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Implementation of a light Flickermeter in a low cost embedded system

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Abstract: This study presents the development and implementation of an alternative Flickermeter based on a low cost embedded electronic system. The development of this new device is based on the original Flickermeter proposed by the IEC 61000-4-15, but with important modifications added. These modifications allow for direct quantification of light variation, in such a way, so as to eliminate the effect associated with the different lamp technologies available through the correct quantification of flicker severity. In order to achieve this objective blocks 1 and 3 of the original IEC Flickermeter were altered and block 2 was completely eliminated. The implementation of a low cost embedded electronic system represents the differential of the developed system in relation to equipment currently available on the market, which is based on solutions of a more elevated cost. The developed prototype was appropriately tested and thus provided encouraging results. In addition, the article also presents an analysis that refers to the susceptibility of lamps manufactured upon the same technologies to flicker, such as compact fluorescent and LED lamps, widely used nowadays for substituting traditional incandescent lamps.

1 Introduction

Flicker is a phenomenon that can cause headaches, visual tiredness and loss of concentration among other adverse effects in an individual that is continually submitted to the phenomenon [1]. Severe levels of flicker may also cause epileptic fits in those prone to the affliction [2].

The phenomenon associated with the effect of flicker represents the luminous variation perceived by the human eye in lamps submitted to voltage fluctuations. In general, voltage fluctuations are associated with the rapid and abrupt alterations in the power of large loads, such as cooling loads or arc furnaces. These variations in the power load (which result in current variations of the same frequency) cause voltage variations resulting in flicker on illumination systems that are connected to various electrical buses [3].

Flicker can be measured by the device called the Flickermeter, proposed by the standard IEC 61000-4-15 [4]. The working structure of the IEC Flickermeter is based on the perception of light variation by human beings, thus making the quantification of flicker possible through the emulation of a lamp-eye-brain system. Although used amply on a worldwide scale, the IEC Flickermeter does in fact present significant limitations [5, 6].

The main problem concerning the IEC Flickermeter is related to its use of an incandescent lamp in its original modelling, thus creating a system that is limited to the dynamics of the referred lamp, which is especially sensitive to variations of the effective voltage value. Those illumination systems based upon non-incandescent lamps can also produce flicker, even in situations in which the IEC Flickermeter presents values below the limit suggested for such indicators [7, 8]. On the other hand it may be also possible to register flicker while users of non-incandescent lamps would not complain about flicker.

The correct quantification of the flicker effect is currently one of great challenges in the area of power quality. The limitations of the IEC Flickermeter stimulated research into alternative methods for the measurement of flicker [9–11]. However, as flicker depends on the functionality and dynamics of the lamp, the most promising alternatives use the direct measuring of flicker that being the direct measurement of the light (illuminance) variations [12–14], as this method generates a measurement independent of the lamp technology. The limiting factor of this proposal is the fact that these measurements are based on computational platforms and virtual platforms of an elevated cost.

The major contribution of this paper refers to the development of an alternative Flickermeter (based on luminous measurement) and its implementation into a low cost embedded electronic system. This proposal is in contrast to those elevated cost proposals based on virtual instrumentation (or computational). The developed and implemented system enables the alternative Flickermeter application to measure the effect of flicker in an efficient and practical approach – make it appropriate for the daily workings of industry. This proposal is based upon the elimination of block 2 from the IEC Flickermeter, as well as the modifications made to blocks 1 and 3, which adapted them for the input of illuminance. Another contribution made by the paper is the preliminary study of lamps of the same technology and their performance when submitted to voltage fluctuations. In this manner, it was observed that lamps of the same technology can present lower or higher susceptibility to flicker. The following sections present the details of the developed system, its implementation and the main results and experiments carried out through use of the prototype.

2 IEC Flickermeter

The parameters which are able to characterise the waveform with voltage fluctuation are the fluctuation frequency f_m and amplitude m, in %. Fig. 1*a* presents the waveform of a rectangular fluctuation $v(t)$ with its respective parameters appropriately indicated. The rms value for $v(t)$ in time (cycle to cycle) is indicated by the waveform $V(t)$. The modulation m is defined by $\Delta v/\bar{v}$, which is a good approximation of $\Delta V/\bar{V}$ [4]. The values of f_m and m in Fig. 1*a* are 3.5 Hz and 5%, respectively. (This study uses an rms voltage of 120 V and a frequency of 60 Hz.)

When the $v(t)$ fluctuation is applied to an incandescent lamp (IL) of 60 W, a variation in its luminosity is provoked. The waveform for the illuminance $l(t)$ produced by IL is presented in Fig. 1*b*. There is a considerable fluctuation of the signal (obtained from the light meter), with an amplitude variation of $\Delta l/\bar{l}$ of approximately 25%. The fact that the variation frequency f is also 3.5 Hz is herewith highlighted. In accordance with the perception of the selected observers, as well as with a set of options that classify the level of flicker (posteriorly presented), the intensity of the flicker evaluated was 'strong'.

The quantitative determination for the flicker severity index is realised by the Flickermeter, through the emulation of the lamp-eye-brain system and the statistical analysis of the results. The system model eye-brain was determined from the investigation of the eye-brain dynamics [15, 16] and the relationship between flicker perception and variation of luminosity intensity [17–19]. The block diagram illustrated in Fig. 2 represents the IEC Flickermeter in a simplified manner, which is divided into 5 blocks (1–5) and the signal flow is indicated by the letters a–f.

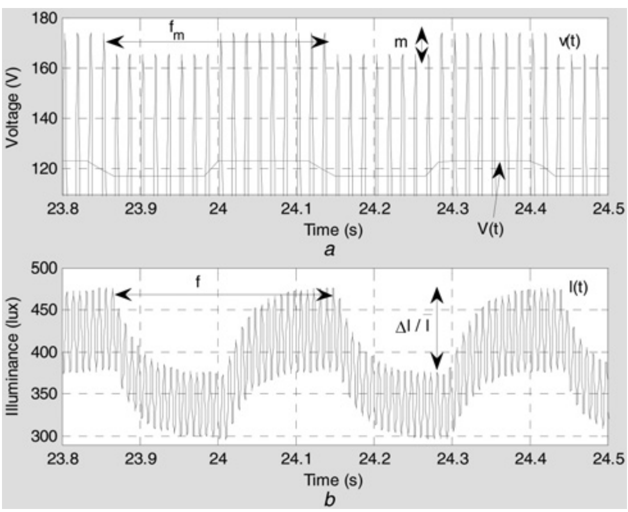

Fig. 1 *Fluctuation waveform*

a $v(t)$ with $f_m = 3.5$ Hz and $m = 5\%$ and its rms value $V(t)$
b Illuminance produced by an IL of 60 W submitted to fluctuation $v(t)$

The Flickermeter input is the monitored voltage, indicated by 'a'. The voltage value is conditioned and digitalised by block 1. The normalised output 'b' is applied to block 2. Block 2 carries out a quadratic operation, which simulates the quadratic relationship between power (luminosity) and voltage. The output 'c' equals the light signal produced by the IL.

