A ZVT DC-DC BOOST CONVERTER WITH REDUCED AUXILIARY SWITCH LOSSES

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***Abstract* - This paper presents an improved ZVT DC-DC boost converter using a regenerative snubber. The proposed snubber uses a magnetically coupled cell to reduce the turn-off switching loss of the auxiliary switch. The method has been employed to build a 500W / 100kHz prototype. The experimental results show the ZVT DC-DC boost converter waveforms with and without the regenerative snubber. A high efficiency is achieved using the proposed improvement.**

I – INTRODUCTION

High switching frequency (f_s) operation allows weight and size reduction of reactive components in switching converters, but turn-on and turn-off switching losses increase along with f_s increase. The switching losses can be minimized by using active snubbers [1-4]. These snubber circuits allow to increase the power density of DC-DC converters, without exceeds the semiconductor thermal restrictions.

Among several solutions available, the ZVT cell [1] is one of the most robust and simplest. The circuit diagram of a ZVT boost DC-DC converter is shown in Fig.1.

The converter shown in Fig. 1 operates as follows: just a little time interval before starting a new switching period of S_o, the auxiliary switch S_x is turned on. The current across L_r - S_x increases linearly from zero to the input current I_{in}. At this moment, the output-diode current i_{Do} reaches zero and the output diode turns off without recovery losses. A resonance between L_r - C_r takes place, and the capacitor voltage v_{Cr} starts to resonate from V_o to zero. At this point, the body diode of S_o conducts, and S_o can be turned on at zero-voltage. S_x can be now turned-off. At the end of the turn-on time, the S_o voltage increases slowly due to C_r capacitor. Therefore, the main switch S_o turns on and off with no losses.

The auxiliary switch S_x is kept conducting during a little time interval in a switching period. Thus, it process an average current that is only a fraction of the rated current. However the ZVT-based converters present the following drawback: the S_x turn-off is dissipative (its turn-on is ZCS). Recently, many solutions have been presented to overcome this problem, which improve the overall efficiency in about 1 - 2 % [5,6].

This paper presents a simple way to improve auxiliary switch turn-off, which is based on a regenerative turn-off snubber that uses a magnetically coupled cell [7].

II – THE PROPOSED IMPROVED TOPOLOGY

The improved ZVT DC-DC cell, applied to a boost converter can be seen in Fig.2.

The S_o ZVT operation remains the same of the conventional ZVT converter [1]. However, the switch S_x is now turned-off at zero-voltage (ZVT), due to the snubber capacitor C_{sx}. When the voltage $v_{Csx} = V_o$, D_x starts conducting, clamping v_{Csx} voltage. At turn-on, S_x starts conducting at zero current (ZCS), with small losses caused by the intrinsic capacitor (C_{oss}). The magnetic coupling between L_r and L_{mx} transfers to the converter output the energy stored in C_{sx} ($\frac{1}{2} C_{sx} V_o^2$) in a resonant way (C_{sx}-L_{rx}). This causes small increasing in S_x conduction losses, due to the L_{mx} reflected current. However, it can be neglected if compared to the turn-off losses saving. Therefore, the main switch S_o presents ZVT turn-on and turn-off, while the auxiliary switch present ZCS turn-on and ZVT turn-off. A compact structure is obtained if L_{rx} is the secondary leakage inductance of the magnetic coupling [8].

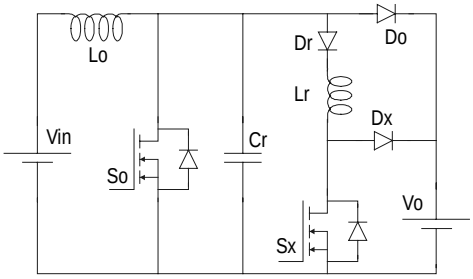


Fig. 1 - ZVT-PWM boost DC-DC converter.

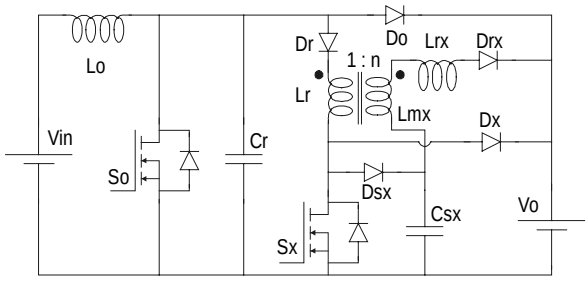


Fig. 2 - Improved Topology for ZVT-PWM boost converter.

