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Parameter estimation procedures for compact fluorescent lamps with electronic ballasts

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ABSTRACT

Compact fluorescent lamps (CFLs) are increasingly present in low voltage distribution systems due to their small energy consumption in comparison with traditional incandescent lamps. This damages power quality because CFLs have a non-linear behavior and inject harmonics into the distribution system. This paper studies estimation procedures for CFLs and presents estimation algorithms based on a “black box” CFL model and actual measurements. The estimation procedures are validated with laboratory measurements.

1. Introduction

CFLs also known as low-cost, energy-efficient light bulbs due to their high light output, are used increasingly because of their low energy consumption, especially compared to traditional incandescent bulbs, and their long average useful life. However, disadvantages also exist in that these bulbs are linear time-variant electrical loads and the current waveform they absorb is extremely distorted (far removed from the sinusoidal form). These lamps are small-power single-phase loads (<25 W), but they can be an important source of harmonics because a large number of them can be connected to the same bus. This results in a considerable increase of harmonic voltage levels in power distribution systems, which causes problems in installations and has a negative impact on voltage waveform quality [1,2]. Nevertheless, as the power of these loads is low, the directives governing the injection of harmonics are not particularly strict (IEC 61000-3-2 standard for Class C electronic lighting systems) [3], and bulbs with total harmonic distortion levels (THD) of over 100% can be found on the market [4]. Several studies have been conducted to assess CFL impact on harmonic power quality. Initially, some attempted to analyze CFL harmonic behavior from experimental measurements [4–11]. Currently, most examine the prediction of harmonic currents injected by CFLs [1,11–13]. In [1], Norton equivalents are used to characterize CFL harmonic currents. In [11], the concept of tensor analysis with phase dependency is introduced to consider harmonic interaction of the supply voltage in CFL harmonic currents. In [12], the CFL study is based on the CFL equivalent circuit. In [13], external CFL behavior is modeled without regard to the internal electronic circuit, paying particular attention to the current waveform absorbed as a function of the voltage applied. However, unlike CFL modeling, CFL parameter estimation has not been studied so far. The identification of parameter values allows performing further CFL simulations to study the impact of these loads on harmonic distortion of installations. Different studies deal with the estimation of other non-linear loads using weighted least-squares algorithms [14–17].

This paper examines CFL parameter estimation and proposes non-linear least-squares procedures based on actual measurements and the “black-box” CFL model derived from [13]. Moreover, the paper contributes to this CFL model. The function between the current waveform and the supply voltage is better described here, the determination of some parameters of the model is generalized and analytical expressions are provided to determine the CFL harmonic currents. The estimation procedure is experimentally validated with three CFLs tested in the laboratory.

2. CFL modeling

The estimation procedures in the paper are based on the “black box” CFL model presented in [13], where an analytical function between the CFL current waveform and the supply voltage is defined. This model is presented and completed in Section 2.3.

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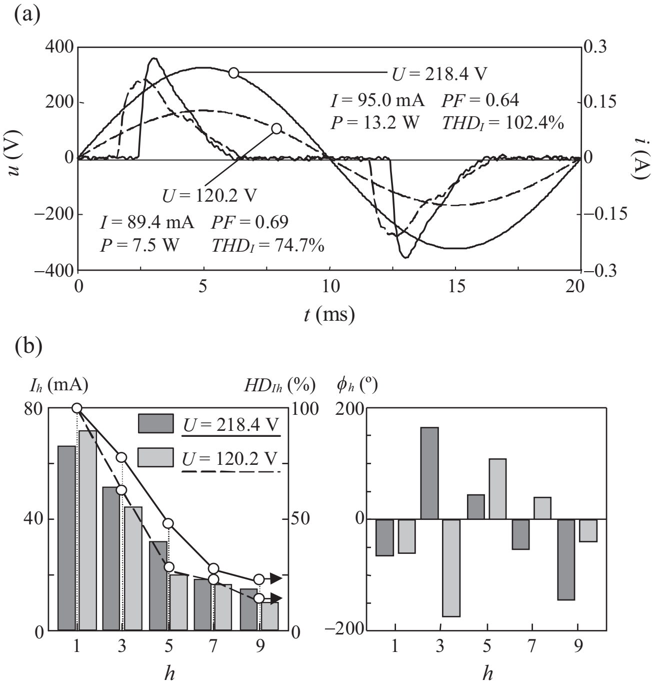

Fig. 1. Measured voltage and ac currents of a Philips Ecotone Economy 14 W CFL (L2P 14 W in [13]): (a) Waveforms. (b) Harmonic spectra.

Previously, the CFL electronic ballast circuit and input current waveform are analyzed.

2.1. CFL electronic ballast

The typical circuit of the CFL electronic ballast is composed of a diode bridge with an ac resistance and a dc-smoothing capacitor that feeds the tube inverter [11,12]. The inverter and tube can be modeled as a resistor to investigate the harmonics of the ac input current *i* because the inverter runs at 10–40 kHz and appears as a constant load for the dc busbar.

