Starting characteristics and steady state operation of dimming electronic ballasts

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Abstract
The aim of this paper is to quantify the impact of electronic dimming ballasts (EDBs) on fluorescent lamps, starting their operation at various dimming levels. Two EDBs and a non-dimming electronic ballast were examined and their parameters are presented in this paper. The preheating scenarios were investigated and the starting parameters and characteristics were measured. The electrode temperature at the starting moment of the lamp was calculated. The variation of the preheat ratio of the lamp during preheating is given in diagrams at different dimming modes. The lamp current, voltage, frequency and current crest factor were measured also at steady state operation. Differences among the systems were determined in order to estimate the advantages, the shortcomings of the ballasts and their impact to the lamp life.

Keywords: Electronic ballasts, Dimming, Fluorescent lamps, Preheating, Starting characteristics, Lamp life

1. Introduction

Application of lighting control technologies and use of their components have increased the public interest. Lighting manufacturers have advanced the dimmable lighting systems using innovative EDBs aiming to greater energy savings and longer life to their systems. In the recent past these ballasts were under consideration whether they really combine optical comfort and energy savings with the long life cycle of lamps as part of a lighting system. Although the dimmable systems have been improved resulting in devices working properly with larger range of products there is lack of experimental data presenting their operation during their start.

Usually electrode preheating ballasts are used for attaining long lamp life in fluorescent lamps. They preheat the electrodes for a period of 500ms to 1500ms before discharge is achieved. The ballast applies a few volts to both electrodes in order to heat them to a temperature high enough to prevent sputtering of the oxides which cover the tungsten filament. Sputtering occurs when the electrode temperature is lower than 1000K because cathode fall voltage increases and result in high speed collisions of positive ions to the cathode. During steady state operation of the lamp the discharge heats the electrodes causing insignificant sputtering besides thermionic emission of electrons. In the case of dimming the lamp, the low value of lamp current reduces electrode temperature if an additional electrode current is not supplied. Thus in dimming systems the ballast must provide the requisite current during both preheat and lamp operation. In order to dim effectively a fluorescent lamp a special equipment to provide the necessary power to the filaments is needed.

During preheating period the frequency of the heating current is above resonance for a given time. After preheat the frequency is decreased till a specific value where a high voltage is generated for ignition. When discharge is accomplished the frequency continues to decrease to its operational value. Basically there are two types of preheating electronic ballasts:

a) Rapid start ballasts: these ballasts preheat the filaments with a small voltage. Simultaneously a medium voltage is applied between electrodes. When filaments are heated enough the conduct is achieved and the lamp operates properly.
b) Programmed-start ballasts: these ballasts preheat electrodes for a definite time to the predetermined temperature. At this moment the required lamp voltage is applied and the ignition is started.

When a different lighting level is required the dimming ballast receives a signal from an external control device which can be a photosensor or just a BMS signal. Then the dimming mechanism is

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forced from the control to alter the lamp current. There are several protocols to communicate a dimming ballast with a controller. The most prevalent methods are the analogue dimming and the digital dimming.

The most common method for dimming uses an analogue control voltage (0-10VDC). Other methods for analogue dimming use two-wire phase-control, three-wire phase-control and wireless infrared. Dimming with a 0-10VDC control signal, the amplitude of the lamp current is controlled through reduction of the lamp power. Simultaneously the lamp voltage increases in order to heat the lamp filaments to the necessary temperature. When the controller voltage is close to 10V the light output is full. By decreasing the voltage to values lower than 10V the ballast reduces the light output. Some manufacturers supply the system with an arrangement which provides full light output each time the lamp switches on. Otherwise, the filaments are preheated to the necessary temperature even when the lamp switches on at a dimming level lower than 10V. The 0-10VDC method is cost efficient and compatible with the most control devices and communication protocols.

