\Delta L}{L}$ are integrated in 2 Hz frequency bands, normalized to the corresponding value of the main frequency component of the fluctuation, $f_\mathrm{m}$. (a) nondimmable lamps and (b) dimmable lamps. |
| Figure 3 | Flicker severity values provided by the illuminance flickermeter for nondimmable and dimmable lamps, normalized to the flicker severity of the incandescent lamp, in terms of fluctuation frequency. (a) nondimmable lamps, (b) dimmable lamps at 100% of the nominal illuminance value and (c) dimmable lamps at 15% of the nominal illuminance value. |
| Figure 4 | Linearity deviation between the experimental and ideal flicker severity values for the LUTs as a function of $f_\mathrm{m}$. |
| Figure 5 | Percentage deviation between the flicker severity values provided by the illuminance and the LUT–adapted flickermeters for $k = 1$ and 5, respectively, in terms of the fluctuation frequency. (a) $P_\mathrm{st}$ range correponding to $k = 1$, i.e., $\frac{\Delta V}{V} = \left.\frac{\Delta V}{V}\right\|_{P_{\mathrm{st,I1}}=1}$ and (b) $P_\mathrm{st}$ range correponding to $k = 5$, i.e., $\frac{\Delta V}{V} = 5 \cdot \left.\frac{\Delta V}{V}\right\|_{P_{\mathrm{st,I1}}=1}$. |

# Table Legends

| | |
|---|---|
| Table 1 | Set of lamps under test. |
| Table 2 | Rating scale for the subjective tests. |
| Table 3 | Results of the subjective tests for each $f_m$, based on the rating awarded by at least 50% of the subjects. |

# Figure 1 and 2

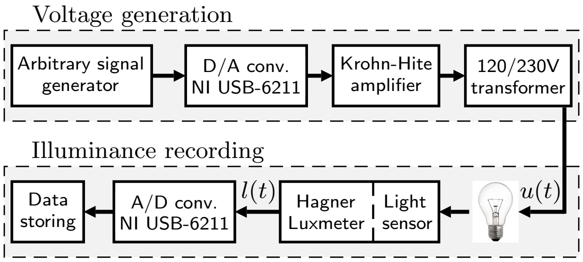
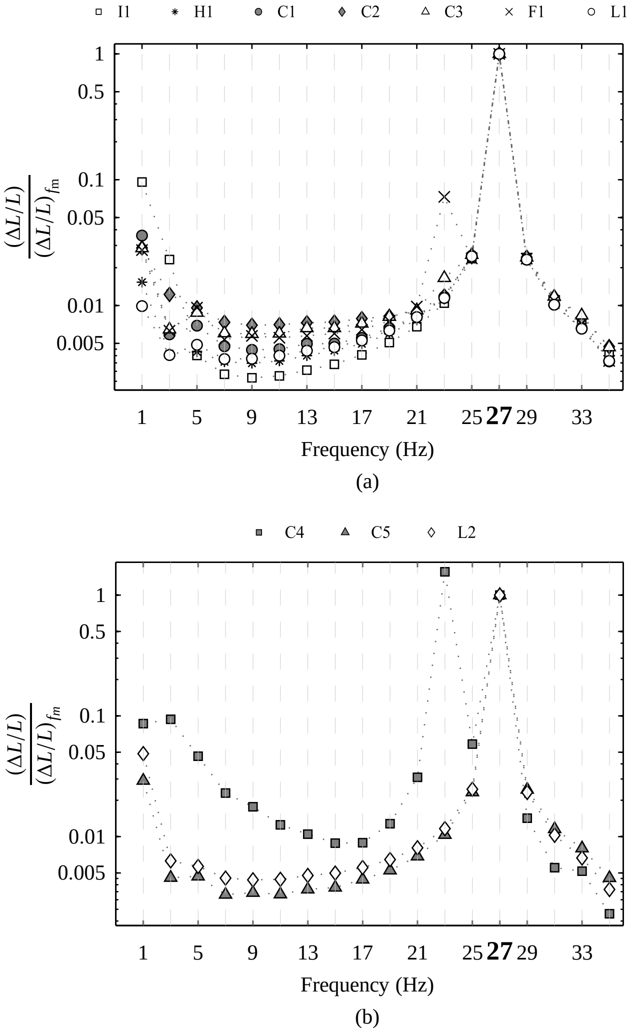