Block 3 is composed of filters that process the light signal. The IEC 61000-4-15 requirement defines a low-pass filter (LPF) and a high-pass filter (HPF). Together with the quadratic operator they carry out signal demodulation. The dc level and the high frequencies are eliminated, such as 120 Hz (result of the quadratic operation at 60 Hz). The frequency components are maintained that make up the fluctuation, which is able to produce a waveform similar to the fluctuation envelope from the light signal. There is a weighting filter associated to the IL response and the response of the human eye to light variation. The signal 'd' produced equals the weighted light fluctuation.

Block 4 processes the signal 'd' in accordance with non-linear characteristics from the eye-brain system, through the use of a quadratic operator. Memory effects are simulated by a 1st order LPF (smoothing). The signal 'e' is equivalent to the instantaneous flicker, which will be noted by an individual. It was agreed that the value 1 pu is equivalent to the flicker perception threshold that being, flicker will be noted by 50% of the individuals [4].

Finally, block 5 will carry out the statistical analysis of the values, along with the occurrences of instantaneous flicker. The analysis allows for the determination of flicker severity 'f'. The severity level is indicated through two parameters, known as Pst (probability short-term) and Plt (probability long-term). Conventionally, Pst equal to 1 pu indicates the irritability threshold [4].

As the Flickermeter model incorporates the dynamics and functionality of the IL, it does not give a correct representation of the flicker that is produced in lamps, which are not of incandescent technology [7, 8]. The context of energy efficiency and advances in the area of illumination have made the question more prominent, as the more traditional IL are rapidly being substituted by more efficient lamp technologies, such as the compact fluorescent lamp (CFL) and LED lamp (LEDL), with different dynamics and functionality. In Brazil [20] and the European Union [21] along with various other countries there exist laws specifically oriented towards the gradual elimination of IL.

Fundamentally, it can be said that IL is sensitive to variations in the supply's efficient voltage values, and at the same time the modern electronic lamps (CFL and LEDL) are as sensitive to low frequency variations of the efficient value as to high frequency variations of the voltage supply wave peak value. As will be presented further on, lamps pertaining to the same technological group, may also present significant differences in the levels of flicker produced.

3 Alternative Flickermeter

To differentiate the Flickermeters, the IEC meter will be identified as original Flickermeter (OFL), whereas the proposed meter will be identified as alternative light Flickermeter (AFL). Studies already carried out have demonstrated that the light Flickermeter is able to give very precise readings and meets the demands of the IEC

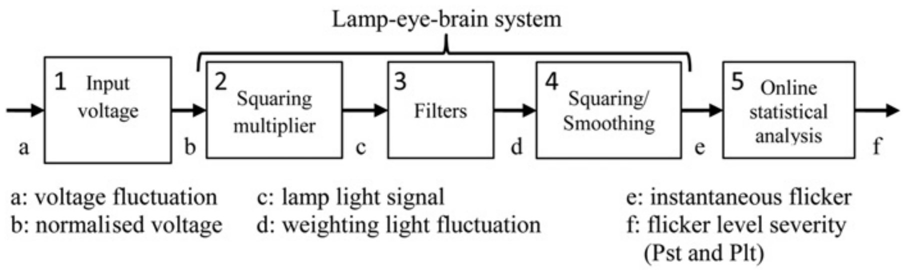

Fig. 2 *Simplified block diagram of the IEC Flickermeter*

61000-4-15 requirements [14, 12]. The obstacle for the application of these proposals is found in the platforms being used (computational and virtual instrumentation), which present an elevated cost. The contribution from this work is an implemented alternative in a low cost embedded system.

The composition of the AFL is made up of four blocks, denominated as A, B, C and D, as shown in Fig. 3. The illumination is the input of block A and the emulation of the eye-brain system is carried out through blocks B and C. The original (eliminated) and modified weighting curves used are indicated on block B. In this proposal, the eye-brain model and the static analysis were maintained. The parts referring to the IL, such as block 2, were eliminated.

3.1 Block A – light input

Block A contains a photosensor to convert the light signal into voltage. Before being sampled and digitalised, the signal is processed by an antialiasing filter, a Butterworth (which guarantees linearity on the pass-band) LPF of the sixth order.

The processing still remaining is digital and is carried out by a microcontroller dsPIC33fj256gp710, from Microchip. The chosen option offers low cost, besides the appropriate processing capacity – part of the hardware is common to digital signal processors. The internal analog-to-digital converter (ADC) was used, operating under a resolution of 12 bits and a sample rate of 2400 Hz (from implementation of Flickermeters [22, 23]). The block diagram in Fig. 4 illustrates the functionality of block A.

The last stage of the block is normalisation, carried out through the division of the signal by the LPF output of the first order, defined on the OFL block 1 [4]. As its time constant is raised (27.3 s), the filtered signal is equal to the mean value. The implemented digital filter is shown in (1)

$$F_{\text{blockA}}(z) = \frac{1.5 \times 10^{-5} z^{-1}}{1.0 - z^{-1}} \tag{1}$$

The elevated time constant implies a slow transition to steady state (tenths of a second), but which can be reduced with an appropriate initial condition, as shown in Fig. 5. An adequate value can be determined by dividing the mean value of the signal (during the 1st second of sampling) by the coefficient of the numerator of (1). Fig. 5 compares the filter transition with the initial value (traced line) and without the initial value (continuous line). The transition is reduced from 2 minutes to a fraction of a second.

3.1.1 Photosensor: The requirements for the selection of the photosensor were an appropriate frequency band for the light variation rates and a spectral sensibility similar to photopic vision defined in [24]. In this work the ISL29101, from Intersil, was used, which is an integrated circuit with photodiode and voltage amplifier. The light sensor bandpass is in the order of 500 Hz, which is sufficient for the application (flicker with frequency superior to 200 Hz is not noted).

