Multi-Lamp High-Power-Factor Electronic Ballast Using a Fixed-Frequency Self-Oscillating Driver

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Abstract – This paper presents a fixed-frequency self-oscillating high-power-factor electronic ballast supplying four independent lamps. The fixed-frequency self-oscillating driver is achieved adding a LC series filter supplying a small resistor. The primary winding of the self-oscillating transformer is the series inductor of the filter. So, if one or more lamps are damaged, the switching frequency will not change. To achieve the power-factor-correction, it is used a passive method, based on a modified valley-fill filter. In order to prove the proposed idea, it is shown the simulation and experimental results of the self-oscillating electronic ballast supplying four independent lamps.

Key-Words: Multi-Lamp, High Power Factor, and Self-Oscillating.

1 Introduction
Fluorescent lamp performance is improved when the lamps are supplied by electronic ballasts instead of electromagnetic ballasts, due to theirs merits, such high efficacy, low audible noise, longer lamp useful life, small size, light weight, and without flicker [1].

Self-oscillating electronic ballasts are well known in the literature, due to its simplicity and low cost. However, the application of this circuit is, generally, limited to one-lamp-ballasts, because of the self-oscillating switching frequency, which is dependent on the load [2]. Multi-lamp electronic ballasts commonly use imposed-frequency integrated circuits to drive the switches, which makes the ballast dependent on a specific dedicated circuit. Besides, luminaries to supply four lamps are a great area of artificial illumination [3].

Another point of concerning in the area of electronic ballasts is about the power quality. To solve this problem, there are power-factor-correction (PFC) active and passive methods. Most used active method is the boost converter working in a discontinuous conduction mode, in a single stage mode. However, the boost converter circuit increases the voltage stress in the main device, and it is dissipative and not cost-effective because it operates with high peak triangular shape current. Besides, to work with variable load and no load, it demands additional power devices, passive components and control circuit [4]. Because of this, many authors prefer to use PFC passive methods. Among these, valley-fill filter and its modifications are the most used. However, many valley-fill filter circuits do not answer to the IEC 61000-3-2 Class C standard. Therefore, this work intends to choose a circuit that answers the standard harmonic limits [5].

2 Fixed-Frequency Self-Oscillating Driver
The idea to develop the fixed frequency self-oscillating driver is to substitute one of the lamps by a resistor, and to connect the primary winding of the self-oscillating transformer in series with it. It is necessary to decrease the resistor’s power to a small value in order to guarantee good ballast efficiency. It can be used a simple LC series circuit in series with a resistor. Besides, the filter inductor can be the same primary winding of the self-oscillating transformer, using only one magnetic element (L_p – L_m1 – L_m2). Proposed circuit, supplying four independent lamps, is shown in the Fig. 1.

2.1 Fixed-Frequency Self-Oscillating Driver Design Procedure
In order to develop the design procedure of the proposed idea, it is necessary to analyze the stability of the self-oscillating driver when it is decreased the resistor’s power. Extended Nyquist Criterion is used to develop this stability analysis. The design can be divided on some steps, described below.

2.1.1 Output Filter Design
The output filter determines the resistor’s power. At first, it is necessary to determine the phase angle, which is the angle between the voltage applied to the filter and the filter current, and it is shown in (1).

\[ \phi(P) = -\arctan\left(\frac{\sqrt{P \cdot R}}{V_{ac}} - 1\right) \]  

Where:
- \( V_{ac} \) is the rms value of the voltage applied to the filter;
- \( P \) is the defined resistor’s power;
- \( R \) is the defined resistor’s value.
Now, choosing a usual value for $C_S$ (15 nF), we determine the value of inductor $L_P$ by (2).

$$L_P(\phi, C_S) = \frac{R.C_S.\omega\tan(-\phi) + 1}{C_S.\omega^2}.$$  \hspace{1cm} (2)

Where:
- $\omega$: is the imposed angular switching frequency.

### 2.1.2 Self-Oscillating Circuit Design
Self-oscillating switching frequency can be found using the Extended Nyquist Criterion. Considering the LC series output filter, the self-oscillating magnetizing inductance can be determined by (3).

$$L_{m1} = L_{m2} = -\frac{1}{K.\omega.n} \left[ (1 - \frac{L_P.C_S.\omega^2}{\alpha C_S - \omega^2.L_P.C_S^2})^2 + \frac{R^2.C_S^2.\omega^2}{\alpha C_S - \omega^2.L_P.C_S^2} \right].$$  \hspace{1cm} (3)

Where:
- $K$: is the relationship between the voltage applied to the filter and the zener voltage;
- $n$: is the self-oscillating transformer turn ratio. This value has to be determined in order to polarize the zener diodes using the current transformer $L_P - L_{m1} - L_{m2}$.

### 3 Self-Oscillating Driver Simulation Results
In order to prove the proposed methodology, it is presented a project example. The electronic ballast supplies four independent lamps (OSRAM FO 32W / 841) that are represented by their model developed in [6], as shown in the Fig. 1. Output filter values are calculated based on [7]. The simulation results are shown to prove that, using the component values calculated by (1), (2), and (3), the self-oscillating driver keeps its switching frequency constant (40 kHz) when the ballast is supplying 1, 2, 3, or 4 lamps. Fig. 2 shows the self-oscillating driver voltage, which determines the switching frequency, for the ballast supplying 1 and 4 lamps, and the frequency value keeps constant. Additional information is presented in the next section in the experimental results.

