A NEW BOOST ASSOCIATED WITH A BUCK CONVERTER USING A SINGLE ACTIVE SWITCH WITH SOFT SWITCHING

Lúcio Reis Barbosa* Carlos H. G. Treviso Adriano A. Pereira Fábio B. C. Muniz

* Corresponding Author
Universidade Estadual de Londrina – UEL
Centro de Tecnologia e Urbanismo – CTU
Departamento de Engenharia Elétrica – DEEL
Campus Universitário – Caixa postal: 6001 CEP: 86051-990
Londrina – PR - Brasil
e-mail : lbarbosa@uel.br

Abstract – This paper presents a new topology of a PWM Boost interleaved with a Buck converter. The circuit proposed, having only one active switch, is able to operate with soft switching in a pulse-width-modulation (PWM) way. In addiction such converter provides a high efficient operating condition for a wide load range at high-switching frequency. In order to illustrate the operational principle of this new converter a detailed study, including simulations is carried out. The validity of this new converter is guaranteed by the obtained results.

I. INTRODUCTION

Higher switching frequencies allow reduction of the magnetic component sizes of the DC-DC converters. Unfortunately, high switching frequencies cause higher switching losses and greater electro-magnetic interference (EMI), having as consequence low efficiency in hard switching converters.

To reduce the switching losses, initially risen the snubbers. Example of these snubbers can be found in the references [1], [2] and [3].

Later on appeared the quasi-resonant converters (QRCs) were proposed in [4]. However, some of their characteristics such as load limitations and control difficulties due to variable frequency operation restrict the practical use of these converters.

Since the pulse width modulation quasi-resonant converters (PWM-QRC) operate with fixed switching frequency they do not present the control problem like the QRCs [5]. On the other hand they present all the other disadvantages of the QRCs that limit their applications.

Nowadays there are many converters that do not present the limitations described above [7-11]. An example of these converters can be seen in the reference [6]. Although this converter presents several advantages, its main switch turns off hard and has high current stress.

The converter presented in this paper is a new structure using a Boost associated with a Buck converter with soft-single-switched (SSS) characteristics. It is composed by only one active switch, what reduces a lot the electro-magnetic interference and the switching losses.

The main advantage of this topology, besides its simplicity, it is the robustness of the topology.

It will be presented in the posterior sections a detailed analysis, to emphasize the characteristics of this converter.

II. A BOOST ASSOCIATED WITH A BUCK CONVERTER USING A SINGLE ACTIVE SWITCH WITH SOFT SWITCHING

The Fig. 1 shows the proposed circuit. The inductor Lr and the capacitor C_r are used to provide ZCS and ZVS (respectively) turning on the switch S_1.

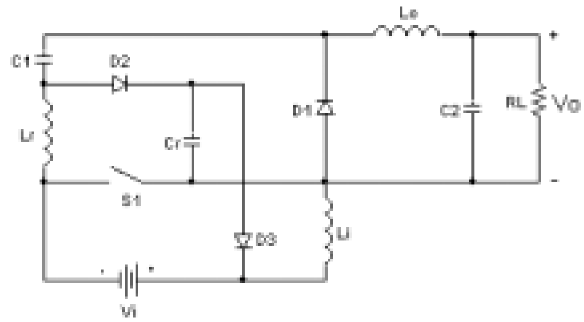


Fig. 1 – Buck / Boost PWM single-soft-switched

As it can be seen, the proposed converter is consisted of the one conventional Boost PWM associated with a Buck PWM converter, in which is added the resonant network composed by the elements C_r, L_r, D_2 and D_1, which are connected as shown in Fig. 1.

The branch composed by L_r, D_2 and D_3 is used to charge C_r with voltage V_{C1}, before turning on S_1, and with the voltage $-V_i$ before turning off S_1. Thus, S_1 will turn in a ZCS and ZVS way, respectively.

