Electrical Power and Energy Systems 92 (2017) 34–41

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Sensitivity of modern lighting technologies at varying flicker severity levels

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ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 17 March 2017
Accepted 20 April 2017

Keywords:
Energy-efficient lighting
Power quality
Flicker
Voltage fluctuations
Linearity

ABSTRACT

Efficient lighting technologies are not necessarily less sensitive to voltage fluctuations than the incandescent lamp, and therefore a procedure for controlling the immunity of lamps to voltage fluctuations was defined in the IEC 61547 standard. This procedure checks that a lamp is not more sensitive than the incandescent lamp to voltage fluctuations corresponding to the $P_{st} = 1$ curve. For a lamp that behaves linearly, these tests are sufficient to guarantee that a lamp is less sensitive than the incandescent lamp at any voltage fluctuation level. This paper analyzes the linearity in the response of a set of lamps with both simulated and real voltage signals. For a given input voltage signal containing fluctuations, a new signal was generated with a voltage fluctuation whose amplitude was proportional to the original one. Both signals were passed through an illuminance flickermeter and the obtained flicker severity values were compared. The results showed that not all the lamps behaved linearly. Some lamps were less sensitive than the incandescent lamp at the reference level, and with other voltage fluctuation amplitudes produced flicker severity values higher than the incandescent lamp. Moreover, the nonlinearity shown with real voltage signals was not reflected with the same nonlinear behavior with simulated fluctuations in all cases. These results lead to the conclusion that the current immunity protocol is insufficient for guaranteeing that a lamp is less sensitive to voltage fluctuations than the incandescent lamp at every voltage fluctuation level.

1. Introduction

Energy efficiency and sustainability have become priorities in a world moving toward reducing carbon dioxide emissions and energy costs. To this end, the lighting industry has addressed important changes with the replacement of incandescent lamps by other efficient lighting technologies [1–3]. However, this change poses different challenges in terms of power quality and more specifically in terms of flicker. The standardized flicker measurement procedure [4] and hence the compatibility levels to voltage fluctuations are based on the response of the incandescent lamp. The progressive banning of inefficient lamps could compromise the utility of the existing flicker measurements [5].

Several studies have focused on the sensitivity of new lighting technologies to voltage fluctuations [6–11]. The two most representative modern lighting technologies, compact fluorescent (CFL) and light emitting diode (LED) lamps, usually present low sensitivity to voltage fluctuations [7]. However, depending on different factors such as the brand and model of the lamp or the complexity of the voltage fluctuations, these technologies present even more sensitive behaviors than the incandescent lamp [8–11]. The diversity of sensitivity between the different technologies available on the market means that the increase in lighting efficiency does not imply an enhancement in the immunity to voltage fluctuations [12].

In view of these results, it has become necessary to keep the existing compatibility levels to voltage fluctuations as the reference for the flicker measurement [13]. Consequently, it is essential to guarantee that the new lighting products are less sensitive to voltage fluctuations than the incandescent lamp. In this scenario, a procedure for testing the immunity of new lighting equipment to voltage fluctuations has been developed within the working group IEC TC34. This procedure has been published as a technical report [14] associated with the immunity standard for lighting equipment IEC 61547 [15]. The procedure for testing the immunity of a lamp consists of the comparison of the flicker produced by the lamp under test and the incandescent lamp, when both lamps are affected by the same voltage fluctuations corresponding to the compatibility threshold, i.e., the $P_{st} = 1$ curve [16]. The lamp under test that produces flicker severity values below 1 is considered immune to voltage fluctuations.

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http://dx.doi.org/10.1016/j.ijepes.2017.04.010

Nevertheless, being less sensitive than the incandescent lamp for voltage fluctuations at the level of $P_{st} = 1$ does not directly imply the same behavior at higher flicker levels. For lighting technologies that are less sensitive than the incandescent lamp at the level of $P_{st} = 1$, the maintenance of this behavior regardless of the voltage fluctuation amplitude will depend on the linearity in the response of the lamp. The incandescent lamp provides a linear relationship between the amplitude of the voltage fluctuation and the corresponding illuminance fluctuation [17], which is also linearly related to the flicker perception by the human visual system. As a consequence, an increase in the amplitude of the voltage fluctuation will produce a proportional increase in the flicker severity value produced by an incandescent lamp. Preliminary experiments using sinusoidal voltage fluctuations pointed to a nonlinear behavior of some lamps [10]. The current work goes further by analyzing the linearity when the lamps are supplied by more complex voltage signals, i.e., simulated rectangular voltage fluctuations and real voltage signals.

In Section 2, the linear relationship between the relative amplitude of the voltage fluctuation, $\frac{\Delta V}{V}$, and the flicker severity value is demonstrated through a numerical example following the block diagram of the IEC 61000-4-15 standard [4]. Section 3 presents the set of lamps, test setup, and methodology used to perform the linearity study. The results are presented in Section 4 and these are discussed in Section 5. Concluding remarks are provided in Section 6.

2. Linearity of the existing flicker measurement

The IEC 61000-4-15 standard defines the functional and design specifications of a flickermeter that provides an objective measurement of the level of annoyance produced by the flickering of the illuminance of a lamp [4]. This measurement procedure is based on a simplified physiological model of the behavior of the lamp-eye-brain system, taking the incandescent lamp as the reference. Fig. 1 depicts the scheme of the IEC flickermeter where the input signal is the supply voltage, $u(t)$, and the output parameters are the short and long term flicker severity values, P_{st} and P_{lt} respectively.