The spectral sensibility of ISL29101 is similar to the response of the human eye, however with a significant difference in the band equivalent to red colour, as shown in Fig. 6. The ideal would be identical sensibility to that of the eye, but precise light sensors and light meters with optic filters [12, 14] are expensive, with some reaching the hundreds of dollars – which in itself will be greater than the total cost of the prototype (around one hundred dollars). This makes a low cost system impracticable. The cost of the chosen sensor is a little more than US$ 2. The difference does not result in a problem as the spectrum of the lamps is

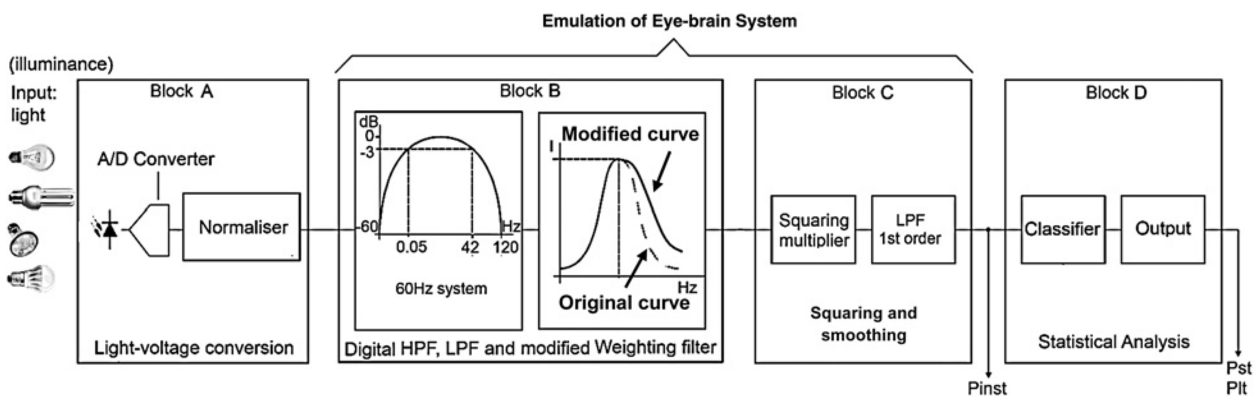

Fig. 3 *Block diagram of Alternative Flickermeter*

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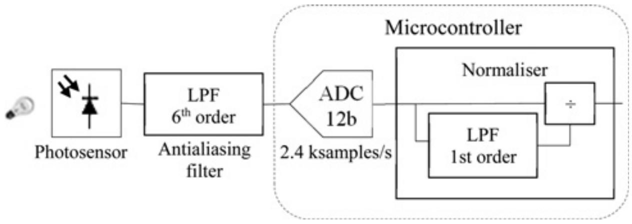

Fig. 4 *Block diagram of 'block A'*

not concentrated only on the red band. The errors introduced onto the spectrum fraction, which refer to the red were not critical and were not prejudicial to the system's objectives (as presented in Section 5).

3.2 Block B – light flutuation

As the AFL measures the lamp luminosity directly, the application of the quadratic relation becomes unnecessary, that is there is no block with a similar function to block 2 of the OFL. Block B contains a demodulation filter and a weighting filter. The block B demodulation filter can be projected for systems of 50 and 60 Hz. As Brazil operates from a 60 Hz electrical system, parameters for this frequency were adopted. The filter is of the bandpass type, made up of a HPF and a LPF. The HPF is of the 1st order, with a cutoff frequency equal to 0.05 Hz, and has as its function to eliminate the dc level, which does not produce flicker. The LPF is of the sixth order with a cutoff frequency of 42 Hz, and eliminates high frequency components, such as 120 Hz that are not notable.

The processing carried out is illustrated through Fig. 7. Fig. 7*a* shows the illuminance (normalised) produced by an IL submitted to a rectangular fluctuation of 3.5 Hz and 5%. Fig. 7*b* shows part of the spectrum, with frequency components of 0 Hz (dc level), 3.5 and 120 Hz. After demodulation, the components outside of the band-pass are heavily attenuated. The produced result is shown in Fig. 7*c*, that being, the luminosity variation waveform. Its spectrum, shown in Fig. 7*d*, was heavily attenuated outside of the bandpass.

Both filters are of the Butterworth type and defined in analogical form. Through the use of classic discretisation techniques (zero-order hold method), equivalent digital filters $F_{\mathrm{HPF}}(z)$ and $F_{\mathrm{LPF}}(z)$ were obtained, indicated in (2) and (3), respectively. The implementation onto the microcontroller was realised through the use of difference

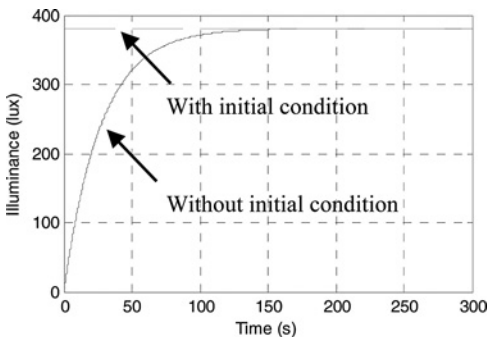

Fig. 5 *Filter transition without initial condition (continuous line) and with a calculated initial condition (traced line)*

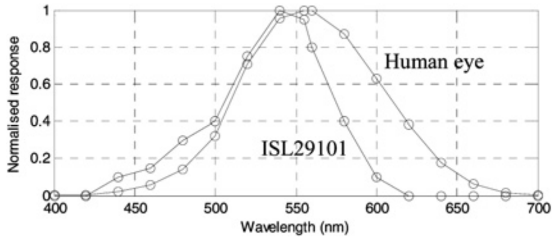

Fig. 6 *Spectral sensibility normalised from the sensor and human eye (photopic vision)*

equations – as with all other filters

$$F_{\mathrm{HPF}}(z) = \frac{0.90 - z^{-1}}{1.0 - z^{-1}} \tag{2}$$

$$F_{\mathrm{LPF}}(z) = \frac{\begin{pmatrix} 0.24 + 1.4z^{-1} + 3.4z^{-2} + 4.5z^{-3} \\ +3.4z^{-4} + 1.4z^{-5} + 0.24z^{-6} \end{pmatrix} \times 10^{-7}}{\begin{matrix} 1.0 - 5.6z^{-1} + 13z^{-2} - 16z^{-3} + 11z^{-4} \\ -4.2z^{-5} + 0.65z^{-6} \end{matrix}} \tag{3}$$

The weighting filter was determined through the IL parameters of 60 W/120 V/60 Hz and from which (4) was obtained [4]

$$F(s) = \frac{5.1s^2 + 93s}{0.0011s^4 + 0.18s^3 + 11s^2 + 453s + 3253} \tag{4}$$