Although various investigations have been carried out on the photometric characteristics and the power consumption of electronic dimming ballasts (EDB) and their corresponding lamps [1-3], the electric characteristics of their starting and steady state operation have received little attention. This paper presents the ignition processes in several lighting systems with fluorescent lamps. Each system consists of a T5 linear fluorescent lamp, an electronic ballast and its dimming controller. The same lamp was used while the ballasts were interchanged. Two of the ballasts were dimmable while the other was non-dimming. The starting of the lamp, especially at low dimming level, is significant for the lamp life [4] while the electrode heating is compulsory [5]. The lamp starting processes were captured with the oscilloscope at various dimming levels. Characteristic oscillograms are presented and the corresponding results are shown in tables and figures. A discussion follows regarding the impact of the starting scenario of each system on the expected lamp life.

2. Experimental Method

Three ballasts were selected driving the same T5 54W fluorescent lamp; two EDBs (Ballast A and B) and a non-dimming one (Ballast C). The linear T5, 54W fluorescent lamp was aged for 100 hours on the standard 2h – 45min on/15 min off cycle before the experimental process [6, 7]. Measurements took place in the Lighting Laboratory of National Technical University of Athens. Ambient temperature was constant at 25±3^{o}C and mains input voltage at 230V, 50Hz through a voltage stabiliser for all test conditions.

The oscilloscope Tektronix DPO4034, (4 channels, 350MHz, 2.5GS/s, 10 Megapoint record length) was used for the capture of the ignition and for the monitoring of the steady state parameters. Two current probes were used, a Tektronix TCP202 and a Tektronix P 6021 AC for capturing electrode and lamp current. A high voltage differential probe Tektronix P 5200 was used for the acquisition of the lamp voltage.

All EDBs were manually dimmed through a digital power supply, from a maximum control voltage (10V) to a minimum (1V). Ten different light levels were selected (from 10V to 1V). The starting electrode current and voltage was measured for each level and the corresponding electrode temperature at the starting moment was also calculated [8]. The electrode resistance was estimated from the oscilloscope data just before the ignition. The temperature was estimated from the Equation (1).

$$T_h = T_c \cdot (R_h/R_c)^{0.814} \quad (1)$$

where T_h is the electrode temperature at the moment of ignition, T_c the ambient temperature (cold electrode temperature), R_h is the electrode resistance at the moment of ignition and R_c is the cold electrode resistance. The ratio R_h/R_c is the cold preheat ratio and its magnitude shows the temperature of the filaments. The proper range of the starting electrode temperature should be between 700^{o}C and 1000^{o}C [6, 9, 10 and 11] and the preheat ratio from 4.25 to 6.25 in order the ignition to be considered correct [9, 11 and 12]. The calculated electrode temperature and preheat ratio were checked at every dimming level for their consistency. The applied frequency and the resultant electrode resistance were derived from the data of the waveform. Their variations were estimated at starting operation and the results are given in real time diagrams. Furthermore the non-dimming ballast was examined. Its preheat ratio (R_h/R_c) was also calculated.

The characteristics which were measured during ignition were: preheating time, glow current, cathode current and cathode voltage (just prior glow to arc transition). The frequency and the other characteristics during the starting process were measured from the oscilloscope's capture. Glow current is the current between the electrodes before discharge is completed. The lower is the glow current the less is the electrode depletion. Its volume is of high importance because with too high values the sputtering is excessive and the preheat ratio is underestimated besides. The glow current during preheat period is recommended to be less than 25A (rms) [13]. At steady state operation the frequency, lamp voltage and lamp current were measured (both p-p and rms). The resistance of the filament was measured under ambient temperature before any measurement was carried out and the electrode resistance was estimated at 25^{o}C.

Measurements were carried out and captures were obtained with a 1Volt step from 1V to 10V. During these measurements the oscilloscope's scale was changed in order to acquire the best waveform view.

3. Measurements

For the measurements was used a 1-10V interface to control dimming. Using a DC voltage supplier (Hewlett-Packard Triple output power supply) the dimming ballasts were adjusted manually. The following figures are representative of the oscilloscope's captures.