The operating states of this converter are presented in the next figures. In the following discussions and in the circuit analysis, for simplicity, we assumed that:

- ac ripples in circuit filters are entirely negligible;
- all the components and switches are ideal;
- the circuit is in steady state;
- the switching frequency is much smaller than the resonance frequency of the circuit.

First Stage [$t_0;t_1$] $\Delta t_1 \rightarrow$ LINEAR DISCHARGE OF L_r :

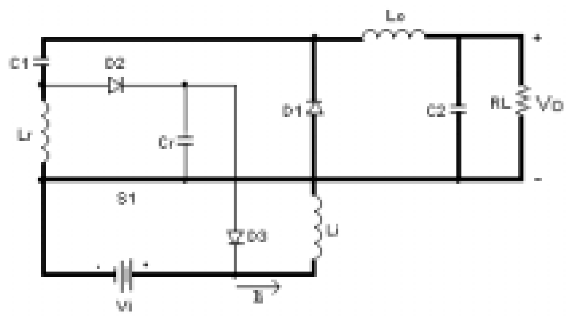


Fig. 2 - First Stage [$t_0;t_1$]

This stage begins when S_1 is turned on. The current in the resonance inductor decreases linearly from the input current (I_i) to -I_0. When it happens, D_2 is on and the stage finishes.

Second Stage [$t_1;t_2$] $\Delta t_2 \rightarrow$ FIRST RESONANT STAGE :

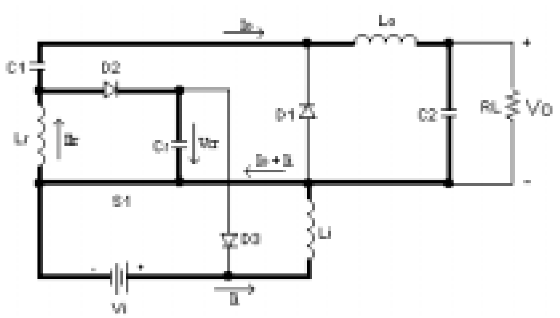


Fig. 3 - Second Stage [$t_1;t_2$]

This stage begins with the conduction of D_2. In this stage happens the resonance between L_r and C_r. V_{cr} decreases from V_{c1} to -V_i. When V_{cr} = -V_i, the diode D_3 is turned on, concluding the stage.

Third Stage [$t_2;t_3$] $\Delta t_3 \rightarrow$ LINEAR CHARGE OF L_r :

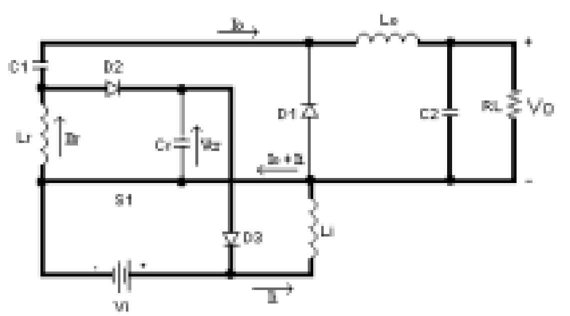


Fig. 4 - Third Stage [$t_2;t_3$]

In this stage V_{cr} remains –V_i due to D_3 conduction, and I_{Lr} increases linearly to -I_o current. At that moment the diodes D_2 and D_3 are turned off concluding the stage.

Fourth Stage [$t_3;t_4$] $\Delta t_4 \rightarrow$ MAGNETIZATION OF L_1:

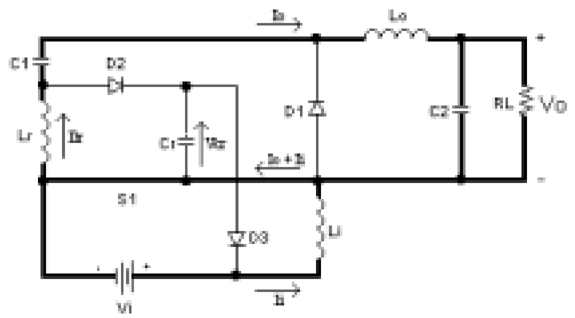


Fig. 5 - Fourth Stage [$t_3;t_4$]

In this stage, the branch V_i , S_1 and L_1 is in conduction. The duration of this stage depends on the duty cycle.

