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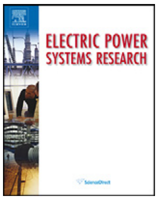

Model of discharge lamps with magnetic ballast

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ABSTRACT

Magnetic ballast discharge lamp modeling has been extensively studied because these lamps can be an important source of harmonics. Discharge lamp models usually represent the arc voltage by a square waveform. However, this waveform can be far from actual arc voltages, which affects the accuracy of the lamp models. This paper investigates the actual arc voltage behavior of discharge lamps from laboratory measurements and proposes a novel characterization of these voltages to reformulate the conventional models. The accuracy of the new model is validated with experimental measurements.

1. Introduction

Nowadays, there is an increasing number of discharge lamps (DLs) in power distribution systems because they have a longer life and higher lighting efficiency than incandescent lights. These lamps are classified according to the use of magnetic or electronic ballasts and the gas and pressure inside the bulb. Fluorescent and compact fluorescent lamps are low-pressure mercury gas lamps in the 5– 150 W range used in residential, commercial and industrial installations [1–6]. High-pressure mercury and sodium gas lamps and metal halide gas lamps are employed in street or public lighting with a power consumption range of approximately 100– 500 W [7–9].

Although compact fluorescent lamps with electronic ballast are now the most commonly installed lamps in commercial and residential installations (in particular in the European Union as a result of the European energy efficiency program), magnetic ballast DLs are still being used. Moreover, they are the only ones used in street lighting installations. Despite the low individual harmonic current consumption of DLs, a large number of them are usually connected at the same bus [3,7,8], increasing network voltage distortion [10]. Thus, many studies on DL modeling have been conducted to determine the harmonic currents injected into installations by these nonlinear loads [5,6,9,11–15], and standards assess and set the limit for the harmonic currents injected by this kind of loads [16]. The square arc voltage waveform is usually assumed in these studies. However, it can be far from actual arc voltages, affecting the accuracy of the DL model [9,17]. DL modeling studies are also used to analyze the distorted power supply influence on lamp bulb luminous flux variation [6,15].

This paper examines actual DL arc voltages by experimental measurements, compares them with the square arc voltage waveform and proposes a model to characterize their behavior. A DL model based on the above study is developed and the analytical expressions of the DL current magnitudes and phase angles are determined. The DL model also considers harmonic supply voltages and the DL ballast resistance. Finally, the study is validated with experimental measurements and the limitations of the square arc voltage waveform are discussed.

2. Discharge lamp modeling

Fig. 1(a) illustrates the typical circuit of magnetic DLs [5,6,9,11–15], which is formed by the magnetic ballast and the lamp bulb. The DL ballast is modeled with its inductance L (together with its associated resistance R) while the arc voltage phenomenon inside the bulb is modeled with the voltage source v_A. Fig. 1(b) shows the ac current and arc voltage (i and v_A, respectively), which characterize the behavior of these non-linear loads, where $\omega_1 = 2\pi f_1$ and f_1 is the fundamental frequency of the supply system. Fig. 1(c) shows the v_A–i characteristic of the arc voltage, which characterizes DL non-linear behavior [5,6].

To obtain the DL fundamental and harmonic currents, the commutation angles θ_1 and θ_2 in Fig. 1(b), which characterize DL behavior, are determined by analyzing the circuit of Fig. 1(a) [9,11–14,17]. Half-wave symmetry assumption is

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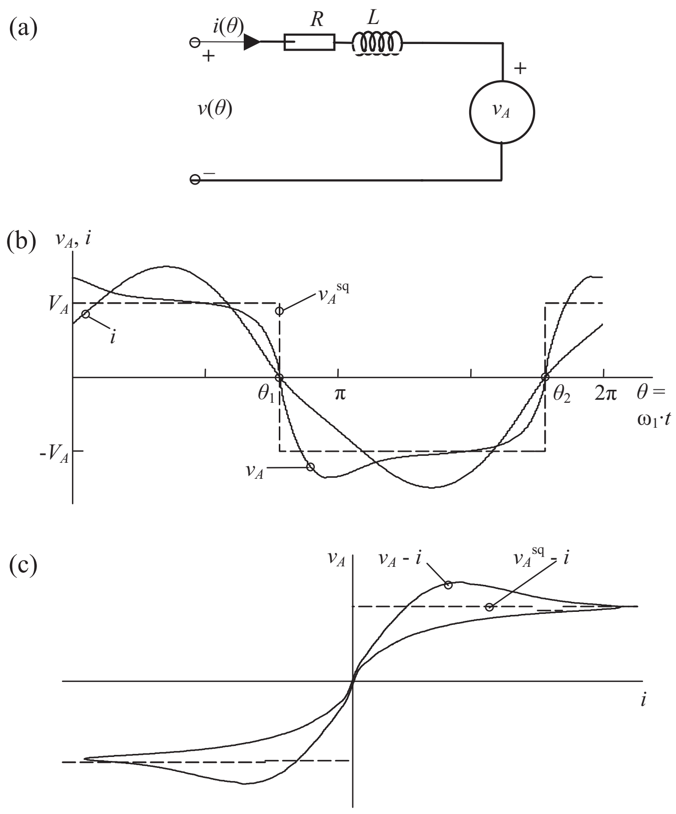

Fig. 1. Discharge lamp modeling: (a) discharge lamp equivalent circuit; (b) current and voltage waveforms; (c) v_A–i characteristic.