Besides the frequency response for the human eye, the weighting filter also contains the IL dynamics, which should be removed. This can be achieved by dividing (4) by the IL transference function, which can be approximated by a function of the 1st order [25], described by (5)

$$F_{\mathrm{IL}}(s) = \frac{K}{\tau_{\mathrm{IL}} s + 1} \tag{5}$$

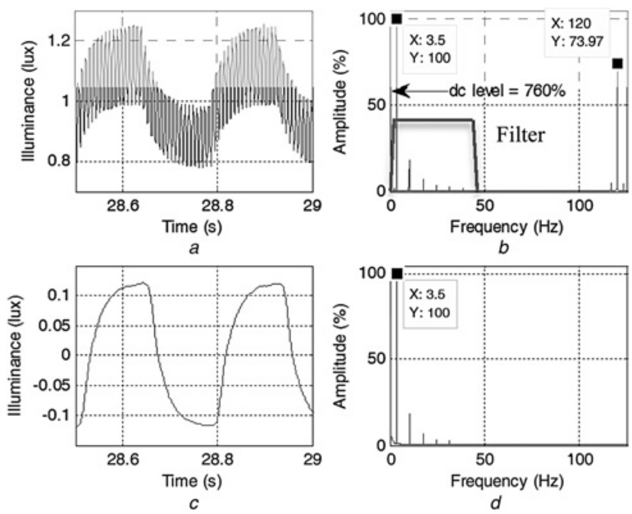

Fig. 7 *Normalised illuminance signal from the IL submitted to a rectangular fluctuation of*

a 3.5 Hz and 5%
b its spectrum
c Resulting demodulated signal
d its spectrum
(Normalisation with component amplitude of 3.5 Hz frequency)

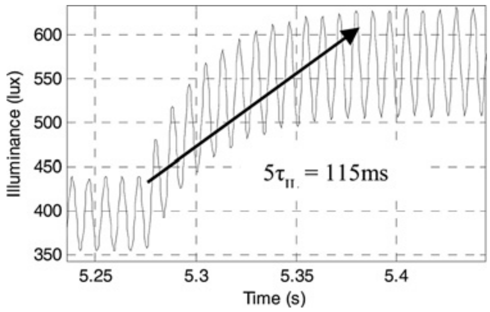

Fig. 8 *Illuminance of the IL for the ac voltage step response. The transient period indicated is equivalent to $5\tau_{IL}$*

The gain is given by K and the time constant τ_{IL} can be determined by the lamp's step response analysis. An experiment was carried out in which the ac voltage was changed from 120 V to 125 V (step) on an IL of 60 W. The time constant can be determined from transient response in Fig. 8, which presented the IL response (in illuminance). The value observed for τ_{IL} is approximately equal to 23 ms.

The division of (4) by (5) (with $K = 1$) results in (6), which is the modified weighting filter $F_{noIL}(s)$ (independent to the dynamics of the IL). Through the discretisation of (6) one obtains (7), which is the filter $F(z)$ implemented on the AFL

$$F_{noIL}(s) = \frac{0.12s^3 + 7.2s^2 + 93s}{0.0011s^4 + 0.18s^3 + 11s^2 + 453s + 3253} \quad (6)$$

$$F(z) = \frac{\left(4.5z^{-1} + 13z^{-2} + 13z^{-3} + 4.4z^{-4}\right) \times 10^{-2}}{1.0 - 3.9z^{-1} + 5.8z^{-2} - 3.8z^{-3} + 0.93z^{-4}} \quad (7)$$

The filtering carried out by block B eliminates a significant part of the signal's spectrum. As in this work, the processing was carried out by a microprocessor with word of 16 bits and a fixed point, it is therefore necessary to adjust the signal scale (multiplying by a constant).

3.3 Block C – instantaneous flicker

The final stage of the emulation for the eye-brain system is carried out by block C, described in the block diagram in Fig. 9. Block C is identical to block 4 of the OFL. The quadratic operation is associated to the non-linear characteristic of eye perception, while the LPF (smoothing) is associated with the memory effect of the brain. The filter time constant is 0.3 s. The discretised filter $F_c(z)$ was implemented as described by (8)

$$F_c(z) = \frac{0.0014z^{-1}}{1.0 - 1.0z^{-1}} \quad (8)$$

The scale adjustment is required to calibrate the output amplitude. The output equates the instantaneous flicker noted by an individual. The requirement specifies a set of fluctuations which produce instantaneous flicker equal to 1 pu,

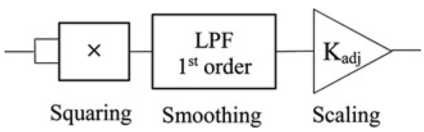

Fig. 9 *Block diagram of 'block C'*

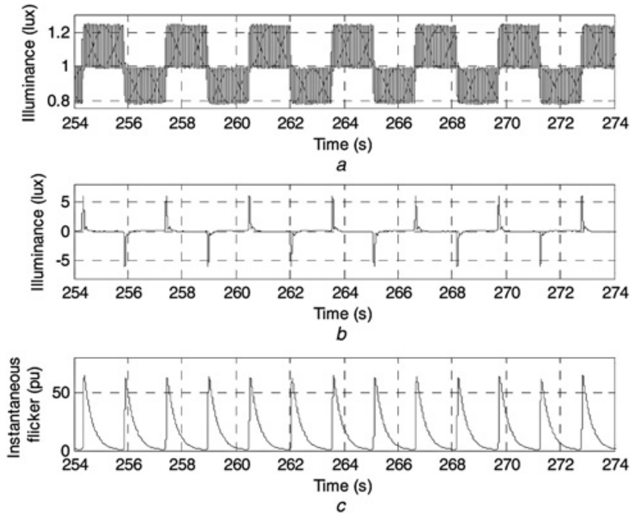

Fig. 10 *Normalised illuminance for an IL submitted to a rectangular fluctuation of*

a 0.325 Hz and 5%
b Demodulated and weighted signal
c Instantaneous flicker

which makes it possible to calibrate the AFL. It was agreed that 1 pu is equal to the threshold of flicker perception (noted by 50% of the individuals) [4].

The processing carried out by blocks B and C is illustrated in Fig. 10. An experiment was carried out in which an IL was submitted to a rectangular fluctuation of 39 changes/minute (0.325 Hz) and 5%. The normalised signal produced by block A is shown in Fig. 10*a*. This signal is filtered in block B, whose result is shown in Fig. 10*b*. The waveform contains only the changes (peaks), product of demodulation and weighting. Fig. 10*c* shows the instantaneous flicker (the changes 'noted' by an individual). The perception is intense on the changes and decays (memory effect). Peak values of 1 pu indicate perception threshold. In the example, the observer would note an elevated instantaneous flicker – which was found by observers that indicated 'strong' flicker level.

3.4 Block D – determining the severity

Block D is similar to block 5 of the OFL, which analyses the values and occurrences of instantaneous flicker to quantify its severity. Instantaneous flicker is sampled at a rate of 240 samples/s, in accordance with an OFL implementation [23].

