A Single-Switch Electronic Ballast for Fluorescent Lighting

André da Silveira Amaral Augusto A . D. de Mattos Dalton Luiz Rech Vidor
ULBRA-Luteran Univertsity of Brazil
Rua Miguel Tostes, 101
91.420-280 - Canoas – RS – Brazil
dvidor@cpovo.net

Abstract: This work describes an electronic ballast for fluorescent lamps that use a single controlled switch. This converter combine the isolated forward converter with the boost converter to achieve high power factor and supply the lamp with high frequency. In spite of these features, the structure could limit the in-rush capacitor current.

I – Introduction

In the world, a great amount of electric energy is consumed in artificial illumination. In this cases high efficient systems and high power factor are desirable.

The fluorescent lamp is a good choice to improve the illumination system's performance because it has high efficacy (lm/W), but, at 50Hz or 60Hz systems, it produces flicker in the twice frequency and requires a ballast. Some electromagnetic ballasts, instead of flicker, present poor power factor and considerable weight and size.

We can make it better designing ballasts that works at high frequency, improving the efficiency and reducing noise and weight, and introducing devices or configurations that increase the power factor.

Companies and researchers are investigating the best way to do these converters with lower cost and have presented solutions that use a close-loop circuit, or two stages, or two or more switches to improve the power factor. The converter studied here presents some features like high power, high frequency and simplicity.

Combining the forward converter, that supply the energy to the fluorescent lamp at high frequency, with the boost converter the input current can be drained at almost sinusoidal shape. Only one controlled switch is used without close-loop control. A self-oscillating configuration can improve the simplicity and reduce cost and the transformer magnetization inductance reduces the input current peak in the turn on process.

This paper presents a topology analysis, operation stages, design equations and considerations, simulation results and some practical results.

II – Topology

In the figure 1 the converter is shown. The circuit is formed by one input inductor, a full bridge diode, one transformer, one switch, one capacitor and a conventional resonant circuit LCC supplying the lamp.

In order to follow the rules and recommendations about EMI, and EMC, and line current THD a second order input filter and shielding must be used but not presented and included in the evaluation circuit.

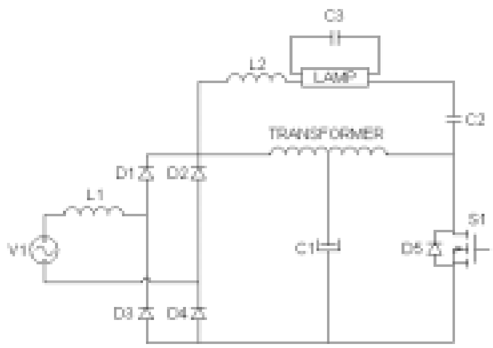


Figure 1 – Converter Topology

The controlled switch operates in high frequency and constant duty cycle (f=20kHz and D=0,49).

The circuit formed by input inductor, full bridge rectifiers, transformer and controlled switch operate as a boost converter in the turn on mode when the transformer demagnetization occur, when the switch is turned on, the input inductor is discharged through the transformer and it’s similar a boost converter in the turn off mode. At the same time that the circuit operates as a boost converter, the transformer, and the switch, and the resonant LCC circuit provide a high frequency and lower crest factor lamp current.

III – Operation Stages

The circuit can be studied considering the high frequency and low frequency sections separately, but the low frequency operation isn’t presented here by considering very simple.

For analysis simplification we consider the following assumptions:

- The input voltage is constant at the switching period,
- The switches and diodes are ideal,
- The resistances losses are negligible,
- The C1 is too large that the voltage is ripple free,
- Fluorescent lamp is modeled as a resistance in steady state.

First Stage

In this stage S1 is turned on and the capacitor voltage is applied to the transformer’s primary right side. The inductor L1 will discharge its energy through the transformer’s left side and it will charge the capacitor and will supply the circuit. The voltage applied to the LCC series parallel resonant circuit and fluorescent lamp will be double of the capacitor voltage.

