An Electronic Ballast for Fluorescent Lamps with No Series Passive Elements

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***Abstract* -This exploratory study examined the possibility of driving a fluorescent lamp at high frequency with no serially connected passive elements. The proposed driver is a full bridge stage controlled by the phase shifted PWM scheme. Current feedback was used to stabilize the average of the rectified lamp current to a set value. The experimental results of this research confirm the conjecture that an all-electronic fluorescent driver is feasible. Lamp V-I characteristics and lamp resistances were found to be comparable to those measured when the lamp is driven by a conventional HF electronic ballast. The measured light output of a lamp driven by proposed ballast was found to be slightly higher than the light output of same lamp when driven by a conventional HF ballast for the same input power. The paper covers the issue of feedback consideration for ensuring dynamic stability.**

I. INTRODUCTION

Electronic ballasts for fluorescent lamps are favored over electromagnetic ballast for several reasons. They provide an overall better efficacy (lumen/Watt), they could prolong the lamp's life and they are lighter and smaller than the electromagnetic counterparts. The main difference between the so-called "electronic ballast" and the electromagnetic ballast is the frequency at which the lamp is driven. Whereas in the case of the electromagnetic ballast it is the power line frequency, the electronic ballast drivers the lamp at a much higher frequency, typically in the range of 20kHz to 70kHz. However, in both cases the ballasting , i.e. current stabilization, is achieved by limiting the lamp's current with a series reactive element (inductor or capacitor) placed in series with the lamp [1-5]. Since the lamp exhibits negative incremental resistance around the operating point, a ballast is needed to ensure stable operation. That is, to overcome the problem posed by the negative resistance, the lamp has to be driven by a high impedance source. In present practice, the serially connected ballast achieves this requirement.

From the theoretical point of view an inductor or a capacitor can serve as a current limiting element (ballast). However, normally an inductor is favored for a number of reasons. It helps to achieve soft switching in half bridge topologies, and it helps to attenuate high frequency components in the lamp's current. In push-pull drivers, capacitors are often used to stabilize the current [5], but a (coupled) resonant inductor is still needed to achieve soft switching and to boost up the voltage. It is thus evident that inductors need to be included in practically all-electronic ballast designs. The magnetic component of the electronic ballast makes it bulky and limits the degree of miniaturization that can be achieved. Further, it is a severe barrier in any attempt to design a true microelectronic driver for fluorescent lamp.

The objective of present work was to investigate the possibility of designing a fluorescent lamp driver that does not need a series passive element to limit and/or control the current through the lamp. It is clear that such a driver must possess a current source characteristic. In this study we explore the simplest possible way to achieve it, applying the PWM technique along with current feedback.

II. THE ELECTRONIC DRIVER

The power stage of the proposed electronic driver is built around a full bridge topology (Fig. 1) controlled by the phase shifted PWM method. Applying this gate drive scheme, the output voltage of the bridge assumes three voltage levels: zero, bus voltage and minus bus voltage (Fig. 2). That is, the lamp is clamped to the bus voltage for the duration of

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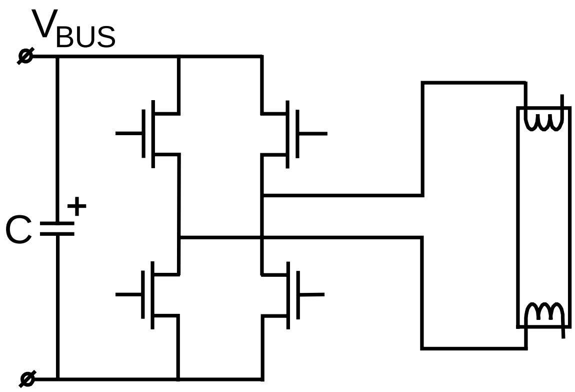


Fig.1. Topology of proposed lamp driver.

the T_{on} time (Fig. 2), clamped to zero during the T_{off} time and then clamped to the bus at reverse polarity. The duty cycle D is defined as T_{on}/ T_s where T_s is half the switching period. At first glance this would look like a dangerous thing to do: feeding the lamp by a voltage source. However, if one adds now a feedback loop (Fig. 3) that controls the current of the lamp, the lamp will see a current source. For the sake of simplicity we have used in the experimental circuit the average of the rectified current of the lamp (I_{av}) as the feedback signal. As the bus voltage changes, the duty cycle (D) will change and the average of rectified current and rms current (I_{rms}) will not track:

$$I_{av} = I_{pulse} \cdot D \tag{1}$$

$$I_{rms} = I_{pulse} \cdot \sqrt{D} \tag{2}$$

where I_{pulse} is the current pulse amplitude.