Instantaneous flicker is sampled and classified in a set of M linear classes, which is equal, in this work to 2048 divisions between zero and the maximum instantaneous flicker value. A class equates the number of occurrences from an amplitude band and is increased at each new occurrence of instantaneous flicker. Fig. 11 illustrates this process along with the block diagram of block D. At the end of the observation period, the classes are analysed (bar graph) and the cumulative function of probability is determined (continuous line). From this curve the flicker severity is determined. Determining the percentiles requires logarithmic or linear interpolation, as suggested by the requirement – in this paper linear interpolation was used.

In the analysis of short duration periods (minutes) the Pst is determined, as in (9) [4]. The percentiles P_i indicate the level of exceeded instantaneous flicker in i% of the observational time period. The suffix 's' indicates that the percentile is

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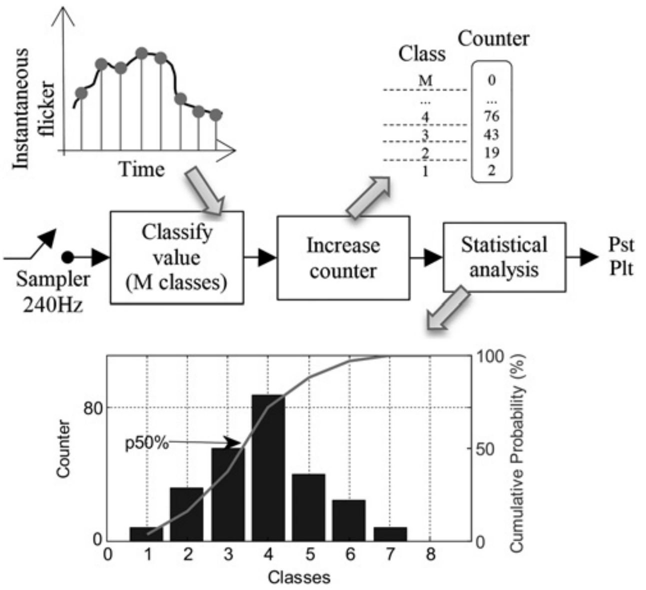

Fig. 11 *Block diagram and processes of 'block D'*

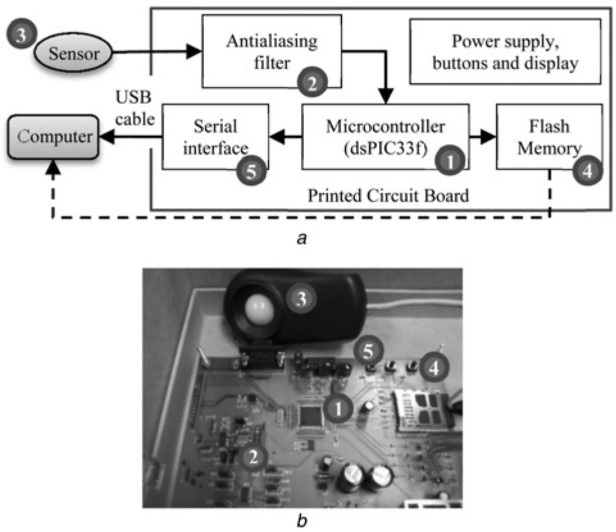

Fig. 12 *Block diagram of*

a AFL's circuit
b implemented prototype

smoothed (see [4]). The usual observational period is 10 min

$$\mathrm{Pst} = \frac{\sqrt{3.14P_{0.1} + 5.25P_{1s} + 6.57P_{3s} + 28P_{10s} + 8P_{50s}}}{10} \tag{9}$$

The Pst is applicable in those cases where the distribution sources have cycles with short operational periods (e.g. rolling mills and residences). For the analysis of long periods of duration (hours), determine the Plt, which is applied to loads with aleatory operational cycles (e.g. motor and solder machines) or long and variable (e.g. arc welder). The Plt is defined as shown in (10), with the mean cube of the Pst in N periods of short duration. The usual monitoring period is of 2 h

$$\mathrm{Plt} = \sqrt[3]{\frac{\sum_{i=1}^{N} \mathrm{Pst}_i^3}{N}} \tag{10}$$

3.5 Hardware

The implemented hardware is described by the functional block diagram illustrated in Fig. 12*a*. The blocks have numeric indication, which allows for their visualisation on the prototype picture, as shown in Fig. 12*b*. As the processing is concentrated on the microcontroller (1), the circuit is relatively simple. The only analog parts are made up of the antialiasing filter (2) and the photosensor circuit (3). To facilitate the data analysis, the prototype was projected with a flash memory card (4) and a serial communication interface (5), which makes it possible to read measurements as well as the results on a computer.

4 Methodology

The methodology for the performance analysis and AFL test follow specifications of the IEC 61000-4-15 requirement. There are up to 8 sets of tests in function of the OFL class, defined as F1, F2 and F3. The class F1 devices have as their proposal to monitor the power quality and carry out compliance tests. Class F2 is aimed at product compliance tests in controlled environments. Class F3 is used to analyse power quality, trouble shooting and applications that do not need high precision. Taking into consideration the objective of the AFL, its class is F3. The tests required for this class are defined in the tables 1, 2 and 5 of [4]. Besides the F3 class not requiring high precision it was also demonstrated that a light Flickermeter can attend to the requirements demanded by class F1 [14].

The experiments were carried out in controlled environments, with measurements realised in a chamber with dimensions 70 × 50 × 50 cm. The inside of the chamber is black to avoid inter-reflections. Inside the chamber there were installed the photosensor and a lamp socket. The diagram of Fig. 13 illustrates the measuring structure.

To supply the lamps programmable AC power supplies were used: HP CSW11000, Chroma 6512 and California Instruments CSW5550. Every lamp tested was maintained on for a minimum period of 30 min to reach steady state (luminous and thermic). The experiments were carried out with general use lamps of various models and makes. The results will be presented for the following lamps:

- Li1: IL classic A, 60 W.
- Lfc1: CFL U format, white light, 20 W, power factor = 0.5.
- Lfc2: CFL spiral format, white light, 30 W, power factor = 0.92.
- Led1: LEDL spot format, white light, 4 W.
- Led2: LEDL bulb format, neutral light, 5 W, dual Volt (120 V/230 V).