### 4 Power-Factor-Correction Circuit
Among the various configurations of the valley-fill filter presented in the literature, it was chosen a circuit that meets the IEC 61000-3-2 Class C requirements. This circuit, supplying one lamp, is shown in the Fig. 3. It can be seen that this proposed circuit only uses passive components.

$C_\text{f3}$ is used to decrease the DC bus voltage ripple, caused by the power-factor-correction circuit. The current that flows by this capacitor causes a voltage increase in the capacitors $C_n$ and $C_p$. Therefore, this circuit does not need any circuit to correct the crest factor value.

### 5 Experimental Results
The experimental prototype was developed putting both ideas together: the fixed-frequency self-oscillating driver, and the passive power factor correction circuit. According to Fig. 4, component values are presented below:

- $C_{f1}$, $C_{f2}$: 100 µF;
- $C_{f3}$: 6.8 nF;
- $C_P$: 10 nF;
- $C_{P1}$, $C_{P2}$: 22 nF;
- $C_Q$: 100 nF;
- $C_r$: 82 nF;
- $C_S$: 15 nF;
- $D_1$ – $D_9$: 1N4007;
- $DZ_1$ – $DZ_4$: zener 12 V;
- $L_F$: 4 mH;
- $L_{m1}$, $L_{m2}$: 1 mH;
- $L_P$: 16 mH;
- $L_S$: 1.7 mH;
- $M_1$, $M_2$: IRF 740;
- $R_{FF}$: 20 kΩ;
- $R_Q$: 220 kΩ.

Proposed circuit is shown in Fig. 4. Some experimental results are presented to prove the ballast behavior, in the Fig. 5: (a) presents ballast input voltage and current, to show the high power factor of the ballast for 1 lamp operation and (b) 4 lamp operation, (c) presents the ZVS operation of the ballast, and (d) presents the lamp low crest factor (1.6). Some numerical results are presented in the Table 1, among them: power factor (PF), crest factor (CF), input power ($P_\text{in}$), output power ($P_\text{out}$), ballast efficiency ($\eta$), switching frequency ($f_s$), and power dissipated in the driver ($P_{\text{com}}$).

In Fig. 6 it is presented results of lamp starting, for the ballast supplying 1 and 4 lamps. These waveforms prove the lamp starting for all load conditions.

In Table 2 it is presented the result of the input current FFT, to confirm that the ballast meets the IEC 61000-3-2 Class C requirements.

<table>
<thead>
<tr>
<th>Table 1 – Experimental Results.</th>
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<td>PF</td>
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<td>CF</td>
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<td>$P_{\text{in}}$ (W)</td>
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<tr>
<td>$f_s$ (kHz)</td>
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<td>$P_{\text{com}}$ (W)</td>
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Fig. 1 – Fixed-frequency self-oscillating driver.

(a) 4 lamps (40.2 kHz).

(b) 1 lamp (39.9 kHz).

Fig. 2 – Drive voltage simulation result.

Fig. 3 – Power-factor-correction proposed circuit.
Fig. 4 – Experimental prototype.

(a) Line voltage and current for 1 lamp operation (100V/div; 500mA/div)

(b) Line voltage and current for 4 lamp operation (100V/div; 500mA/div)

(c) Switch voltage and current for 4 lamp operation (50V/div, 1A/div)

(d) 1 Lamp voltage and current envelopment for 4 lamp operation (100V/div; 200mA/div)

Fig. 5 – Experimental results.
Table 2 – FFT Result.

<table>
<thead>
<tr>
<th>harmonic</th>
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<td>4,2</td>
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<td>5</td>
<td>4,7</td>
<td>5</td>
<td>3,4</td>
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<td>11ª - 39ª</td>
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Fig. 6 – Lamp starting result.

6 Discussion

Proposed ballast is a great solution to 4-lamp luminaries. At first, the lamps have independent behavior. Therefore, if one or more lamps are damaged, the others still work.

Besides, the self-oscillating driver is a low cost and reliable circuit. Its main problem was that the conventional self-oscillating driver is dependent on the load, changing its switching frequency when the load changed. So, proposed circuit is a great alternative to supply a variable load. And, its application is not limited to electronic ballasts.

It has been done a study among many valley-fill circuits, which resulted in the circuit presented in the Fig. 3. This circuit uses only passive components, which means that this is a simple, cheap and reliable circuit. And, this circuit meets the IEC 61000-3-2 Class C requirements for all load conditions.

7 Conclusion

This paper presented a simple, and low cost high-power-factor electronic ballast, to supply four independent lamps. The ballast presented power factor higher than 0.95, efficiency higher than 90%, ZVS operation, crest factor lower than 1.7, and almost invariant switching frequency, for all load conditions. Besides, the ballast does not need any dedicated circuit to work.

References: