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Generalized lamp model for light flicker studies

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ABSTRACT

A new generalized lamp model capable of simulating a lamp's luminous flux in the time domain is presented. Reference is made to low power lamps (up to 25 W). The generalized lamp model consists of a model of the electrical circuit of the lamp and a model of the bulb itself and is based on the use of only three input parameters. The results of a preliminary experimental analysis are first presented with the aim of justifying the hypotheses of the model. Then, the model is described and used to analyze the frequency behavior of a lamp in the presence of voltage fluctuations; the model was experimentally validated for different kind of lamps. Finally, the results of a sensitivity analysis of the model versus its main parameters are presented.

1. Introduction

Light flicker (LF) studies have the goal of predicting the annoyance effect perceived by average people when the luminous flux emitted by a lamp is modulated by the presence of fast fluctuating voltages in the system supplying the lamp.

International standards quantify this annoying effect by means of the P_{st} index, which is measured with an instrument called a flickermeter (FM) [1]. FMs are very practical instruments because they assess the amount of LF using a standard incandescent lamp directly processing the acquired line voltage. This is done by implementing a specific model of the standard incandescent lamp embedded inside the instrument, together with other filters aimed at modeling the eye–brain response to luminous flux oscillations [2].

Worldwide, various energy-saving programs related to the replacement of incandescent lamps by energy-saving lighting equipment, particularly CFLs and LEDs, are in place. The global percentages of installed units and future projections can be found in Ref. [3], where the following percentages are included for the year 2014: 22% INC., 12% HAL., 28% CFL, 3% LED, and 35% linear fluorescent tubes. The number of incandescent lamps installed is projected to fall to less than 4% by 2022. Further projections show that linear fluorescent and CFL technologies will remain prevalent through 2022, while LED-based lamps will replace the incumbent incandescents, with some displacement of halogen technologies.

Recent studies have demonstrated the sensitivity of the new lamps (CFL and LED) in terms of LF [4–14] . Because of the limitations of standard FMs [13], which incorporate only an incandescent lamp model [14], these studies were performed by measuring the oscillations of the luminous flux of the tested lamps and proposing new optical FMs that evaluate the P_{st} directly from the luminous flux oscillations using laboratory tests with real lamps placed in opportune test chambers [4,8,15]. Optical FMs can be considered to be very powerful tools for laboratory comparative purposes and the classification of lamps in relation to their immunity or sensitivity to voltage disturbances, but not for assessing LF in the field.

Indeed, there is a need for new generalized lamp models capable of simulating a lamp's luminous flux in the time domain starting from the measurement of the supply voltage to be easily incorporated in new FMs for LF assessment in the field [14].

In Ref. [16], a preliminary version of such a model was presented, referring only to CFLs with a simplified representation of the AC supply side, with a first experimental validation, but without an analysis of the sensitivity of the model to lamp and supply line parameters.

This paper presents a new generalized lamp model capable of simulating a lamp's luminous flux in the time domain. Reference is made to low power lamps (up to 25 W) with a low-end design [16–20], which are generally most sensitive to supply voltage fluctuations in terms of LF. The model is based on the use of only three parameters that can be easily measured in the laboratory. This

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Nomenclature

LF	Light flicker
P_{st}	Short-term flicker severity index
FM	Flickermeter
CFL	Compact fluorescent lamp
LED	Lamp based on light-emitting diode
INC	Incandescent lamp bulb
HAL	Halogen lamp
v_1 V_1 f_1	Instantaneous value, RMS, and frequency of the system's fundamental voltage
v, i, v_B	Instantaneous AC voltage and current and DC link voltage on the bulk capacitor (Figs. 1 a and B2)
t_{TO}	Time delay between the zero crossing of the voltage and the instant at which the conduction of the bridge diodes begins
i_I, i_{IF},	Actual inverter current and that filtered by a low pass filter (Figs. 1 b and B2)
R_{EL}	Equivalent DC bus load (Figs. 1 and B2)
p_I, ϕ	Instantaneous power absorbed by the inverter and luminous flux versus the time (Figs. 2 and B2)
P_I, Φ	Spectral components of p_I, and ϕ
$P_{I,DC}$, Φ_{DC}	DC components of p_I, and ϕ
$f_{P,IH}$	Interharmonic frequencies of P_I (Fig. 11)
v_s	Generalized supply system voltage (Fig. 6)
Z_s, Z_{sn}	Supply network equivalent series impedance and its normalized value (Figs. 6 and 22)
R_{in}	Lamps' input resistor (Fig. 6)
C_B	Lamps' DC bulk capacitor (Fig. 6)
τ_C	Time constant of the DC load
τ_L	Time constant of the lamp all gain of the lamp from supply voltage input side to luminous flux output
K	Overall gain of the lamp from supply voltage input side to luminous flux
L	Adjustment constant (Eq. (5))
$v_{IH} V_{IH} f_{IH}$	Instantaneous value, RMS, and frequency of the system voltage background interharmonic
m_{IH}	Relative interharmonic component amplitude
GF_{Φ}	Gain factor of luminous flux
$IF_{h\text{-}k}$	Interharmonic families produced by h-th harmonic and k-th interharmonic
$f_{h\text{-}k}$	$IF_{h\text{-}k}$ frequencies
$VIF_{h\text{-}k}$	Visible interharmonic families produced by h-th harmonic and k-th interharmonic

paper demonstrates that the preliminary model presented in Ref. [16] can be used for other types of lamps, and a general formulation and experimental validation of the model are reported.