Table 1 AFL results for the rectangular fluctuation set that produce Pst = 1.00 ± 0.05 pu on the IL of 60 W

Voltage fluctuation		AFL	
Frequency (Changes/minute)	Amplitude, %	Pst, pu	Error, %
1	3.18	1.02	2.2
2	2.56	1.00	0.4
7	1.69	1.04	4.3
39	1.04	1.01	0.9
110	0.84	1.02	1.7
1620	0.55	1.00	–0.2
4800	4.84	0.99	–1.4

Table 2 Flicker level severity according to observers and the AFL measurements

Frequency, Hz	Pst, pu				
	Li1	Lfc1	Lfc2	Led1	Led2
0.5	5.25 ↑	1.49 ↑	1.35 ↕	0.63 ↓	0.13 ↓
8.8	13.5 ↑	4.84 ↑	4.32 ↑	1.85 ↑	0.31 ↓
22	3.75 ↑	2.61 ↑	2.01 ↑	2.63 ↑	0.18 ↓
40	0.93 ↓	0.96 ↓	0.53 ↓	2.69 ↑	0.03 ↓
60	0.13 ↓	0.11 ↓	0.27 ↓	0.52 ↓	0.10 ↓
75	0.28 ↓	0.69 ↓	0.79 ↓	3.56 ↑	0.11 ↓
102	2.56 ↑	2.36 ↑	1.74 ↑	5.84 ↑	0.18 ↓
146.7	1.24 ↓	1.75 ↕	1.25 ↕	3.49 ↑	0.15 ↓
231.2	0.13 ↓	1.77 ↕	1.60 ↕	10.7 ↑	0.15 ↓
296.5	0.10 ↓	0.52 ↓	0.33 ↓	1.55 ↕	0.11 ↓
300	0.10 ↓	0.06 ↓	0.21 ↓	0.41 ↓	0.09 ↓

During part of the experiments three observers were used, between the ages of 30 and 40 years old. They observed the flicker produced and gave qualitative opinions concerning the severity. As a reference to the opinions for the flicker produced, considerations were made as to the flicker produced by the IL submitted to a fluctuation of 1620 changes/minute (13.5 Hz) and 0.55%, which is equal to a Pst unitary [4]. With this reference three severity 'levels' were suggested: 'weak', 'medium' and 'strong'. The medium level is equal to a level of flicker 'near' to the reference and the weak level indicates a lesser intensity or no flicker. The proposal behind the evaluations is to illustrate qualitatively the phenomenon, by supporting the reader with subjective aspects of perception.

5 Experiments and results

As the OFL is based on IL, a 120 V/60 W lamp was used to calibrate the AFL. The first set of tests carried out have as their goal to evaluate the filter response and adjust the gain scale of block C. The tests specify fluctuations that produce instantaneous flicker of 1.00 ± 0.08 pu for an IL of 60 W [4].

The tests carried out present dispersed peaks around 1 pu, as shown in example of the Fig. 14. An algorithm was developed to detect the peaks and determine a mean value of the peaks, as a general mean value. This value was used to determine the gain in block C.

After the adjustment, the test was reapplied for evaluation. Fig. 15*a* presents the result for the rectangular fluctuations on table 2 (worse case) of [4], indicated by the line with circles. The obligatory points of the test are marked with squares and are situated within the tolerance range of ±8% (traced lines).

The line with asterisks indicates the results of a light Flickermeter class F1 for 230 V/50 Hz and obtained in [14] – the point for 33 1/3 Hz was not presented. Fig. 15*b* presents the results of AFL against the results of the 230 V/50 Hz light Flickermeter proposed in [12] (also with asterisks). One observes that the AFL accuracy is less. One of the

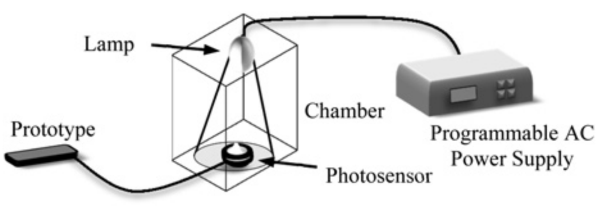

Fig. 13 *Diagram of the structure for AFL tests*

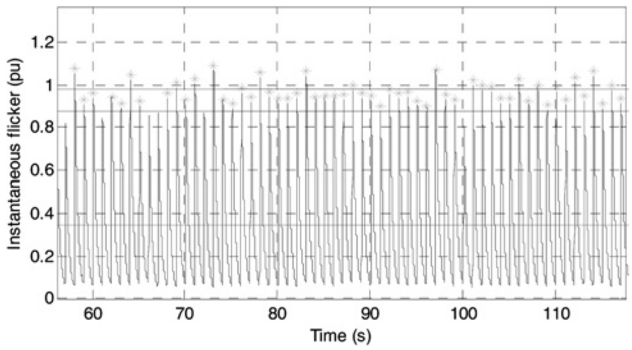

Fig. 14 *Example of dispersed peaks of instantaneous flicker produced on the IL by the rectangular fluctuation of 1.5 Hz and 0.5%*

Upper line indicates the mean

reasons is the simplification of the system (e.g. operating from a fixed point, word of 16 bits and low cost photosensor), all the same, the cost of the proposed meter is less, as well as being able to attend to the requirements of the IEC 61000-4-15 (obligatory points within the tolerance range).

Fig. 15*c* shows the relative error in the tests. The error in the obligatory points is inferior to 8%. Some of the non-obligatory points go over the limit, however the maximum error is 11%.

The second set of tests for validation is specified on table 5 of [4]. Its purpose is to test the classification algorithm and statistic evaluation. There are 7 rectangle fluctuations specified that produce Pst equal to 1.00 ± 0.05 pu (irritability threshold). These fluctuations are characterised in column 1 and 2 of Table 1. The results obtained by the AFL are presented in column 3 and the relative error in

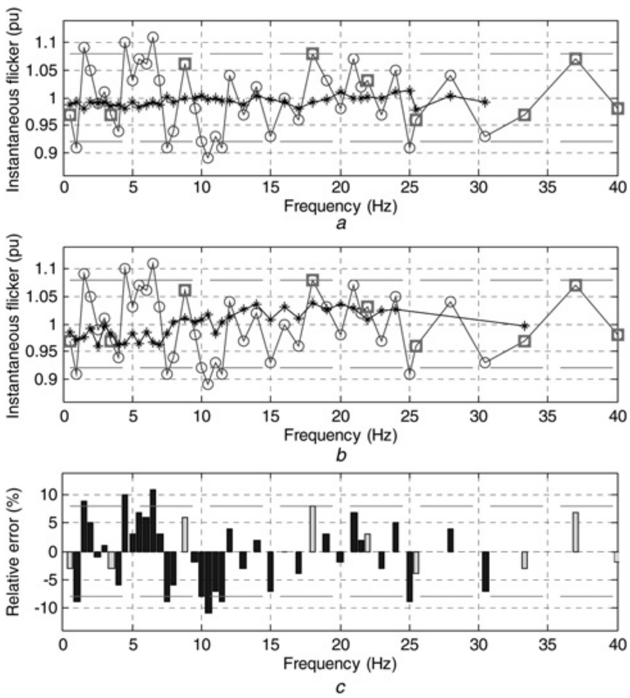

Fig. 15 *AFL results (line with circles)*

a and *b* Compared with the meter proposed in [14] (a) and [12] (b), both highlighted by the line with asterisks
c Relative AFL error. (The obligatory points are highlighted)