Figures 1 and 2 present the starting conditions when the ignition is taking place at the selected dimming levels. Each oscillogram shows the traces of the electrode voltage, electrode current and the glow current for a period of 4 seconds. Different starting scenarios of the two examined dimming ballasts were observed. Both preheating time and applied electrode voltage have indicated diversities.

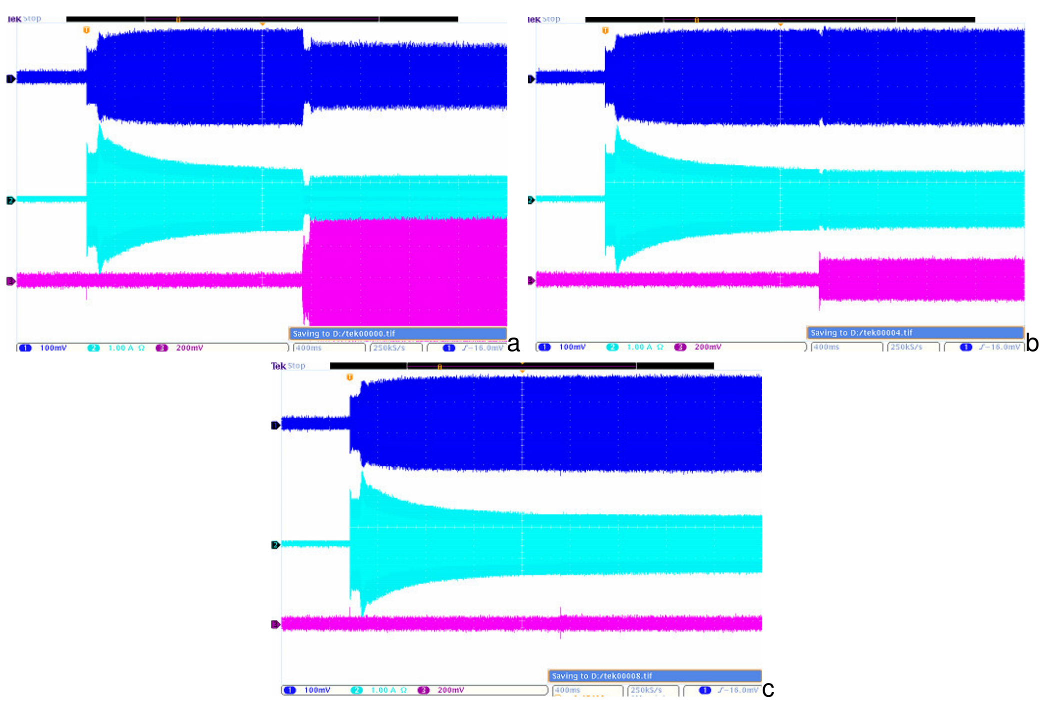

Figure 1. Ballast A: Electrode voltage (top trace), electrode current (middle trace) and lamp current (bottom trace) at preheating period (400 ms/div) when starting at 10V (a), 6V (b) and 2V (c) dimming levels.
Scale: 5V/div, 1A/div, 400mA/div