According to the compromise between CFL current harmonic distortion, cost, life-time and power-factor control, CFLs can be divided into four main CFL electronic ballast categories: simple CFL ballast circuit, passive filtering circuit, valley-fill circuit and active filtering circuit. These circuits are associated with the four categories of the CFL ac current harmonic spectra (poor, average, good and excellent, respectively) [1,11]. The discussion between manufacturers and electricity companies focuses on the choice between CFL acceptable power quality and cost. That is why the second and third CFL categories are the most common. The CFL model presented here corresponds to the “poor-average” CFL ac current harmonic spectra category (see next section).

2.2. CFL current waveform

Fig. 1 shows the typical ac current waveforms of the “poor-average” CFL category and their harmonic spectra. They were measured using a Philips Ecotone Economy 14 W compact fluorescent lamp (L2P 14 W in [13]) fed with a 218.4 and 120.2 V rms non-sinusoidal supply voltage ($HD_{Uk=3,5,7}$ = 0.22, 1.13, 0.53% and 0.54, 0.78, 0.62%, respectively). The voltage and current rms values, U and I, consumed active power, P, total power factor, PF, and total and individual harmonic distortion of the ac current, THD_I and HD_{Ih}, of the measured waveforms are also shown in Fig. 1. The above CFL characteristic values are defined as

$$F^2 = \frac{1}{T}\int_0^T f^2(t)dt, \quad P = \frac{1}{T}\int_0^T u(t)\cdot i(t)dt, \quad PF = \frac{P}{UI},$$

$$THD_F = \frac{\sqrt{\sum_{h=3}^{5,7,\ldots} F_h^2}}{F_1}, \quad HD_{Fh} = \frac{F_h}{F_1} \quad (f = i, u \ \text{and} \ F = I, U). \tag{1}$$

The current phase angles ϕ_h are referred to the phase angle of the fundamental supply voltage. The CFL current measurements reveal that

- Half-wave symmetry can be considered to characterize the CFL ac currents.
- The ac current waveforms start with a delay from the zero-crossing of the supply voltage.
- Steep and gentle slopes occur in the ac current rising and falling edges, respectively.
- The current waveforms have a very pronounced peak.
- The current rms value and the total power factor remain more or less constant with rms supply voltage variation while the active power and the total harmonic distortion decrease when the rms voltage drops. This was studied in detail in [13].

2.3. CFL analytical model

According to the above observations and considering the sinusoidal supply voltage [$u(t) = \sqrt{2}U\sin(\omega_1 t)$], the CFL current waveform can be determined as follows [13]:

$$i(t) = g(t)\cdot u(t) = G\cdot h(t - t_d)\cdot u(t), \tag{2}$$

where

$$h(t) = h_1\left(t - n\frac{T}{2}\right) \quad n = \left\lfloor \frac{t}{T/2} \right\rfloor,$$

$$h_1(t) = \begin{cases} \exp\left(-\dfrac{t}{\tau_1}\right) - \exp\left(-\dfrac{t}{\tau_2}\right) & 0 < t < \dfrac{T}{2} \\ 0 \quad t < 0 \quad \text{or} \quad t > \dfrac{T}{2} \end{cases}, \tag{3}$$

where $T = 2\pi/\omega_1$ is the period of voltage and current waveforms and

$$G = \frac{K_G}{\sqrt{U}}, \quad t_d = K_{td}\sqrt{U}, \quad \tau_1 = \frac{K_{\tau 1}}{\sqrt{U}}, \quad \tau_2 = K_{\tau 2}. \tag{4}$$

It must be noted that since CFLs are linear, time-variant devices, they are characterized by the time-variant conductance $g(t)$, which is the reason for their non-linear behavior. The proposed mathematical function of $g(t)$ [i.e., (2)–(4)] is an equivalent but more comprehensive way of characterizing the current waveform than the function in [13]. In the present paper, the relationships (4) between the current function parameters G, t_d, τ_1 and τ_2 and the voltage rms value in [13] are introduced in the model directly by using the parameters K_G, K_{td}, $K_{\tau 1}$ and $K_{\tau 2}$. Based on the typical values U = 230 V, G (mS) = (1...10), t_d (ms) = (1.5...3), τ_1 (ms) = (0.7...1.5) and τ_2 (ms) = (0...0.5) [13], the parameter ranges K_G (mS V$^{1/2}$) = (15...151.7), K_{td} (ms V$^{-1/2}$) = (0.099...0.2), $K_{\tau 1}$ (ms V$^{1/2}$) = (10.6...22.7) and $K_{\tau 2}$ (ms) = (0...0.5) are considered in the study. The sinusoidal supply voltage approach is a limitation of the model because actual supply voltages are generally non-sinusoidal and harmonic voltages affect CFL behavior [11]. Nevertheless, considering the usual distortion levels in power systems (below 2%), the influence of harmonic voltages might be