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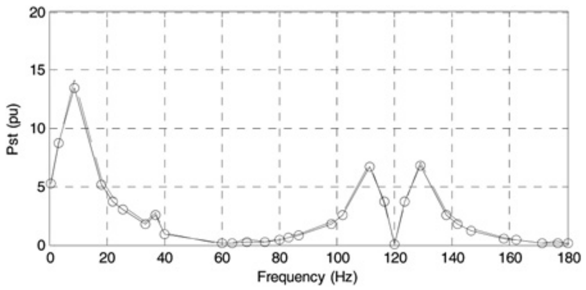

Fig. 16 *Results from the AFL (line with circles) and from the virtual OFL (traced line) for rectangular fluctuations of 5%*

column 4. All the tests obtained adequate results (within the tolerance range).

Although not specified by the IEC 61000-4-15 requirement, a third set of tests were carried out to evaluate the performance of the AFL, along a wider range of frequencies. In the test a set of rectangular fluctuations were applied to the IL, the frequencies used varied from 0.5 to 180 Hz and amplitude was fixed at 5%. The measured Pst values are indicated by the line with circles, as in Fig. 16. The performance was evaluated by comparing the AFL results with the results from an OFL implemented (and validated) in MATLAB. The fluctuations were applied to the virtual OFL and the obtained results are indicated in Fig. 16 by the traced line. The maximum error (in relation to the OFL) to values greater than 0.5 pu were in 10%. The consistency of the results corroborates to the adequate performance finding of the AFL.

5.1 General use lamps

After the AFL validation quantitative and qualitative experiments were realised with lamps of general use, that is, besides evaluating the severity of the flicker produced, the 'real' perception of the phenomenon by observers was also evaluated. The objective behind this stage of this paper was to carry out a preliminary analysis of distinct types of CFL and LEDL performance, when submitted to voltage fluctuations.

In experiment 'A' the lamps Li1, Lfc1 and Led1 were submitted to rectangular fluctuations with amplitude fixed at 5%. The severity levels of measured flicker, over a wide range of frequencies, are presented in Fig. 17*a*. Fig. 17*b* shows the results for experiment 'B', in which Lfc2, Led2 and Li1 (reference), were evaluated.

Fig. 17 confirms various aspects concerning flicker, the first is the inexistence of flicker produced by harmonic frequencies. One also observes that the IL was more susceptible to flicker in low frequencies than lamps with electronic ballast or drivers. The contrary can occur in high frequencies, where CFL and LEDL present greater flicker. The experiments show the limitations of OFL, as in fluctuations with a frequency greater than 150 Hz, for example, where Li1 does not produce flicker, while other lamps (Lfc1 and Led1) do.

It should be highlighted here that in the previous observation, the lamp's variation in the luminosity frequency is not 150 Hz (unnotable), but of 30 Hz. In single inter-harmonic case in [26] it was demonstrated that the modulation frequency f (flicker) is the differential module between the inter-harmonic frequency f_{ih} and the nearest harmonic f_h as determined by (11). In fact, the modulation

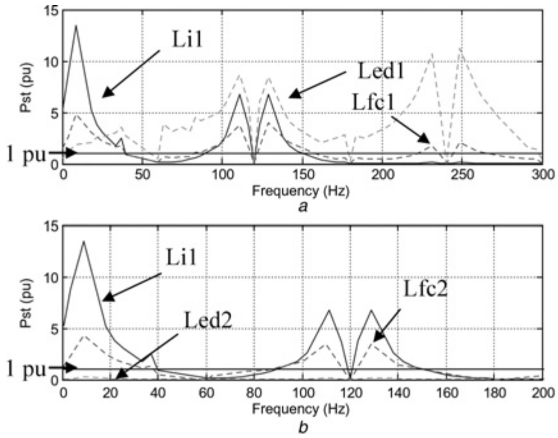

Fig. 17 *Severity of flicker produced by*
a Li1, Lfc1 and Led1 (0–300 Hz)
b Li1, Lfc2 along with Led2 (0–200 Hz)
Submitted to fluctuations with amplitude fixed at 5%

frequency is restricted to 0 Hz to (about) 30 Hz. A similar effect occurs in the rectangular fluctuation with the main inter-harmonic – this can be demonstrated by representing a rectangular wave as a sum frequency

$$f = |f_{ih} - f_h| \tag{11}$$

Finally, discrepancies found in the performance among lamps with the same technology are highlighted, such as the case of Led1 and Led2. While Led1 is susceptible to flicker, Led2 did not present any flicker, with an insignificant Pst (order of 0.2 pu).

5.2 Qualitative analysis

The selected observers evaluated the experiments and gave opinions as to the severity of the perceived flicker. The objective behind qualitative analysis is to compare visual subjective perception – which may actually result in different opinions – with the measurement (quantitative) results. Some of these results are presented in Table 2. Column 1 indicates the frequency of the fluctuation (amplitude fixed at 5%). The remaining columns indicate the Pst measured by the AFL along with the opinions of the observers, using the following labeling criterion: strong = ↑, medium = ↕ and weak = ↓ (The result represents the majority opinion.)

From the analyses made from the observers, a relationship between the severity level (quantitative) and the perception of this severity (qualitative) was analysed. The graph in Fig. 18 presents an approximate synthesis of this relationship. As perception is a subjective and individual element (even if the reference is the same), there was an overlapping of the qualitative results. It is herewith highlighted that although the results are related to perception and the level of observed flicker, the analysis strives only to illustrate, in an

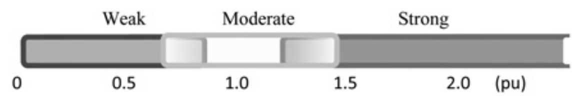

Fig. 18 *Relationship between flicker level severity (quantitative) and its perception (qualitative)*

approximate manner, the numeric relationship associated with severity that is measured and what is observed.

5.3 Susceptibility to flicker

The performance associated with lamps brought about the definition of two different classes within a single technology. This division is not used in literature, but found to be suitable for this paper. In this division, those lamps from class 1 were most susceptible to producing flicker, while lamps from class 2 were less susceptible.