Since V1 remains constant during the period that S1 is on, the inductor voltage is the difference between the transformer’s primary left side voltage and V1 and the inductor current decrease linearly. At the same time the magnetizant current will increase and some energy will be stored on this element.

In the figure 2 this stage is shown.

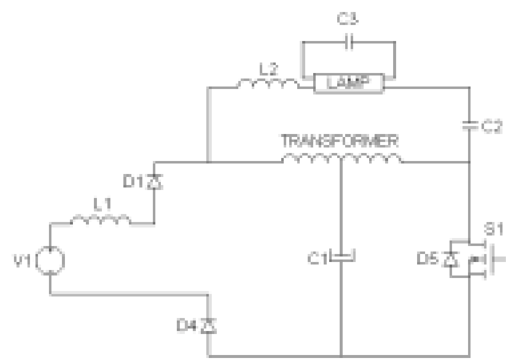


Figure 2 – First stage.

Second Stage

When the switch S1 is turned off, as shown in figure 3, the energy stored by the transformer magnetizant will be discharged through rectifier bridge. The voltage applied in the LCC series parallel resonant circuit will change its polarity.

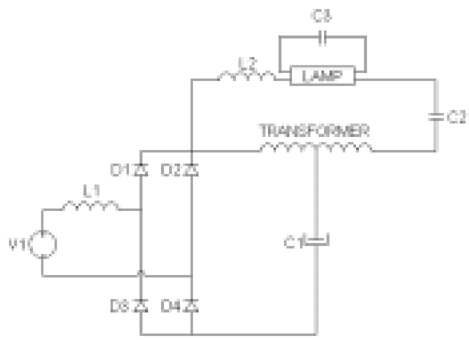


Figure 3 – Second Stage.

As the rectifier bridge is operating as freewheeling diodes, the inductor voltage is equal to V1 and the inductor current increase linearly.

Third Stage

The third stage happens when the transformer's magnetizant current falls and became equal to the difference between the inductor L1 and L2 currents. The stored energy in L1 and transformer magnetizant will be discharged slowly through V1, rectifier bridge and C1.

In order to improve the lamp current crest factor this stage will be done as short as possible.

In the figure 4 the circuit configuration is shown.

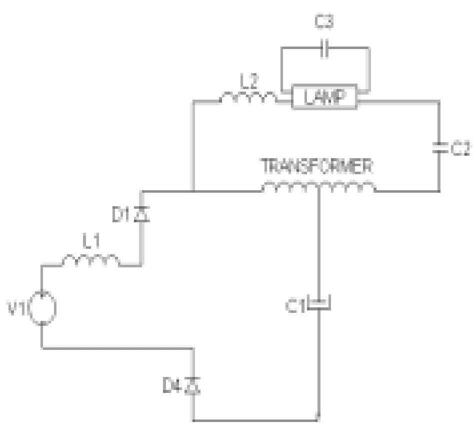


Figure 4 – Third stage.

Start-up Phase

At the same way as shown in figure 2 the input current in the start-up phase flows through the transformer, rectifier bridge, S1 intrinsic diode and L1. The start-up operation mode makes the input current be reduced by the magnetizant and transformer voltage ratio.

IV – Theoretical Analysis

The LCC series parallel resonant circuit analysis has been studied and presented in lots of papers [1,2,5]. As shown at reference [5] the components are designed and calculated by the following equations:

$$C3(\theta) = \frac{1}{\omega R V_{rms}^2}\sqrt{\frac{P}{R}\left(R^2 + \left(R.\tan(\theta)\right)^2 - 1\right)}$$

$$L(\theta) = \frac{R.\tan(\theta).\omega^{-1} + C3(\theta).R^2}{1+\omega^2 C3^2(\theta)R^2} + \frac{1}{C2.\omega^2}$$

Where:

- $V_{rms} = \frac{\sqrt{2}.V_{pp}}{\pi}$ That is the square wave rms voltage applied to LCC,