Since the rms current governs the power of the lamp, it should be used in a practical application as the feedback signal, to achieve constant power operation. However, as far as the output impedance is concerned, both the average of the rectified current and rms current feedback will make the driver look like a current source. Since the discrete electronic circuitry needed for rectification and filtering is much simpler than a circuit that computes rms values, we chose to adopt in this study the average current scheme.

The expression for the output impedance of a closed loop negative feedback system ($Z_{of}(s)$) is:

$$Z_{of}(s) = R_o \cdot (1 + LG(s)) \tag{3}$$

where:
R_o= output resistance of the power stage in open loop,
LG(s)= loop gain of system.

Hence, by proper selection of LG(s), while taking into account the dynamics of the fluorescent lamp [6-8], the output impedance can be tailored to behave as a stable current source.

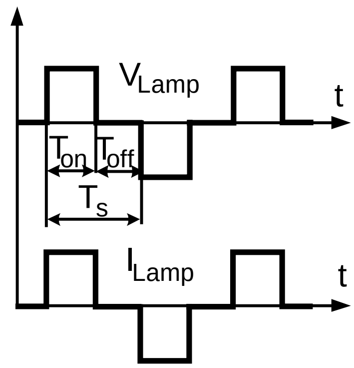


Fig. 2. Lamp voltage and current when driven by proposed lamp driver.

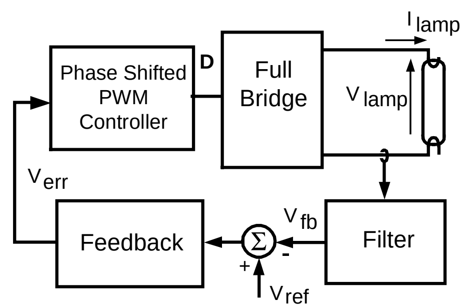


Fig. 3 Active current source scheme.

III. CONTROL LOOP DESIGN CONSIDERATION

The frequency (f) dependent small signal transfer function between the voltage across a lamp, $V_{lamp}(f)$, and the current through it, $I_{lamp}(f)$, is defined as the incremental admittance of the lamp $Y_{inc}(f)$. Applying the behavioral model of the fluorescent lamp (Fig. 4), one can easily obtain $Y_{inc}(f)$ by SPICE simulation [7, 8]. To this end we estimated the constants of the lamp that was used in the experimental stage of study (9W Osram Dulux). The constants include a nonlinear fit to the V-I characteristics of the lamp, and the value of the time constant (R_iC_i in Fig. 4). The definition of the model's dependent sources and the extracted parameters were:

$$E_1 \equiv \{i(lamp)\}^2 \tag{4}$$

$$E_2 \equiv \sqrt{v(p)} \tag{5}$$

$$G_1 \equiv \frac{v(lamp)}{\left(\frac{26.3}{(v(rms))^{1.35}}\right)} \tag{6}$$

$$R_iC_i = 50\mu S \tag{7}$$

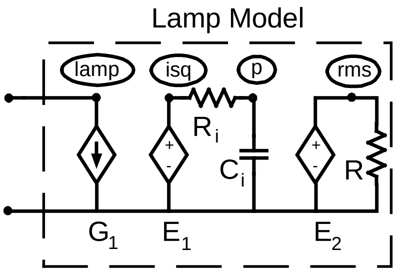


Fig. 4. SPICE compatible equivalent circuit of a fluorescent lamp. See text for definitions of dependent sources.

The denominator of (6) represents the high frequency static resistance of the lamp. Notice that v(rms) represents the voltage coded rms current of the lamp [7, 8]. The expression for the current dependent lamp resistance is extracted by nonlinear curve fitting to the experimental V-I characteristic of the lamp (rms values). In previous studies we applied a linear or polynomial curve fitting [4,7,8] while here we used a power fit. The polynomial and power fit offer a better match over a wider current range. The power fit used here is more compact as it includes only two parameters: the factor term (in this case 26.3) and the power term (1.35).