Fifth Stage [$t_4;t_5$] $\Delta t_5 \rightarrow$ LINEAR DISCHARGE OF C_r:

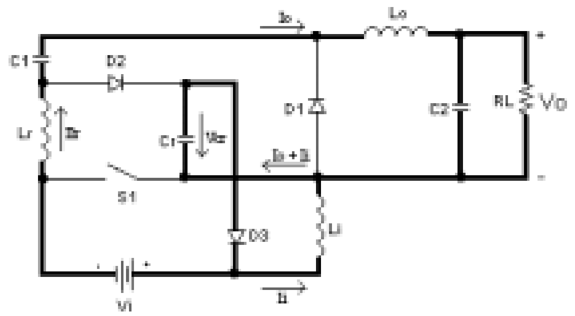


Fig. 6 - Fifth Stage [$t_4;t_5$]

This stage begins when S1 is turned off and it finishes with the conduction of D_1. With the blockade of S_1, the diode D_3 turns on and the resonant capacitor C_r is discharged from -V_i to (V_{C1} – Vi), concluding this stage. This way, the S_1 turning off is under zero voltage (ZVS), since the initial voltage V_{cr} of that stage is V_i.

Sixth Stage [$t_5;t_6$] $\Delta t_6 \rightarrow$ SECOND RESONANT STAGE:

This stage begins with the conduction of D_1, and it finishes with the conduction of D_2. With the conduction of D_1 a resonance takes place between Lr and Cr through the branch C_r, D_3, V_i, L_r, C_1, D_1. In this period, the V_{Cr} voltage will vary from (V_{C1} – Vi) to V_{C1}, when D_2 in turned on concluding the stage.

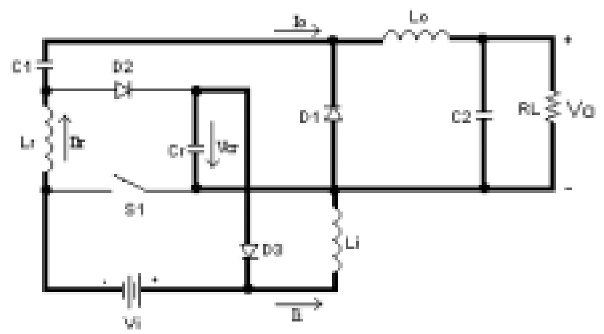


Fig. 7 - Sixth Stage [$t_5;t_6$]

Seventh Stage [t_6;t_7] $\Delta t_7 \rightarrow$ LINEAR CHARGE OF L_r:

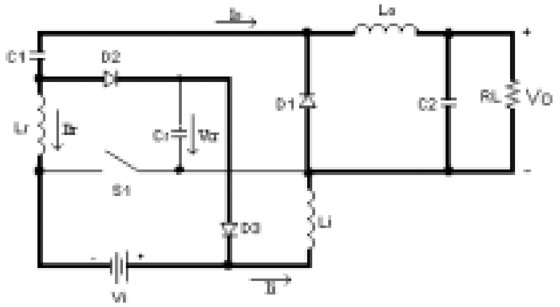


Fig. 8 - Seventh Stage [t_6;t_7]

This stage begins with the conduction of D_2. The current in the inductor L_r will grow linearly until reaching its maximum value (I_i). When it happens, the diodes D_2 and D_3 are turned off concluding this stage.

Eighth Stage [t_7;t_8] $\Delta t_8 \rightarrow$ TRANSFER OF ENERGY:

This stage begins when the current in the resonant inductor reaches Ii and it finishes with the S1 turning on.