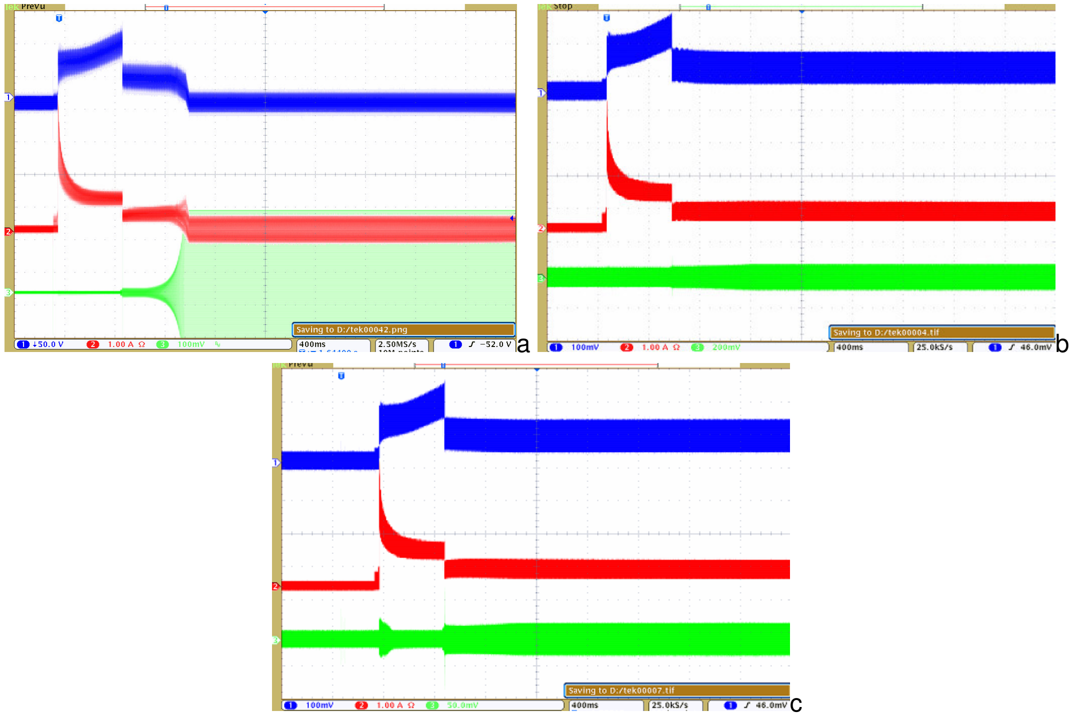

Figure 2. Ballast B: Electrode voltage (top trace), electrode current (middle trace) and lamp current (bottom trace) at preheating period (400ms/div) when starting at 10V (a), 6V (b) and 2V (c) dimming levels.
Scale: 2.5V/div, 1A/div, 100mA/div (a), 5V/div, 1A/div, 400mA/div (b), 5V/div, 1A/div, 100mA/div (c)

Ballast A preheats the filaments applying a constant voltage with an almost AC current without a DC component. Ballast B applies a strong DC component while the AC voltage and current are lower than the corresponding values in Ballast A. Ballast B uses two distinguishable steps of supplied voltage. The starting of the lamp is not immediate, as the glow current of the oscillogram indicates. This may be comfortable for the customer but for a few milliseconds the glow current exceeds the 25mA limit, which means that this can damage the electrodes. Ballast A is expected to provide a longer lamp life if only the glow current is taking into account as a parameter for long lamp life.

Figures 3 and 4 present the operating lamp voltage and current. The oscilloscope's captures are after the discharge stabilization. Discharge stabilization considered one hour after ignition of the lamp. The current crest factor (CCF) of these waveforms was examined. Figure 3 shows waveforms and the corresponding CCFs from 1.51 (10V) to 1.18 (2V) for various dimming levels. This means that the impact to the electrodes is more harmful at full light output than in lower light levels. On the other hand, Ballast B has the following CCFs: 1.42 (10V), 1.56 (6V) and 1.71 (2V). In this lamp the impact of CCF is different, as it is higher at lower dimming levels. ANSI determines 1.7 as the upper limit for CCF in fluorescent lamps for an optimum use [13].

