

Neutral conductor current in three-phase networks with compact fluorescent lamps



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ABSTRACT

In this paper, expressions of the neutral conductor current in three-phase networks with compact fluorescent lamps (CFLs) are obtained from a CFL “black-box” model proposed in the literature. These expressions allow studying and performing a sensitivity analysis of the impact of CFLs on neutral current. The influence of CFL model parameters, as well as supply voltage unbalance, number of CFLs per phase and different types of CFLs per phase, on the neutral current is also investigated. The obtained results are validated with measurements and PSCAD/EMTDC simulations.

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1. Introduction

CFLs are used increasingly because of their low energy consumption and long average useful life compared to traditional incandescent bulbs. However, the former are linear time-variant electrical loads and the current waveform they absorb is extremely distorted (far removed from the sinusoidal form). Although they are small-power single-phase loads (<25 W), they can be an important source of harmonics because a large number of them can be connected to the same bus, causing problems in installations and affecting voltage waveform quality [1,2]. One of these problems is the harmonic current flow in the neutral conductor [3–5]. In balanced three-phase systems, the first- and fifth-order harmonics in the phase currents ($k=1, 7, \dots$ and $k=5, 11, \dots$, respectively) are a positive sequence system and a negative sequence system, respectively, while the third-order harmonics ($k=3, 9, \dots$) are a zero sequence system. In this situation, only the third-order harmonic currents flow into the neutral conductor and are three times as high as the corresponding harmonics in phase currents. System unbalances such as supply voltage unbalance and load unbalance cause the loss of positive and negative sequence symmetry in the first- and fifth-order harmonics. Hence, the sum of these harmonics in the neutral conductor is now not zero. This can increase the rms value of the neutral conductor current. Studies on this harmonic problem require CFL models to calculate the harmonic currents

injected into the installation [1,6–9]. In [1], the Norton equivalents are used to characterize the CFL harmonic currents. In [6,7], the concept of tensor analysis with phase dependency is introduced to consider the harmonic interaction of the supply voltage in CFL harmonic currents. In [8], the CFL study is based on the CFL equivalent circuit. In [9], external CFL behaviour is modelled paying particular attention to the current waveform absorbed as a “black-box” function of the voltage applied.

This paper studies the impact of CFLs and three-phase unbalances on the neutral conductor current. Section 2 presents the CFL model used in the neutral conductor current study, which is based on the “black-box” model in [9]. In Section 3, the expression of the neutral conductor current is determined based on the above model, and the influence of CFL parameters on the neutral current is studied. Analytical expressions to determine the impact of supply voltage unbalance, different number of converters per phase and converters with different parameters per phase on the neutral conductor current are provided in Sections 4–6. Moreover, this influence is analyzed using the previous expressions. Section 7 gives an overview of the simplifications of the study. In Section 8, the obtained results are validated with four experimental tests and PSCAD/EMTDC simulations.

2. Compact fluorescent lamp modelling

2.1. CFL electronic ballast and current waveform

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 [6–8]. The inverter and tube can

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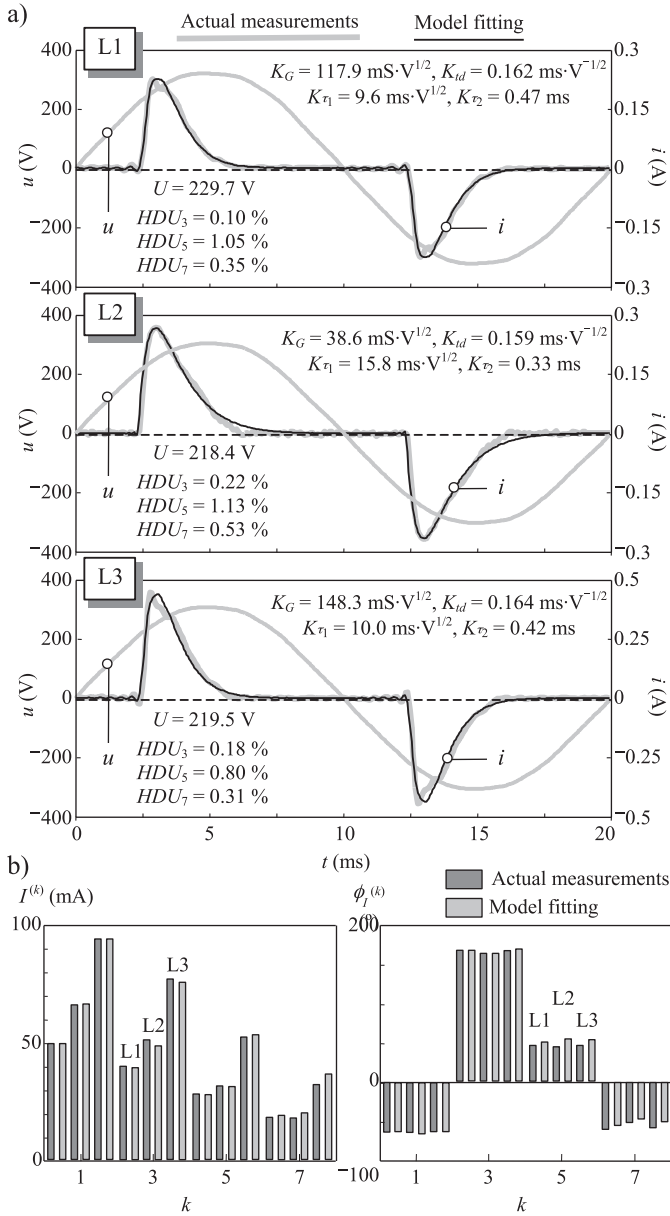


Fig. 1. Measured and simulated voltage and ac currents of CFLs: (a) waveforms and (b) harmonic spectra.

be modelled as a resistor to investigate the harmonics of the ac input current i because the inverter usually runs at 10–40 kHz and appears as a constant load for the dc busbar [6], [7]. 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 [1,6,7]. 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 category.

Fig. 1 shows the typical ac current waveforms of the “poor-average” CFL category and their harmonic spectra. They were measured using the CFLs L1P 11W (L1), L2P 14W (L2) and L4P 20W (L3) in [9] fed with the non-sinusoidal supply voltages in the figure.

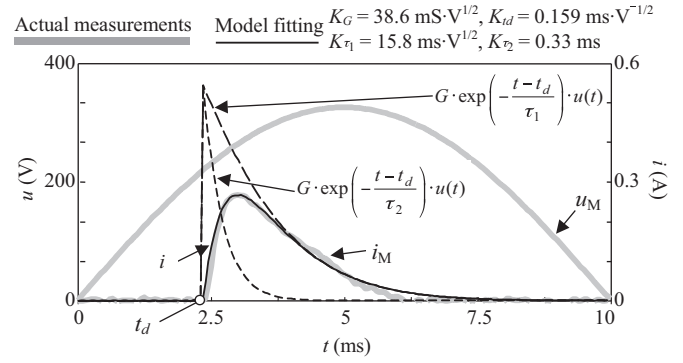


Fig. 2. Example of the CFL L2 analytical model fitting.

The current phase angles $\phi_1^{(k)}$ 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 have a very pronounced peak, which starts 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.

2.2. CFL analytical model

According to the above observations and considering the sinusoidal supply voltage $u(t) = \sqrt{2}U \sin(\omega_1 t + \varphi)$, the CFL current waveform can be determined as follows [9]:

$$i(t) = g(t) \cdot u(t) = G \cdot h(t - t_d) \cdot u(t), \quad (1)$$

where the function $h(t - t_d)$ is represented by a double-exponential function:

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

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

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

$$G = \frac{K_G}{\sqrt{U}}, \quad t_d = K_{td} \sqrt{U}, \quad \tau_1 = \frac{K_{\tau_1}}{\sqrt{U}}, \quad \tau_2 = K_{\tau_2}. \quad (3)$$

In the present paper, the relationships (3) between the current function parameters G , t_d , τ_1 and τ_2 and the voltage rms value in [9] are introduced in the model directly by using the parameters K_G , K_{td} , K_{τ_1} and K_{τ_2} . In this way, an equivalent but more comprehensive way of characterizing the current waveform than the model in [9] can be proposed. It must be noted that since CFLs are time-variant devices, they are characterized by the time-variant conductance $g(t)$, which is the reason for their non-linear behaviour. Based on the typical values $U = 230$ V, G (mS) = (1.. 10), t_d (ms) = (1.5.. 3.5), τ_1 (ms) = (0.6.. 1.5) and τ_2 (ms) = (0.. 0.5) [9], the parameter ranges K_G (mS·V^{1/2}) = (15.. 151.7), K_{td} (ms·V^{-1/2}) = (0.099.. 0.23), K_{τ_1} (ms·V^{1/2}) = (10.6.. 22.7) and K_{τ_2} (ms) = (0.. 0.5) are considered in the study. Fig. 2 illustrates the model fitting to the ac current of the CFL L2 in Fig. 1. The supply voltage is also plotted as a reference. It is worth noting that

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