By inserting the experimental parameters in the model and running a SPICE based AC analysis (around the nominal operating point of 170mA) we obtained the incremental admittance of the lamp (Fig. 5). The simulation was carried out on OrCad version 9.1 simulator. The simulation results of Fig. 5 reveal that at frequencies above about 10kHz the incremental admittance of the lamp is practically of a resistive nature. Consequently, if the bandwidth of the feedback loop is say, 5kHz or higher, the system could be easily stabilized. Since the phase shift at 5kHz is about 45^0, a first order feedback network that is designed for an overall cross over frequency of 5kHz, would provide a stable system. This cross over point is sufficiently lower than the experimental drive frequency (120kHz), so possible aliasing problems are avoided.

The loopgain, magnitude and phase, of the experimental unit are shown in Fig. 6. The high gain at low frequency (about 41db) ensures good current stability while the phase margin of 45^0, at the cross over frequency of 5kHz, guarantees a well-behaved dynamic response.

IV. CREST FACTOR

A major concern of electronic ballast designer is the value of the current crest factor (CF) defined as:

$$CF = \frac{I_{pulse}}{I_{rms}} \tag{8}$$

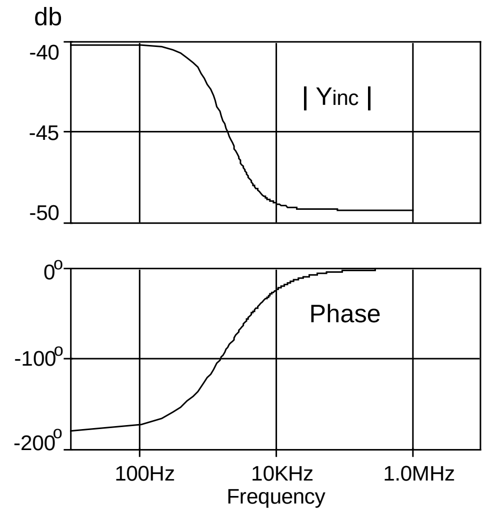


Fig. 5. Incremental admittance of experimental lamp obtained by simulation.

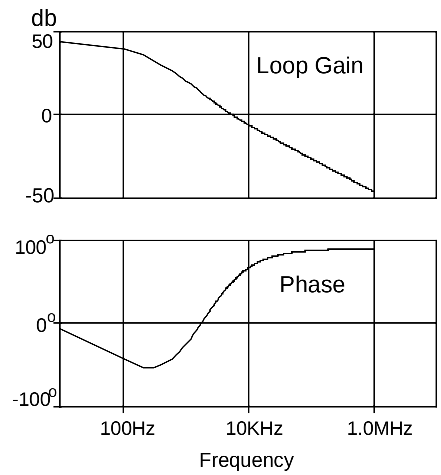


Fig. 6. Loop gain (amplitude and phase) of experimental system. Phase margin= 45^0.

High CF is considered harmful as it might shorten the life of the lamp. A CF value of about 1.7 is considered a safe upper limit. In pulse operation, proposed here, the CF is a function of the duty cycle:

$$CF = \frac{1}{\sqrt{D}} \tag{9}$$

This relation is depicted in Fig. 7. It is evident that safe operation can be obtained down to relatively low D values (0.35). This implies that the proposed pulse ballast will be able to accommodate a rather large variation in the bus voltage.

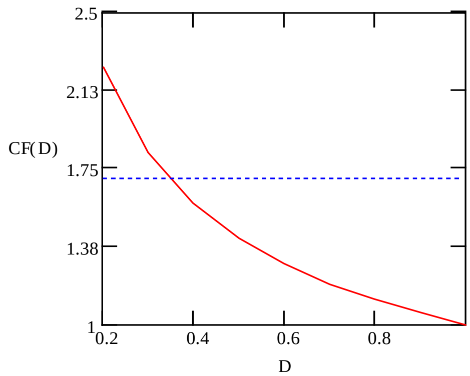


Fig. 7. Crest factor as a function of duty cycle of proposed fluorescent lamp driver. Horizontal line: CF=1.7