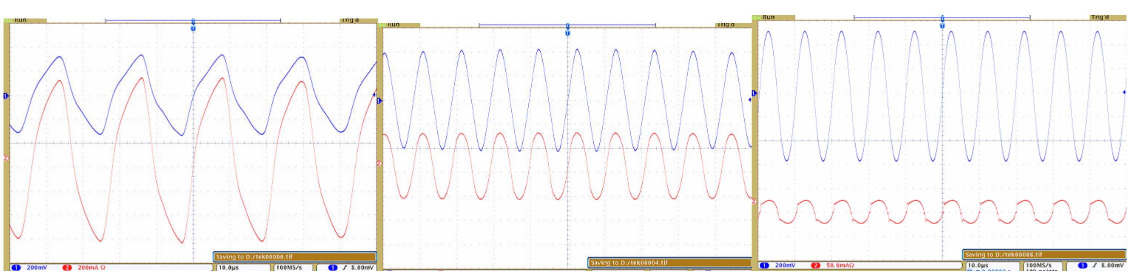
Figure 3. Ballast A: Lamp voltage (top trace) and lamp current (bottom trace) at steady state operation at 10V, 6V and 2V dimming levels (from left to right)
Scale: 50V/div, 200mA/div (left), 50V/div, 200mA/div (centre), 50V/div, 50mA/div (right)

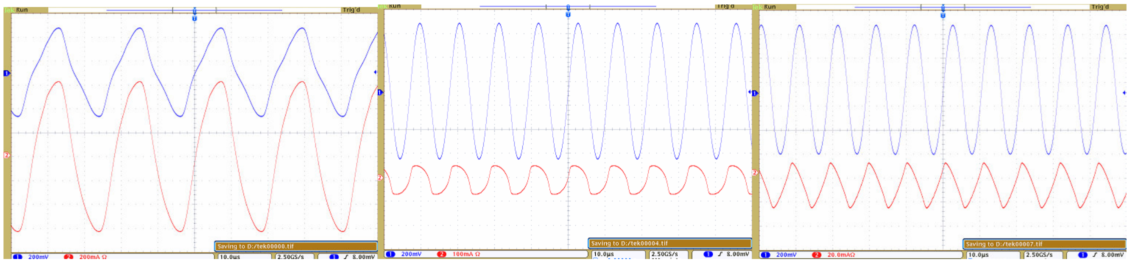

Figure 4. Ballast B: Lamp voltage (top trace) and lamp current (bottom trace) at steady state operation at 10V, 6V and 2V dimming levels (from left to right)
[Scale: 50V/div, 200mA/div (left), 50V/div, 100mA/div (centre), 50V/div, 20mA/div (right)]

Figures 5 and 6 present the resulting electrode preheat ratio R_h/R_c during preheating time for Ballasts A and B at full light output. It was found that Ballast A applies an erratic frequency to the lamp in regard with Ballast B which may result in damaging the electrodes. Electrode current and voltage were monitored during preheating in real time with the oscilloscope. The graphs show smoothed curves because of the calculation of the preheat ratio during preheating process from the corresponding measurements.

Figure 7 shows the preheat ratio in real time during preheating period in the non-dimming Ballast C.

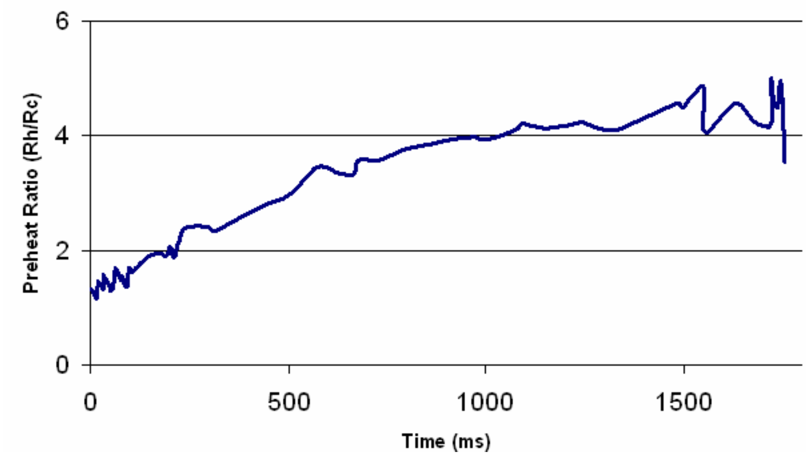

Figure 5. Preheat ratio during preheating (at full light output) in real time. Ballast A: Preheat time 1760ms.