commonly assumed, and the commutation angles verify the relation $\theta_2=\theta_1+\pi$. Moreover, as can be seen in Fig. 1, the following hypotheses are also considered in the proposed DL model:

- Non-sinusoidal supply voltage:

$$v(\theta)=\sqrt{2}\cdot V_1\cdot\cos(\theta)+\sqrt{2}\sum_{k>1}V_k\cos(k\cdot\theta+\phi_{Vk}),\qquad(1)$$

  which allows incorporating the DL model into *iterative harmonic analysis* (IHA) programs to analyze the interaction between the network and DLs.
- Linear inductive ballast with its associated resistance:

$$\underline{Z}_h=Z_h\angle\phi_{Zh}=R+jh\cdot X\quad(h\geq 1),\qquad(2)$$

  where $X=L\cdot\omega_1$.
- Arc voltage represented with its Fourier series:

$$v_\mathrm{A}(\theta)=\sqrt{2}\sum_{h\geq 1}V_{\mathrm{A}h}\cos(h\cdot\theta+\phi_{V_{\mathrm{A}h}}).\qquad(3)$$

In the literature, the arc voltage is commonly modeled as a square voltage waveform [5,6,11–15,17]. However, this waveform cannot correctly fit actual voltages (v_A^sq and v_A in Fig. 1(b)) [9,17], affecting the accuracy of the DL model. The new arc voltage characterization (3), which is discussed in Section 2.1, improves the DL model results substantially.

Thus, by analyzing Fig. 1(a) under the previous hypotheses, the current waveform $i(\theta)$ is obtained by solving the equation characterizing DL behavior,

$$R\cdot i(\theta)+X\frac{\mathrm{d}i(\theta)}{\mathrm{d}\theta}+v_\mathrm{A}(\theta)=v(\theta),\qquad(4)$$

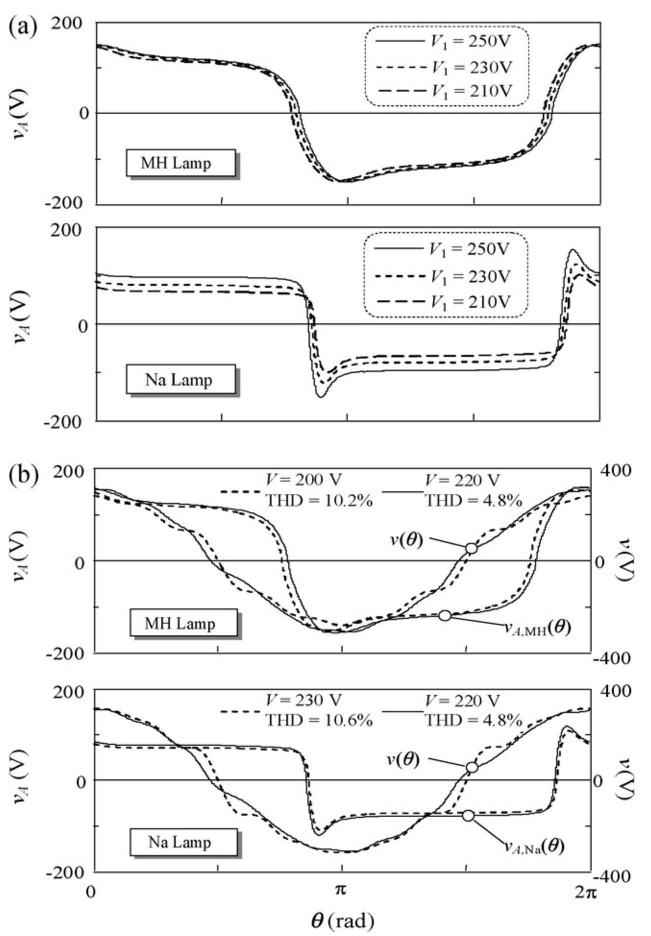

Fig. 2. Measured arc voltage waveforms of the 400 W metal halide lamp (up) and the 400 W high-pressure sodium lamp (down): (a) supplied with sinusoidal voltages; (b) supplied with distorted voltages.

under periodicity and segment change conditions

$$i(\theta_1)=i(\theta_1+2\pi)=0,\qquad i(\theta_2)=0.\qquad(5)$$

In Section 2.2, the DL fundamental and harmonic currents are determined from (4) and (5) considering the non-square arc voltage waveform.

2.1. Arc voltage model

To study arc voltage modeling, two public lighting lamps were tested in the laboratory (details of the power supply and nominal data and circuit parameters are given in Appendix A).

According to arc voltage measurements for different supply voltage conditions, the proposed DL model is based on the arc voltage stable performance and linear relation with respect to supply voltage in the ±10% range of DL rated voltage. As an example, Fig. 2 shows values of the arc voltage of a 400 W metal halide lamp and a 400 W high-pressure sodium lamp for different supply voltage conditions (210, 230 and 250 V sinusoidal supply voltages in Fig. 2(a) and distorted supply voltages in Fig. 2(b)). Table 1 shows the harmonic spectra of the distorted supply voltages in Fig. 2(b). It can be observed that the patterns of the arc voltage waveforms do not change significantly except for a small difference in their amplitudes depending on the supply voltage rms value V. This variation is characterized in Fig. 3(a), where the arc voltage rms value V_A is