V. EXPERIMENTAL RESULTS

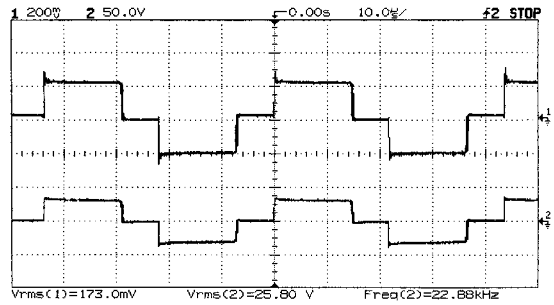
Experiments were conducted on a 9W lamp (Osram Dulux). The switching frequency was about 120kHz. Some experiments were run at 22kHz, but the results were practically the same. The bus voltage was varied in the range of 60V to 120V while the rms current of the lamp was adjusted in the range of 70mA to 200mA. The nominal lamp current is 170mA. Comparison was made to the performance of an electromagnetic ballast and a conventional HF electronic ballast. Light output was compared by measuring the luminous flux of the lamp at a fixed distance from the tube.

Typical experimental lamp waveforms for 22kHz drive are shown in Figs. 8a,b. The difference between the two cases is the bus voltage (66V and 95V). As pointed out earlier, the feedback signal of the experimental unit was the rectified average current of the lamp. However, to help compare the two cases of Figs. 8a and 8b, we have adjusted the reference signals such that the rms currents of the lamp were identical (170 mA). For the set rms current of the lamp, duty cycle D was automatically adjusted by the feedback loop to comply with the bus voltage.

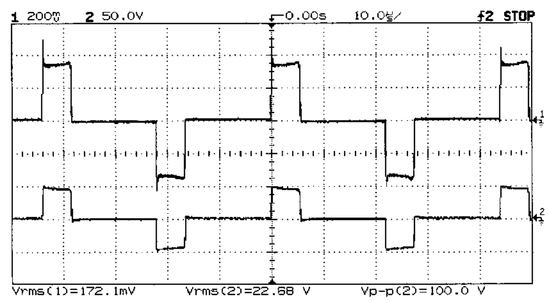
Comparison between the light output of the proposed pulse ballast to the conventional ones suggests that the light output of the new ballast is somewhat higher than that of the electronic ballast (Fig. 9). The V-I characteristics of the lamp under pulse operation were found to be similar to the one measured under the conventional HF drive (Fig.10).

Despite the wide variation of lamp pulse voltage (V_{pulse}) and pulse current (I_{pulse}) when the bus voltage is changing, lamp resistance (R_{lamp}) is still only a function of lamp rms current and hence lamp power. This can be seen in Fig. 11, which displays results for two different rms lamp currents. It is evident that when the rms current is constant, the ratio of pulse voltage to pulse current is fixed:

$$R_{lamp} = \frac{V_{pulse}}{I_{pulse}} = f(I_{rms}) \qquad (10)$$



(a)



(b)

Fig.8. Experimental waveforms for two bus voltages: (a) 66V and (b) 95V. Upper trace: lamp current, 200mA/div. Lower trace: lamp voltage, 100V/div. Horizontal scale: 10uS/div. Lamp current: 170mArms.

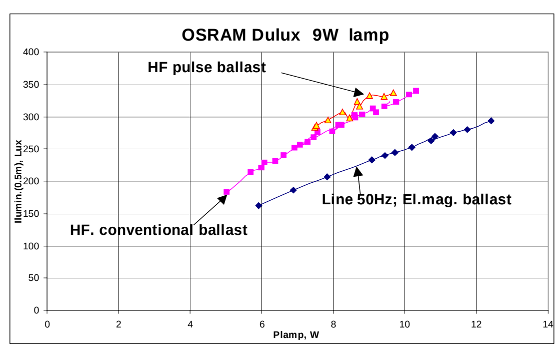


Fig. 9. Light output (relative scale) versus lamp power of fluorescent lamp when driven by proposed driver (HF pulse ballast), HF conventional ballast and electromagnetic ballast.