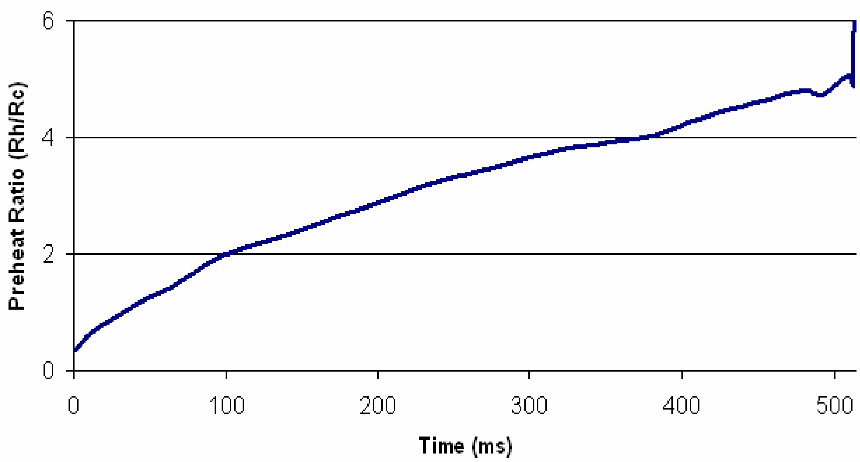

Figure 6. Preheat ratio during preheating (at full light output) in real time. Ballast B: Preheat time 510ms.

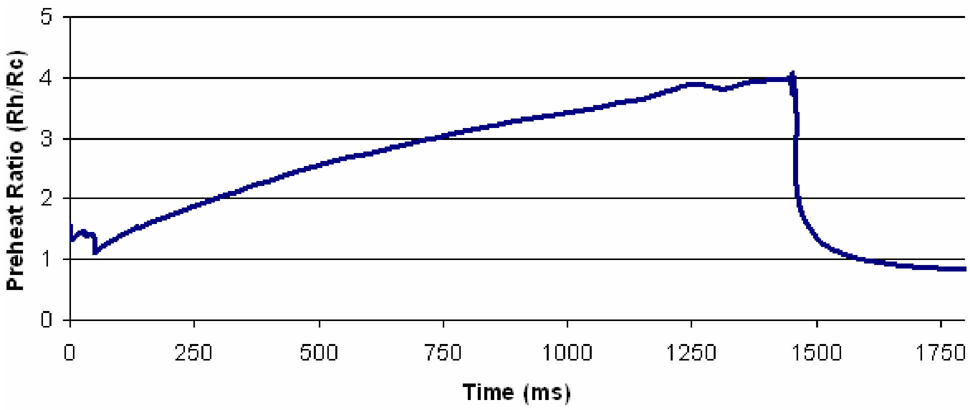

Figure 7. Preheat ratio in real time in non-dimming ballast. Ballast C: Preheat time 1760ms.

In Figure 8 the waveforms of electrode voltage, electrode current and lamp glow current are presented for Ballast B at full light output. DPO4034 oscilloscope provides the ability of mathematical processing of the recorded waveforms. Thus the preheat ratio in real time was computed by the oscilloscope The $R_h/R_c=V/(I \cdot R_c)$ equation was used by the oscilloscope for the whole record length (1 M) in order the preheat ratio waveform to be constructed point by point as is shown in the figure. It is worth mentioning that preheat ratio is well defined only for the period that the glow current is low. Thus reliable values are only for the preheating time where the glow current is few mA, namely for the first 520ms.