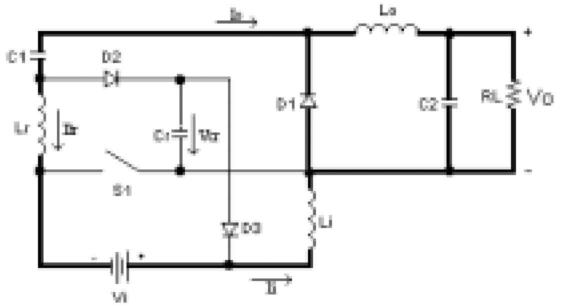


Fig. 9 - Eighth Stage [t_7;t_8] Δt_8

The main theoretical waveforms of the proposed converter are shown in Fig. 10:

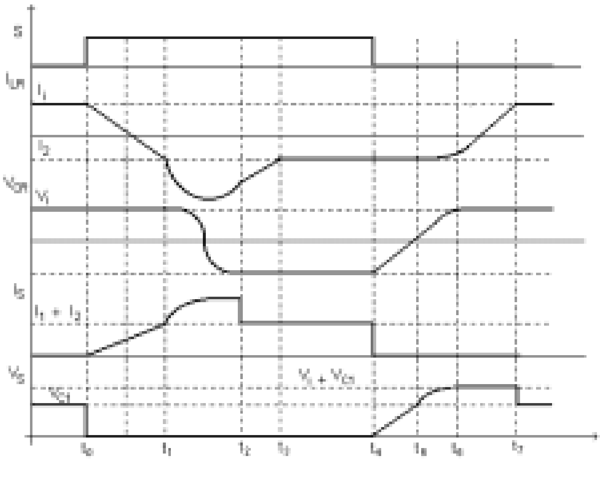


Fig. 10 - Main theoretical waveforms for circuit in Fig. 1

It can be seen above in the illustration that the converter operates in a soft switching way (ZVS and ZCS).

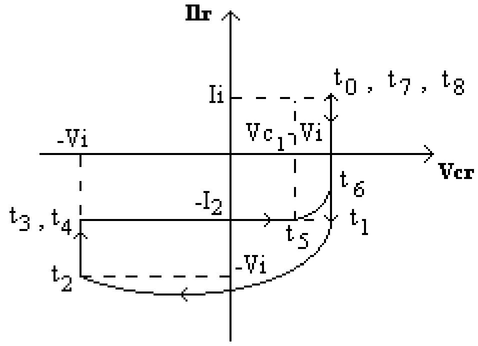


Fig. 11 – State plane for the proposed circuit

Fig. 11 shows the state plane for the proposed converter. It is observed that the maximum value of the Vcr is equal to V_{C1} which is reached at the beginning of the seventh stage *[t_6;t_7]*.

III. CIRCUIT ANALISYS

To determine the voltage gain of the PWM Boost converter, presented in this paper, the following definitions were used:

$$\omega o = \sqrt{\frac{1}{Cr.Lr}} \tag{1}$$

$$\alpha_1 = \frac{Ii}{V_{C1}} \cdot \sqrt{\frac{Lr}{Cr}} \tag{2}$$

$$\alpha_2 = \frac{I_0}{V_{C1}} \cdot \sqrt{\frac{Lr}{Cr}} \tag{3}$$

$$G_1 = \frac{V_{C1}}{Vi} \tag{4}$$

$$G_2 = \frac{V_0}{V_{C1}} \tag{5}$$

A. *First Stage [t_0;t_1]:*

$$V_{CR}(t) = V_{C1} \tag{6}$$

$$I_{Lr}(t_0) = I_i \tag{7}$$

$$I_{Lr}(t) = I_i - \frac{V_{C1}}{Lr} \cdot t \tag{8}$$

$$\Delta t_1 = \frac{\alpha_1}{\omega_0} - \frac{\alpha_2}{\omega_0} \tag{9}$$

B. *Second Stage [t_1;t_2]:*

$$I_{Lr}(t_1) = -I_0 \tag{10}$$

$$V_{Cr}(t) = V_{C1} \cdot \cos(\omega_0 .t) \tag{11}$$

$$I_{Lr}(t) = -I_0\left(1+\frac{\mathrm{sen}(\omega_0 t)}{\alpha_2}\right) \qquad (12)$$