Figure 1

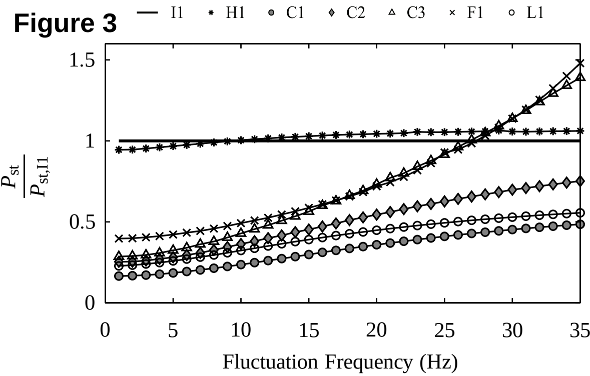


(a)

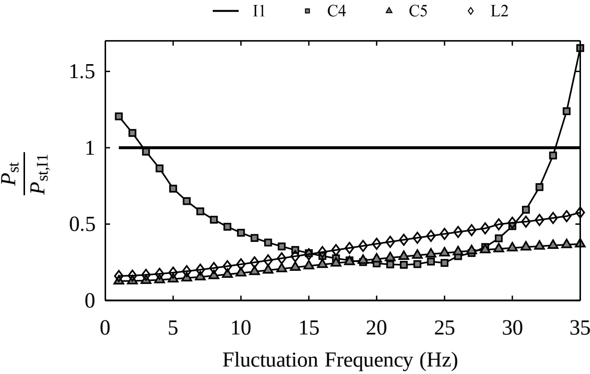
(b)

Figure 2

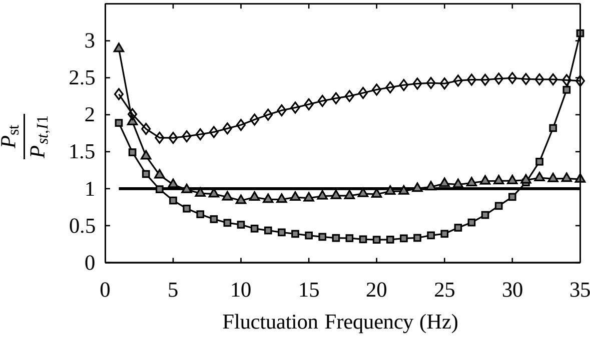
**Figure 3**


I1
H1
C1
C2
C3
F1
L1
1.5
1
0.5
0
$\frac{P_{st}}{P_{st,I1}}$
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)

(a)


I1
C4
C5
L2
1.5
1
0.5
0
$\frac{P_{st}}{P_{st,I1}}$
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)

(b)


3
2.5
2
1.5
1
0.5
0
$\frac{P_{st}}{P_{st,I1}}$
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)

(c)