_ The output power is

$$P(\theta) = \frac{V_{rms}^2 R\left(1+w^2.C2^2(\theta).R^2\right)}{R \ + w^2\left[\left(L(\theta) - \frac{1}{w^2 C2}\right)\left(1+w^2.C3^2.(\theta).R^2\right) - R^2.C3\right]}$$

- R is the lamp equivalent resistance,

-And

$$\theta = \tan^{-1}\left[\frac{w}{R}\left(L - \frac{1}{w^2 C2}\right)\left(1 + C3^2.R^2.w^2\right) - R^2.C3\right]$$

The input peak current follows a sinusoidal shape and is given by:

$$I_{in_{peak}} = \frac{V1.D}{L1.f_{S1}}$$

Where:

$V1 = V_{\max}.sin(2\pi f_{LINE}t)$ and

$D = \frac{t_{on}}{T}$

f_{S1} is the switching frequency.

Considering that the input current is averaged on a switching period, the expression became:

$$Iin = \frac{V1.Vc1.D^2}{L1.f_{S1}.(2.Vc1 - V1)}$$

Where: V_{C1} is the capacitor C1 voltage.

As V_{C1} is at least equal to Vmax, the input current have almost sinusoidal shape. The design must do the voltage V_{C1} as bigger as possible in order to reduce the input current THD, but we notice that the transformer help us by a factor two as we can see at Iin expression.

The value of input rms and average currents can be obtained using classics expressions in the Iin equation. Multiplying the rms input current by the rms input voltage we can draw the total input power.

$$Iin_{rms} = \sqrt{\frac{1}{T_{line}}\int Iin.dt}$$

$$Pin = V1_{rms}.Iin_{rms}$$

The displacement between the input current and voltage is near zero and the power factor is obtained by:

$$PF = \frac{\cos\phi}{\sqrt{1 + THD^2}}$$

The switch voltage is:

$V_{S1}=2.V_{C1}$

And its current is obtained by:

$$I_{S1_{AVG}} = Iin_{AVG} + I_{IsoltatedForward}$$

V – Design Considerations

The converter design is done by a simple way as following:

Selecting a lamp and a line system:

V1=127V

$fline = 60\text{Hz}$

Lamp Power=40W

The input power can be obtained by:

$$Pin = \frac{Plamp}{\eta}$$

Where: η =efficiency

Choosing a maximum voltage across the switch S1 we can obtain the voltage in the capacitor C1 (Let it with a voltage margin factor). Supposing that the input current is almost sinusoidal and that the peak occurs when the line voltage is in the peak too. Select the switching frequency and notice that the duty cycle must be almost 0.5, then we can obtain the input inductance L1 using Iin equation.

The capacitance C1 must be obtained to achieve a low ripple voltage.

The transformer must have a magnetization bigger than ten times the input inductance in order to not disturb the input current in its shape.

Another elements can be obtained as explained in reference [5].

VI – Simulation and Experimental Results

The electronic ballast circuit has been simulated and evaluated to show its performance.

We fix the simulation at the same point of practical results in order to compare this point, but it’s not the main operation point. At this moment some problems limit the prototype.

The main ratings have been as follows:

Vin = 37Vrms,

f_{line} = 60Hz,

Lamp Power = 40W,

f_{SW} = 20kHz,

D=0.48

The main parameters and components of the topology are:

L1 = 95uH,

Lmagnetizant = 5mH,

C1 = 220uF

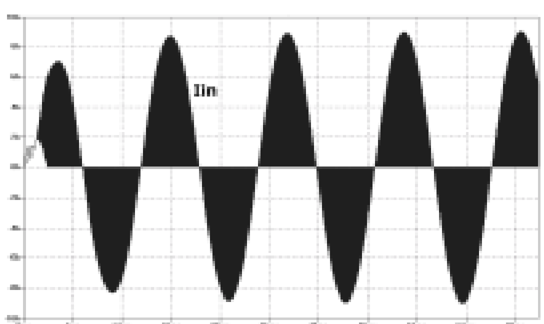
L2=1.085mH

C2=82nF

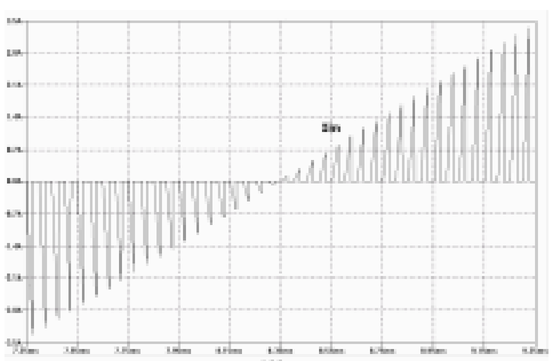
C3=33nF

Rlamp equivalent=16kΩ

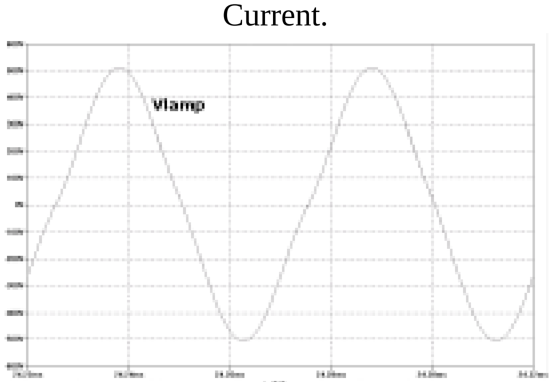
The waveforms found are:



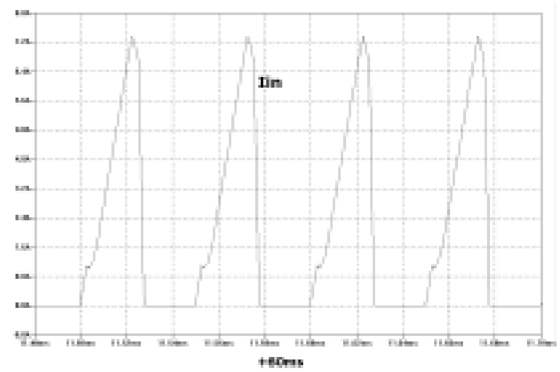
At start-up simulated I_{IN} current.



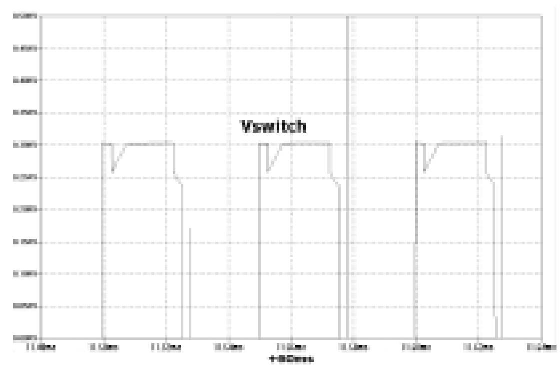
Simulated Input Current.