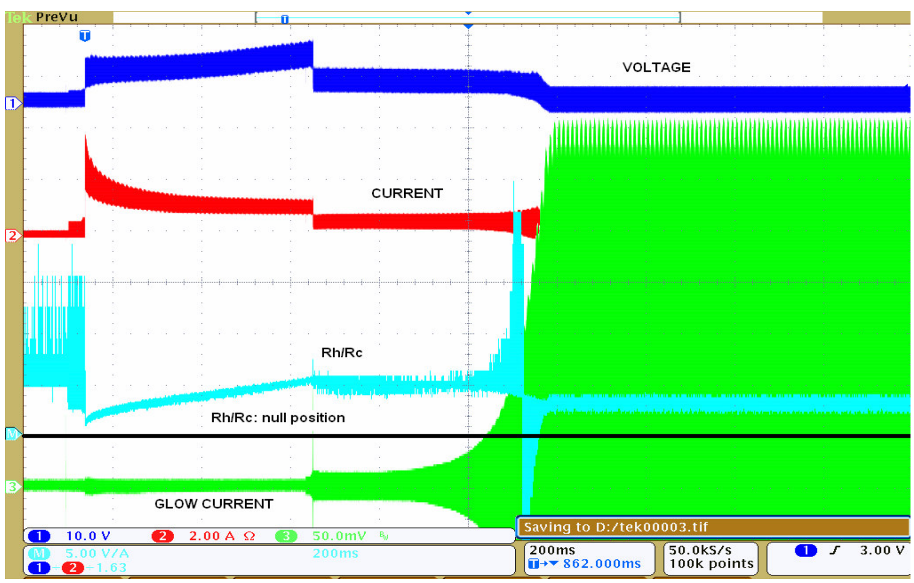

Figure 8. Electrode voltage, electrode current, lamp glow current and preheat ratio waveforms when the Ballast B starts.

(Scales: Voltage: 10V/div, Current: 2A/div, Glow current: 100mA/div, Preheat ratio: 5 units/div, Time: 200ms/div)

Tables 1 and 2 present the preheat time and preheat ratio of the starting process at selected dimming levels. Lamp current, voltage and frequency is also available for steady state operation.

Figure 9 shows the glow and lamp current for the Ballast B during preheating at a low dim level. At low dimming levels the glow current was over the recommended value for a few milliseconds at the outset of the preheating period.

Table 1. Ballast characteristics at starting and during operation (Ballast A)

	Ignition		Operation		
V DC	Preheat time (ms)	Preheat Ratio R_h/R_c	I lamp (mA)	V lamp (V)	Frequency (kHz)
10	1760	4.90	488.6	100	44.1
9	1760	4.75	458.0	107	46.4
8	1750	4.70	358.0	112	59.1
7	1750	4.82	268.0	133	81.6
6	1760	4.92	196.0	162	95.1
5	1750	4.87	121.7	190	98.5
4	1750	4.82	70.5	218	97.7
3	1760	4.70	46.6	233	96.8
2	1760	4.70	33.4	232	97.2
1	Low Resolution				

Table 2. Ballast characteristics at starting and during operation (Ballast B)

	Ignition		Operation		
V DC	Preheat time (ms)	Preheat Ratio R_h/R_c	I lamp (mA)	V lamp (V)	Frequency (kHz)
10	508	5.52	450.0	116	45.0
9	512	5.55	390.0	133	53.8
8	520	5.59	154.0	160	76.0
7	520	5.65	78.0	183	91.1
6	512	5.58	41.0	208	92.7
5	520	5.96	25.0	210	93.5
4	524	5.56	18.0	212	94.0
3	516	5.56	14.0	208	94.5
2	520	5.90	12.8	204	95.2
1	516	5.64	12.0	204	95.0