The characteristics of the incandescent lamp and the eye-brain system provide a linear relationship between the amplitude of the voltage fluctuation and the flicker severity value.

For the incandescent lamp, there is an empirical relationship between the luminous intensity and the supply voltage:

$$\frac{L}{L_n} = \left(\frac{V}{V_n}\right)^{\gamma} 3.4 < \gamma < 3.8, \qquad (1)$$

where V_n represents the rated *rms* value of the voltage and L_n is the corresponding luminous intensity [17]. For small voltage changes, the relative response of the lamp can be expressed as follows:

$$\frac{\Delta L}{L_n} = \gamma \cdot \frac{\Delta V}{V_n}. \qquad (2)$$

A linear increase in the relative amplitude of the voltage fluctuation means a proportional increase of the relative amplitude of the illuminance fluctuation. This behavior is modeled jointly by blocks 2 and 3 of the IEC flickermeter (Fig. 1). For a sinusoidal voltage fluctuation, $u(t)$ has the form:

$$u(t) = A\sqrt{2}\left(1 + \frac{1}{2} \cdot \frac{\Delta V}{V} \sin(w_m t)\right) \sin(w_0 t) \ , \qquad (3)$$

where $A = 230$ V, $w_0 = 2\pi \cdot 50$ rad/s, and $w_m = 2\pi \cdot f_m$ rad/s, with f_m being the frequency of the voltage fluctuation. The fluctuation at the output of the demodulation filters of block 3 is characterized as follows:

$$u_2(t) \simeq C_2 \cdot \frac{1}{2} \cdot \frac{\Delta V}{V} \cdot \sin(w_m t + \phi_2) \ , \qquad (4)$$

where C_2 and ϕ_2 are the magnitude and phase of the frequency response of the demodulation filters at f_m. This signal is then weighted by the band-pass filter of block 3, obtaining the illuminance fluctuation, $u_3(t)$, that presents a fundamental component linearly related to the voltage fluctuation as follows:

$$u_3(t) \simeq C_3 \cdot C_2 \cdot \frac{1}{2} \cdot \frac{\Delta V}{V} \cdot \sin(w_m t + \phi_2 + \phi_3) \ , \qquad (5)$$

where C_3 and ϕ_3 are the magnitude and phase of the frequency response of the weighting filter at f_m. The term $C_3 \cdot C_2 \cdot \frac{1}{2} \cdot \frac{\Delta V}{V}$ represents the relative amplitude of the illuminance fluctuation linearly weighted by the eye response.

The remainder of the chain models the brain response to illuminance fluctuations and also presents a linear behavior. The square of the output signal of block 3 is linearly processed by the sliding mean filter of block 4, obtaining the instantaneous flicker perception as a linear combination of two main frequencies, the direct current component (DC) and $2f_m$:

$$u_4(t) \simeq \frac{C_3^2 \cdot C_2^2}{2} \cdot \left(\frac{1}{2} \cdot \frac{\Delta V}{V}\right)^2 \cdot (C_4 - C_5 \cdot \cos(2w_m t + 2\phi_2 + 2\phi_3 + \phi_5)), \qquad (6)$$

where C_4 and C_5 are the magnitudes of the frequency response of the filter at DC and $2f_m$ and ϕ_5 is the phase at $2f_m$. Finally, block 5 implements the statistical evaluation of $u_4(t)$ providing the P_{st} value.

To demonstrate the linear behavior of the brain system, the input voltage fluctuation was changed so that its relative amplitude was k times higher than the previous value:

$$\left(\frac{\Delta V}{V}\right)' = k \cdot \frac{\Delta V}{V}. \qquad (7)$$

Consequently, the new output signal of block 3, $u_{3k}(t)$, also presents a single component at f_m with an amplitude k times higher than $u_3(t)$:

$$u_{3k}(t) \simeq k \cdot C_2 \cdot C_3 \cdot \frac{1}{2} \cdot \frac{\Delta V}{V} \cdot \sin(w_m t + \phi_2 + \phi_3) = k \cdot u_3(t) \ . \qquad (8)$$

In the same way, the output signal of block 4 can be expressed as:

$$u_{4k}(t) = u_{3k}(t)^2 = k^2 \cdot u_3^2(t) = k^2 \cdot u_4(t) \ , \qquad (9)$$

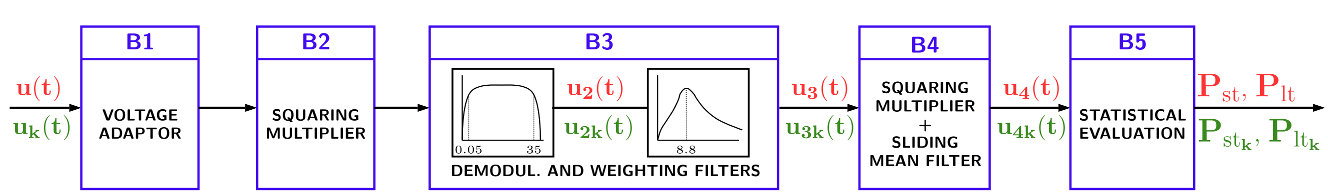

Fig. 1. Scheme of the IEC flickermeter according to the IEC 61000-4-15 standard [4].