$$I_{Lr}(t_2) = -I_0 - \frac{I_0}{\alpha_2}\cdot\sqrt{1-\frac{1}{G_1^{\,2}}} \qquad (13)$$

$$\Delta t_2 = \frac{\pi - \cos^{-1}\left(-\frac{V_i}{V_{C1}}\right)}{\omega_0} \qquad (14)$$

C. *Third Stage [t_2;t_3]:*

$$V_{CR}(t) = -V_i \qquad (15)$$

$$I_{Lr}(t) = I_{LR}(t_2) + \frac{V_i}{L_R}\cdot t \qquad (16)$$

$$I_{LR}(t) = -I_0 \qquad (17)$$

$$\Delta t_3 = \frac{\sqrt{G_1^{\,2}-1}}{\omega_0} \qquad (18)$$

D. *Fourth Stage [t_3;t_4]:*

$$I_{LR}(t) = -I_0 \qquad (19)$$

$$V_{CR}(t) = -V_i \qquad (20)$$

E. *Fifth Stage [t_4;t_5]:*

$$I_{LR}(t) = I_0 \qquad (21)$$

$$V_{Cr}(t) = -V_i + \frac{I_1 + I_0}{Cr}.t \qquad (22)$$

$$V_{Cr}(t_5) = V_{C1} - V_i \qquad (23)$$

$$\Delta t_5 = \frac{1}{(\alpha_1+\alpha_2)\cdot\omega_0} \qquad (24)$$

F. *Sixth Stage [t_5;t_6]:*

$$V_{Cr}(t) = V_{C1} - V_i + (I_i + I_0)\cdot\sqrt{\frac{L_r}{C_r}}\cdot\mathrm{sen}(\omega_0 .t) \qquad (25)$$

$$V_{Cr}(t_6) = V_{C1} \qquad (26)$$

$$I_{Lr}(t) = -I_0 + I_i\cdot[1-\cos(\omega_0 .t)] \qquad (27)$$

$$I_{Lr}(t_6) = I_i\cdot\left(1-\sqrt{1-\left(\frac{1}{G_1(\alpha_1+\alpha_2}\right)^2}\right) \qquad (28)$$

$$\Delta t_6 = \frac{1}{\omega_0}\cdot\mathrm{sen}^{-1}\left(\frac{1}{G_1(\alpha_1+\alpha_2}\right) \qquad (29)$$

G. *Seventh Stage [t_6;t_7]:*

$$I_{Lr}(t) = I_{Lr}(t_6) + \frac{Vi}{L_r}\cdot t \qquad (30)$$

$$I_{Lr}(t_7) = I_i \qquad (31)$$

$$\Delta t_7 = \frac{\alpha_1}{\omega_0}\cdot\sqrt{(G_1(\alpha_1+\alpha_2)^2 - 1} \qquad (32)$$

H. *Eighth Stage [t_7;t_8]:*

$$I_{Lr}(t) = I_i \qquad (33)$$

$$V_{CR}(t) = V_{C1} \qquad (34)$$

From the preceding equations we can determine the static gain of the converter:

$$G_1 = \frac{V_{C1}}{V_i} = \frac{1}{1 - D - \frac{1}{T.\omega_0}\cdot\left(-\alpha_1 + \frac{1}{2.\alpha_1}\right)} \qquad (35)$$

$$G_2 = \frac{V_0}{V_{C1}} = D + \frac{1}{T.\omega_0}\cdot\left(-\alpha_2 + \frac{1}{2.\alpha_2}\right) \qquad (36)$$

where:

$$\mathbf{D} = \frac{\Delta\mathbf{t_1} + \Delta\mathbf{t_2} + \Delta\mathbf{t_3} + \Delta\mathbf{t_4}}{\mathbf{T}} \;\rightarrow \text{duty cycle} \qquad (37)$$

$$\mathbf{T} = \Delta\mathbf{t_1} + \Delta\mathbf{t_2} + \ldots + \Delta\mathbf{t_8} \;\rightarrow \text{switching period} \qquad (38)$$