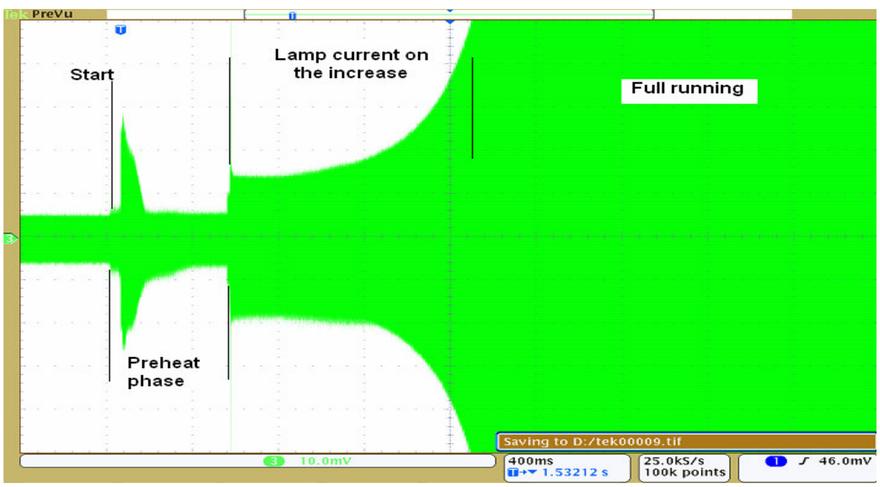

Figure 9. Lamp current during preheating period and on the beginning of the full operation. Dimming level: 2VDC (Scales: Current: 10mA/div, Time: 400ms/div)

Preheating period is terminated approximately 520ms after switching on. Nevertheless, a small incremental current flows in the lamp before the implementation of the discharge. This current causes sputtering to the coating compounds of the electrodes resulting in lower lamp life.

Figure 10 shows in detail the applied voltage at the moment of ignition of Ballast A. An incremental voltage was observed instead of an expected constant high voltage. The ignition is accomplished at the end of voltage application.

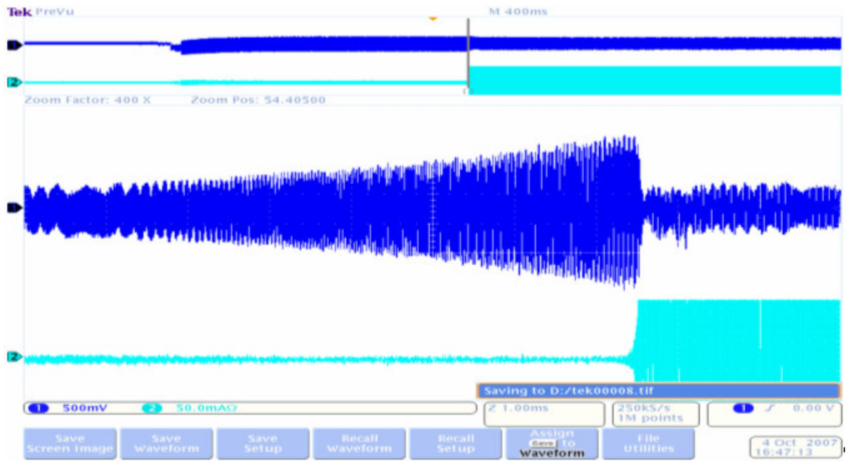

Figure 10. Ballast A. Detailed waveform (10ms) from the lamp voltage (top trace) and current (bottom trace) from the moment of ignition (Time: 1ms/div, Voltage: 250V/div).
The upper pair of traces presents the entire phenomenon (Time: 400ms/div).

4. Discussion - Conclusions

An additional electrode current is supplied to heat the electrode when a dimmable system is turned on or during its operation while at dimming level. Results show that the dimming ballasts apply the correct combination of electrode voltage and current to achieve the appropriate temperature to the electrode at the moment of ignition and operation at all dimming levels. As a result the lamp will attain its rated life.

All the systems achieve the desired electrode temperature at the end of the preheating time. Occasionally glow current exceeds the recommended limits. This results in lower lamp life. Necessary ballast improvements regarding the lamp life must be implemented for the protection of electrodes from the effects of glow current.

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