In the results presented in Fig. 17, one observes that there is a great difference in the responses for Led1 and Led2. One reason for this divergence is the distinct behaviour of the drivers for each type or model of lamp. The behaviour of electronic ballast and drivers in the production of flicker by lamps is not as well understood as the behaviour of IL (see [27]). A justification for this is the non-linearity and the complexity of the behaviour associated with these devices, along with their topological diversity.

The analysis carried out in this paper has demonstrated that different lamps, even from the same technology, can present distinct performances. Thorough investigations in respect to the role of electronic ballasts and drivers are necessary, although preliminary evaluations were carried out in respect to the problem with the objective of instigating hypotheses concerning the question.

The luminous flow from the LEDL has a significant dependence upon the power supplied to the LEDs [28]. If the driver control circuit does not have a 'good' performance, the lamp can become more susceptible to flicker. Through an analysis of the illuminance produced by Led1 and Led2, submitted to the seventh test on Table 1, the graph in Fig. 19*a* was obtained. While the illuminance of Led2 is practically constant, the illuminance peaks on Led1 show obvious variation. The reason is because of the lamp's electronic circuits.

Fig. 19*b* shows the circuit (left) and diagram (right) for Led1. The simplified (low cost) driver has a rectifier, a capacitive filter and a resistor for limiting the current. The open loop control of the power supplied to the LEDs did not have a good performance, making the lamp very susceptible to flicker. The poor performance is seen by observing the variation range of the luminosity peak produced by Led1 in Fig. 19*a*. On the other hand, the driver for Led2 is elaborated, using inclusively, an integrated circuit. The circuit (left) and its diagram (right) for Led2 are shown in Fig. 19*c*. After this rectification stage

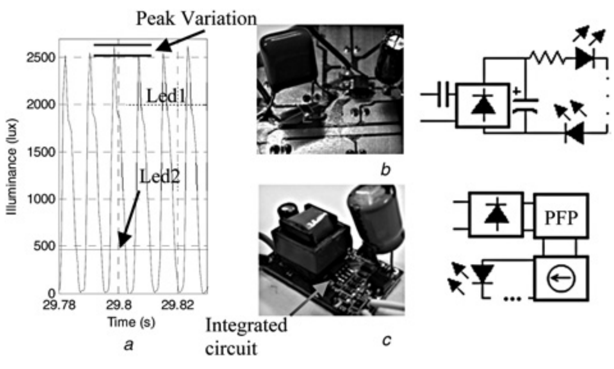

Fig. 19 *Illuminance of Led1 and Led2*

a Under fluctuation of 40 Hz and 4.84%
b Circuit and diagram of Led1
c Led2

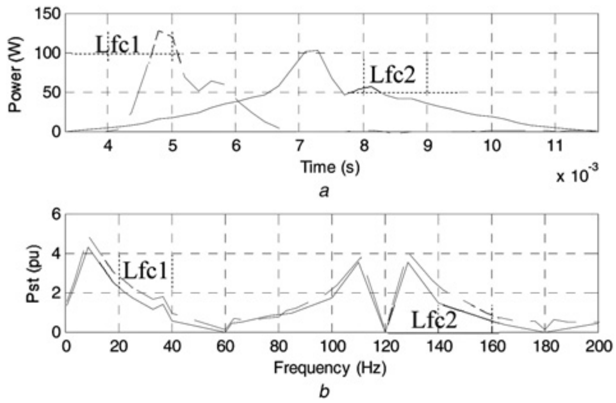

Fig. 20 *Absorbed power (half cycle) by*

a Lfc1 and Lfc2
b Pst values for fluctuations between 0–200 Hz and 5%

there is a power factor pre-regulation stage (PFP) and a current supply. The good performance of the closed loop control makes Led2 robust, being almost insensitive to the most common fluctuation levels on a distribution network. In the experiments carried out flicker was not observed on Led2 for fluctuations inferior to 10%.

In Lfc1 and Lfc2 the instantaneous power absorbed by the lamps was analysed. Fig. 20*a* presents the power absorbed by each lamp in a half cycle. Lfc1 absorbs power in a discontinuous form, in only 1/3 of the period. On the other hand, Lfc2 absorbs power in a continuous form. This difference is because of power factor correction carried out by the electronic ballasts, such that Lfc1 presents a power factor of 0.50 and Lfc2 of 0.92.

As the voltage fluctuation can in some cases change only the voltage waveform and maintain the rms value constant [29], the fluctuation alters the peak value of the voltage waveform. As the waveform peaks for the current can also suffer alterations, the variation of the absorbed power can become more significant as in the case of Lfc1. This is because Lfc1 absorbs power in a discontinuous and 'concentrated' form near to the peak (maximum value).

In electronic ballasts with a less efficient control, the disturbance can propagate easily through the converters and affect the luminous flow produced. The difference between the levels of flicker in lamps can be seen in Fig. 20*b*, in which the Pst of Lfc1 is superior to that of Lfc2. The best distribution of power consumption in Lfc2, besides the electronic ballasts having more efficient control, it seemed to contribute to a better performance in this lamp.

This stage of the study is only initial and more in depth studies on the operation and (most popular) topologies are necessary, however the indications are that more elaborate (efficient control) electronic ballasts and drivers can make the lamps less susceptible to flicker.

6 Conclusions

The IEC Flickermeter presents limitations as demonstrated in this paper, which do not allow for the correct determination of the severity level of flicker produced in lamps which are not of incandescent technology, such as CFL and LEDL. Under the present context of energy efficiency and the advance of illumination technologies, the limitation on the Flickermeter is ever worsening, as the IL is being substituted by more efficient lamps. Based on these aspects found in this work, an

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alternative light Flickermeter was developed and implemented. The adopted methodology permits correct measurement of the phenomenon, independent of the lamp type.

This paper demonstrated that it is possible to implement a low cost embedded system with adequate precision for implementing a F3 class light Flickermeter. The encouraging results of the implemented prototype for various experiments were presented. The simplified circuit and its low cost obtained for the prototype (in the order of 100 dollars), make it appropriate for the analysis of problems related to flicker in the daily workings of industry (or even for residential applications).

The responses of general use lamps (CFL and LEDL) to flicker were evaluated. It was demonstrated that susceptibility of a lamp to flicker depended as much upon the technology used as to the lamp model. The preliminary analyses suggest that the susceptibility of a lamp to flicker can be associated to 'performance' of the electronic ballast/driver control. In the tests, electronic ballast with high power factors (CFL) or efficient power control (LEDL) were less susceptible to the production of flicker. Also in this context, the implemented light Flickermeter could be used in the development as well as the testing of lamps less susceptible to flicker.

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