From equations (35) and (36) it is observed that the converter static gain (G_1) and (G_2) depend on: the duty-cycle (D), resonant frequency (w_0), the ratio (α) and the period of switching frequency, as shown in Fig. 12 and 13.

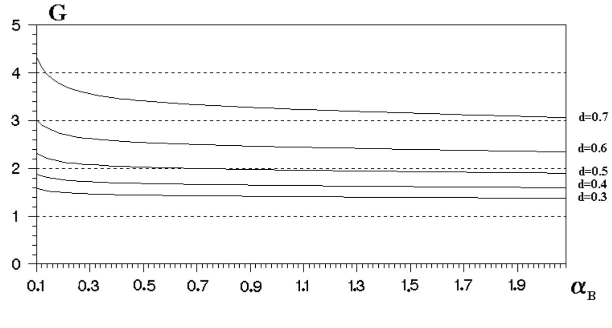


Fig. 12 – Theoretical curves of G_1 vs α_1 when D varied

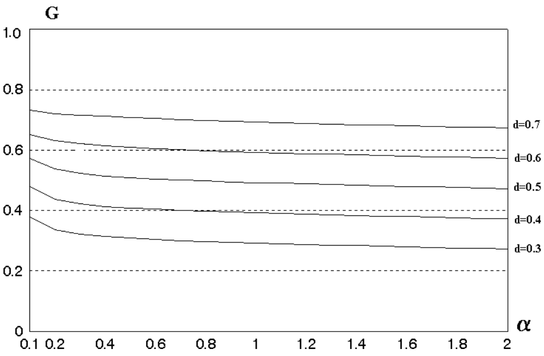
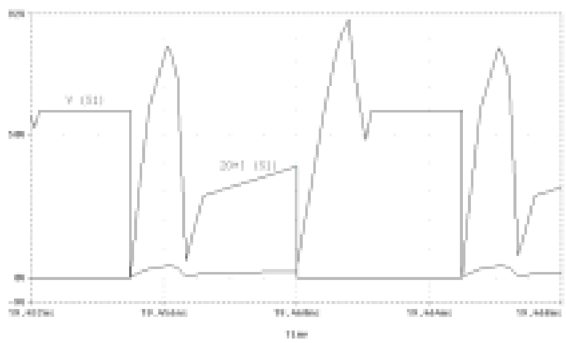


Fig. 13 – Theoretical curves of G_2 vs α_2 when D varied

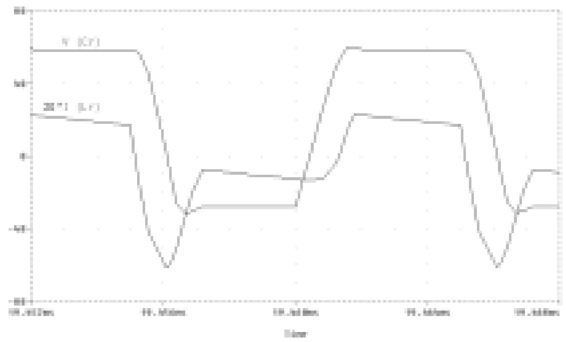
IV. SIMULATIONS RESULTS

In order to illustrate the efficiency of the Boost converter shown in Fig. 1, it was simulated with the following parameters:

- ✓ Input voltage (Vi) = 30V
- ✓ Resonant capacitor (Cr) = 30nF
- ✓ Filter Capacitor (C1) = 350µF
- ✓ Filter Capacitor (C_2) = 500µF
- ✓ Filter Inductor (L_1) = 300µH
- ✓ Resonant Inductor (Lr) = 10µH
- ✓ Switching frequency (*f*) = 100kHz
- ✓ Duty cycle (D) = 0,50
- ✓ Load resistance (RL) = 100Ω