This result implies that when driven by high frequency pulses, the lamp maintains a resistive nature over the high frequency cycle. This is evidently due to the fact that when the drive frequency is high, as compared to the plasma time constant, the charge density within the lamp does not change much over the high frequency cycle. Hence, for all practical purposes, the lamp can be considered to be a pure resistor if

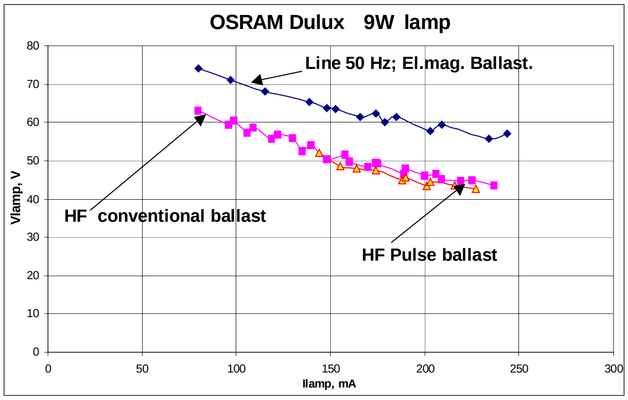


Fig. 10. V-I characteristics of fluorescent lamp when fed by proposed driver (HF pulse ballast), HF conventional ballast and electromagnetic ballast. V, I are rms values.

the drive frequency is sufficiently high. When the lamp is driven by proposed ballast, this equivalent resistor is connected to the bus (bipolar) during the 'on' period and shorted out during the 'off' time.

VI. DISCUSSION AND CONCLUSION

The results of this pilot study suggest that a fluorescent lamp can be safely and effectively driven by an electronic current source with no series passive elements. The design of the feedback network needed to ensure dynamic stability can be based on the behavioral model of the fluorescent lamp as discussed above.

This study did not address the issue of filament warm-up and ignition. The experimental unit applied an auxiliary starter to ignite the lamp (cold ignition, no filament heating). Practical solution to the warm up and ignition problem could be based on a resonant network that can be driven by same driver at a high frequency. If the warm up and ignition frequency is high enough, the physical size of the resonant network could be rather small.

Another issue that needs some attention is the generation of the bus voltage. Since the bus voltage is imposed on the lamp, it should be kept within the limits of V_{lamp} to V_{lamp}/D_{min}, where D_{min} is lower limit of the duty cycle. This range depends on the type of lamp used. For the experimental lamp (9W Osram, Dulux) the range would be from 65V to about 120V. This would imply that for a line fed ballast, a step down converter would be needed.

An additional concern that should be investigated is the effect of the pulse operation on lamp life. The increase in the light output suggests that the pulse-drive results in a somewhat higher electron temperature. Higher light output is indeed desirable, but the implications on lamp life, are of serious concern.

Notwithstanding the open issues that clearly need further investigation to solve, the present study demonstrates the possibility of operating fluorescent lamps in pulse mode. Once the series ballasting element is removed, a ballast-on-a-chip seems to be closer to reality.

ACKNOWLEDGMENT

This work was supported by a grant from General Electric's Corporate Research and Development center.

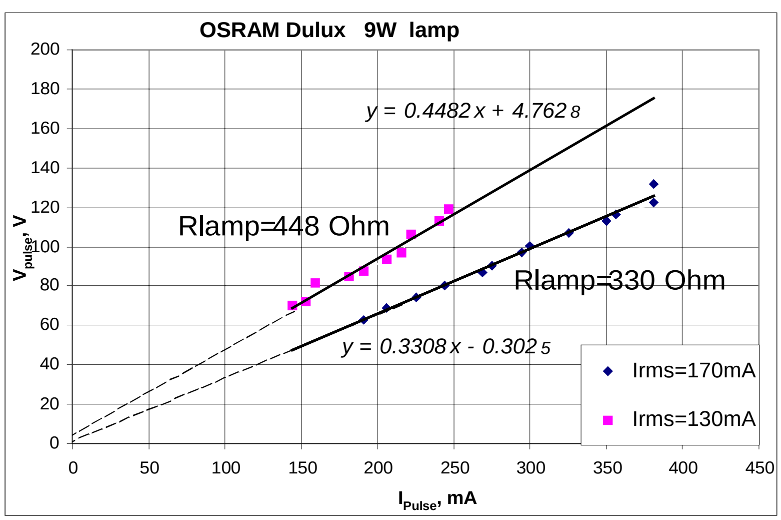


Fig. 11. Lamp pulse voltage and pulse current for two rms currents.

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