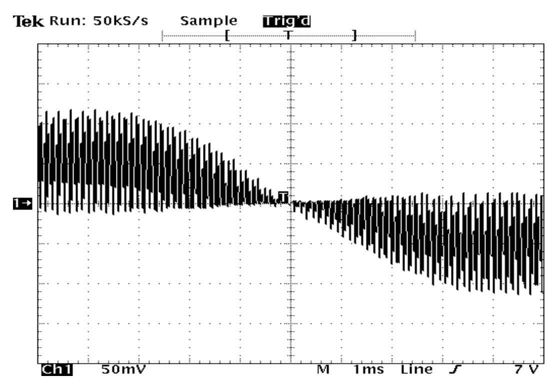
Simulated Lamp Voltage



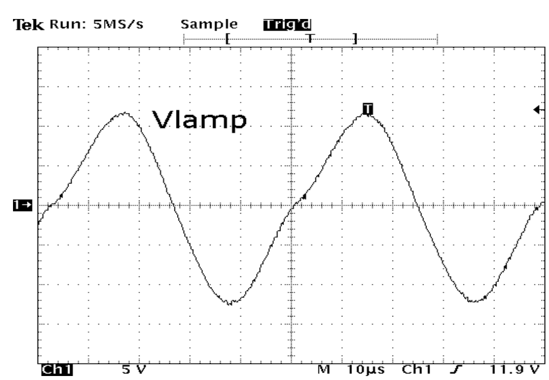
Simulated Input Current.



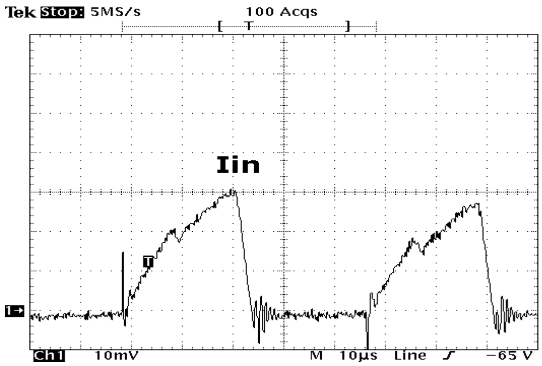
Simulated Switch Voltage.



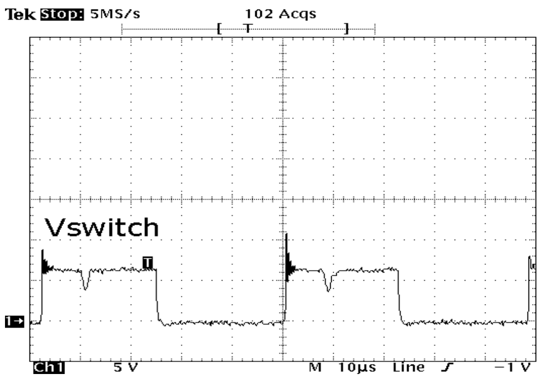
Prototype Input Current



Prototype Lamp Voltage



Prototype Current Iin.



Prototype Switch Voltage.

VII – Conclusions

This paper shows a very low cost and very simple high power factor electronic ballast with only one controlled switch. The topology could supply fluorescent lamps with low crest factor current and absorb a sinusoidal input current with low THD. In spite of these features, the circuit presents lower in-rush current than its counterpart.

This converter is a simple and effective high power factor electronic ballast that mixes a boost and a isolated forward converter controlled by only one switch. The boost converter operating is discontinuous conduction mode. It’s similar to another converters but a careful topology, as shown here, could improve secondary characteristics like in-rush current, number of components, cost and circuit drive complexity.

This idea, of mix two converters, could be choose to various applications that need supply a load with fixed voltage and drive a sinusoidal current reducing cost and complexity.

VIII – References

[1] R.N. Prado and S.A. Bonaldo. “A High-Power-Factor Electronic Ballast Using a Flyback Push-Pull Integrated Converter” , IEEE Transactions on Industrial Electronics, pp. 796-802, Vol. 46, NO. 4, August 1999.

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[3] Y.Yang and C.Chen, “ Steady State Analysis and Simulation of a BJT Self-Oscilating ZVS-CV Ballast Driven by a Saturable Transformer” , IEEE Transactions on Industrial Electronics, Vol. 46, NO. 2, April 1999.

[4] M.K. Kazierczuck and W. Szaraniec, “ Electronic Ballast for Fluorescent Lamps” , IEEE Transactions on Power Electronics, Vol. 8, pp. 386-395, Oct. 1993.

[5] R.N. Prado, A.R. Seidel, F.E. Bisogno, M.A.D. Costa, “ A Design Method for Electronic Ballast for Fluorescent Lamps”, pp. 2279- 2284, IECON 2000, record.