A



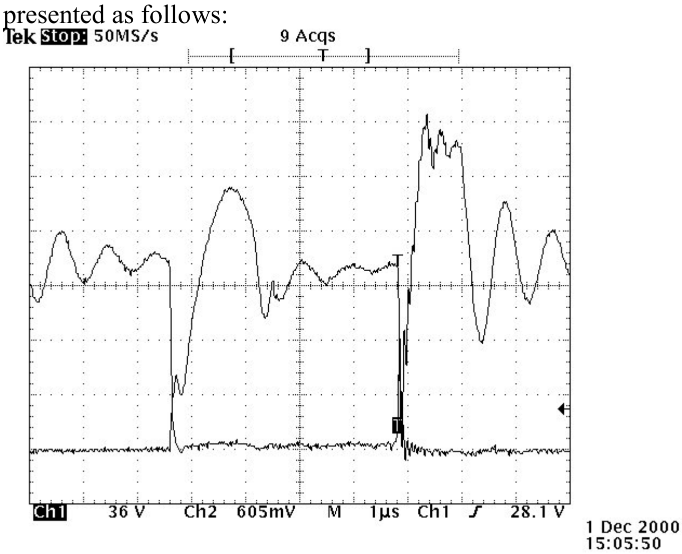
B

Fig. 14: (A) V (S_1) and I(S_1) ; (B) V (Cr) and I(Lr)

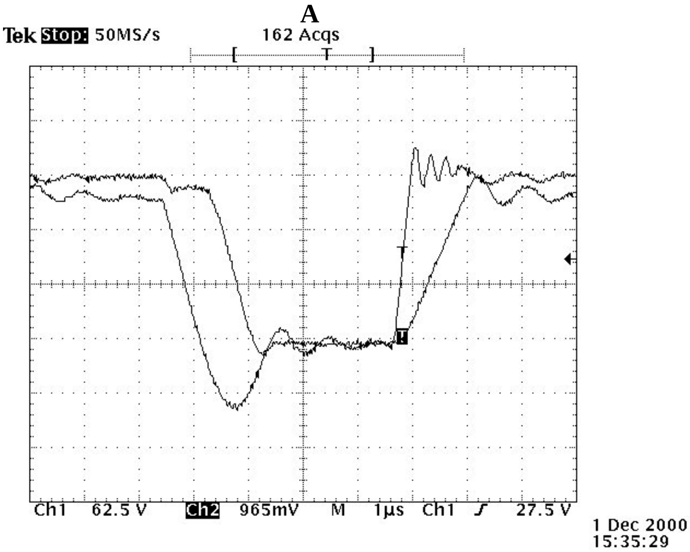
In these results obtained through simulation it is possible to verify the efficiency of the converter operating in a soft switching way. The S_1 switch is turned on under zero-current and turned off under zero-voltage.

V. EXPERIMENTAL RESULTS

The proposed converter was tested experimentally to verify its operation and efficiency. The parameters used in the experimental tests were the same as those used in the simulation. The active switch used was IRF740 and the diodes were HFA15TB60. The resultant waveforms are presented as follows:



A



B

Fig. 15: (A) V (S_1) and I (S_1); (B) V (Cr) and I (Lr)

In the obtained results, the soft-switching achievement is observed (ZVS and ZCS). It is also verified an amount of noises in these waveforms that are due mainly to the non-ideal characteristics of the power circuit components, such as parasitic inductances and capacitances of electronic devices.

VI. CONCLUSION

A Boost associated with a Buck PWM soft switched converter has been presented. This converter with only one active switch can operate in a soft-switching way with PWM characteristics and high frequency for a wide load range.

The presented simulation and the experimental results validate the proposed converter.

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