**Figure 4**

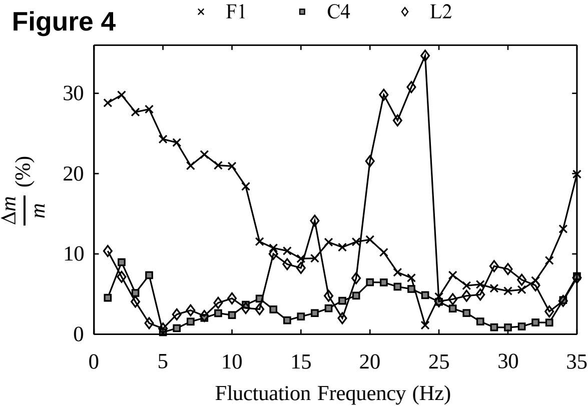
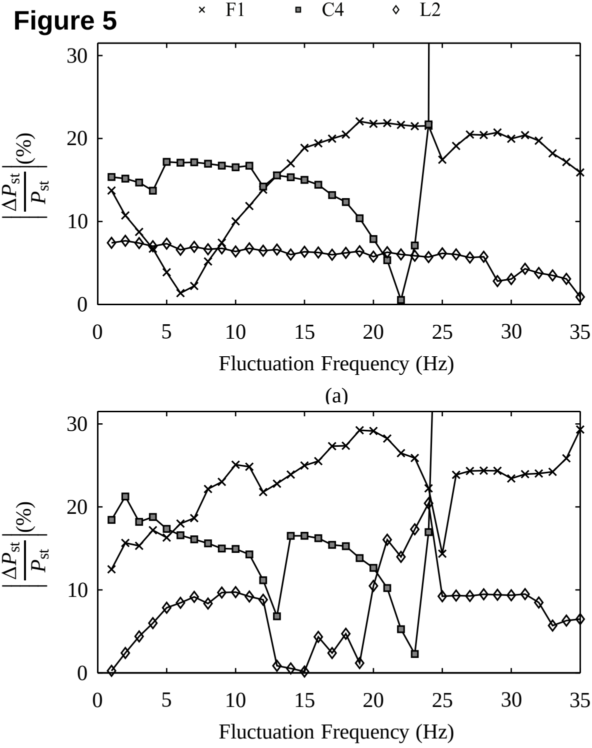

× F1
■ C4
◇ L2
$\frac{\Delta m}{m}$ (%)
0
10
20
30
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)

**Figure 5**


× F1
■ C4
◇ L2
30
20
10
0
$\left|\frac{\Delta P_{\mathrm{st}}}{P_{\mathrm{st}}}\right|(\%)$
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)
30
20
10
0
$\left|\frac{\Delta P_{\mathrm{st}}}{P_{\mathrm{st}}}\right|(\%)$
0
5
10
15
20
25
30
35
Fluctuation Frequency (Hz)

(a)

(b)

**Table 1,2 and 3**

## TABLE I

| Id. | Lamp Technology | Power[1] (W) | Lum Flux (Lumen) | Class[2] | Remarks[3] |
|---|---|---|---|---|---|
| I1 | Incandescent | 60 | 850 | E | ND |
| H1 | Halogen | 42 | 630 | C | ND |
| C1 | CFL | 11 | 570 | A | ND, EB |
| C2 | CFL | 23 | 1380 | A | ND, EB |
| C3 | CFL | 18 | 1050 | B | ND, EMB |
| F1 | LFL[4] | 18 | 1050 | B | ND, EMB |
| L1 | LED | 12 | 650 | A | ND |
| C4 | CFL | 12 | 600 | A | D, EB |
| C5 | CFL | 11 | 570 | A | D, EB |
| L2 | LED | 8 | 470 | A | D |

[1] 230 V / 50 Hz

[2] Energy efficiency classes defined by the European Union

[3] Nondimmable (ND), dimmable (D), electronic ballast (EB), electromagnetic ballast (EMB)

[4] Linear fluorescent lamp

## TABLE II

| Perception Scale | Code |
|---|---|
| $P_{\mathrm{LUT}}{}^{1} \gg P_{\mathrm{inc}}{}^{2}$ | ++ |
| $P_{\mathrm{LUT}} > P_{\mathrm{inc}}$ | + |
| $P_{\mathrm{LUT}} = P_{\mathrm{inc}}$ | = |
| $P_{\mathrm{LUT}} < P_{\mathrm{inc}}$ | − |
| $P_{\mathrm{LUT}} \ll P_{\mathrm{inc}}$ | −− |

[1] Perceptions from the LUTs.

[2] Perceptions from I1.

## TABLE III

| Lamp | $f_{\mathrm{m}}$ (Hz) | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 10 | 15 | 20 | 30 | 35 |
| H1 | = | = | = | = | = | = |
| C1 | + | = | + | + | + | = |
| C3 | = | = | = | + | + | + |
| F1 | = | − | = | = | − | = |
| L1 | = | = | = | = | = | = |
| C4 | = | = | + | + | + | = |
| L2 | + | + | = | = | = | + |