In what follows, the results of an exhaustive preliminary experimental analysis are first presented with the aim of justifying the hypotheses of the model. Then, the generalized lamp model is described and used to analyze the frequency behavior of a lamp in the presence of voltage fluctuations. After the experimental validation of the model for different kinds of lamps, the results of sensitivity analyses of the lamps' responses versus their main parameters and versus the parameters of the supply network, which were performed using the proposed model, are finally reported.

2. Preliminary experimental analysis

The aim was to experimentally show that the two main hypotheses for the model described in Section 3 were valid. The aforementioned hypotheses were based on the concept that the circuitry of the majority of the lamps on the market consists of a diode rectifier (supply side) with a smoothing capacity feeding fixed controlled inverters without regulation loops (bulb side).

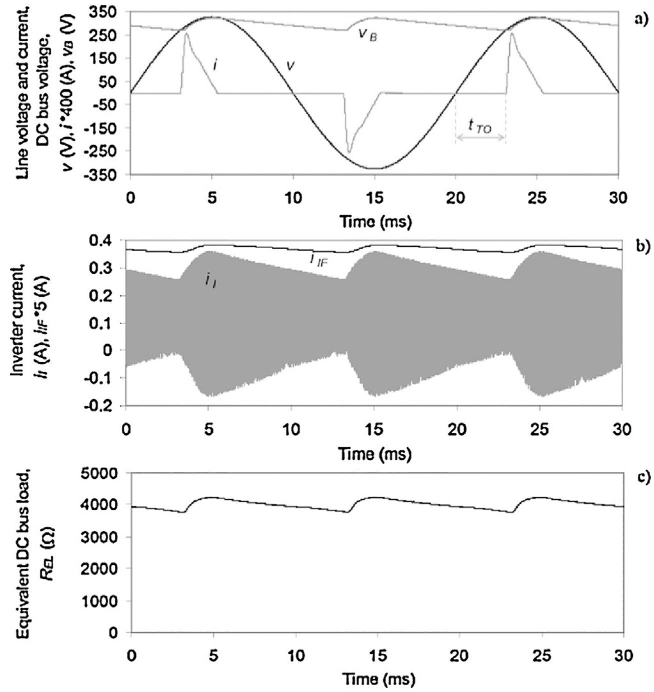

Fig. 1. Measurements on CFL8: a) AC voltage v and current i multiplied by factor of 400 for representation scale reasons and DC link voltage on bulk capacitor, v_B; b) current absorbed by inverter, i_I, and same current filtered by low pass filter, i_{IF}, and multiplied by factor of 5 (for representation needs), as well as c) instantaneous ratio between v_B and i_{IF}, which is called equivalent DC bus load R_{EL}.

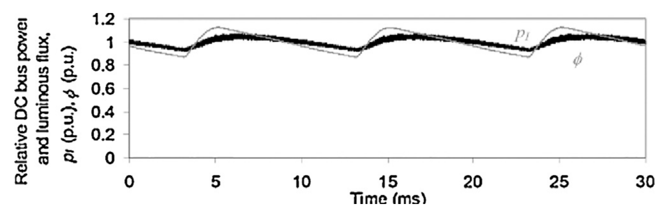

Fig. 2. Measurements on CFL8: DC instantaneous power absorbed by inverter and luminous flux versus time.

The hypotheses are as follows:

1) the behavior of the circuitfed by the DC link of the rectifier can be approximated by an equivalent resistive load;
2) an appropriate transfer function can be used to obtain the instantaneous luminous flux from the instantaneous power absorbed by this equivalent resistance.

An experimental analysis was conducted in a laboratory test using the 27 different lamps listed in Appendix A, which had the typical circuitry reported in Appendix B. The supply voltage was an ideal waveform $v_1(t)$ of nominal amplitude V_1 (e.g., 230 V) and nominal frequency f_1 (e.g., 50 Hz) generated by a CI15003iX programmable power source, which fed, with minimal achievable source-side impedance, a lamp placed in a test chamber [16] equipped with a photo-head with spectral correction for standardized human photopic vision [15]. The measured waveforms presented below were acquired using a scopecorder DL850 with 701250 analog input modules (AA-F, 1 MS/s, 16-bit) and Yokogawa 701933 current transducers (DC-50 MHz).