III - PRINCIPLE OF OPERATION

The operation stages of the improved ZVT boost converter are shown in Fig. 3, whereas the theoretical waveforms are shown in Fig. 4. The operation is as follows:

First Stage [0,t_o]:
During this stage both switches are off and the power is transferred to the load through the output diode D_o as in the conventional boost converter.

Second Stage [t_o,t_1]:
At t_o, the auxiliary switch is turned on and L_r current starts to increase turning the D_{rx} diode on. During this stage a resonance between C_{sx} and L_{rx} occurs transferring the energy stored in C_{sx} to the load through the magnetic coupling. This resonant current is present in the L_r current.

Third Stage [t_1,t_2]:
At the end of C_{sx} - L_{rx} resonance, L_r current continues increasing, now linearly, until it reaches the input current value I_{in}.

Fourth Stage [t_2,t_3]:
At t_2, D_o turns off and start the main resonance between L_r and C_r , as in the conventional ZVT-PWM converter.

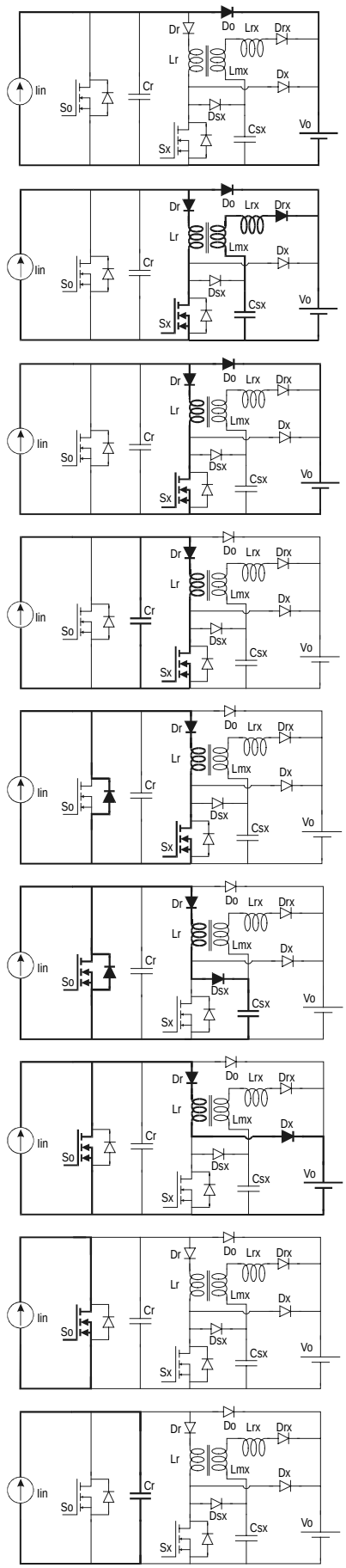
Fifth Stage [t_3,t_4]:
When v_{Cr} reaches zero the body diode of the main switch conducts providing a freewheeling way for L_r current. Now S_o can be turned on at zero voltage.

Sixth Stage [t_4,t_5]:
At this stage S_x is turned off and S_o is turned on. The snubber cell guarantees ZVT to S_x during the turn-off. The S_o current starts to change its direction.

Seventh Stage [t_5,t_6]:
At t_5 the C_{sx} voltage reaches V_o and D_x starts to conduct clamping v_{Csx}. The L_r current decreases linearly until the main switch assumes all the input current I_{in}. In some cases the body diode of the main switch still conducts for a very short time interval [t_5^-,t_5], not considered in the analysis.

Eighth Stage [t_6,t_7]:
This is the conventional charging stage of the boost converter.

Ninth Stage [t_7,t_8]:
At t_7 S_o is turned off and C_r guarantees ZVT to the main switch. The S_o voltage increases linearly up to V_o and D_o starts to conduct.



First Stage [0,t_o]
Second Stage [t_o,t_1]
Third Stage [t_1,t_2]
Fourth Stage [t_2,t_3]
Fifth Stage [t_3,t_4]
Sixth Stage [t_4,t_5]
Seventh Stage [t_5,t_6]
Eighth Stage [t_6,t_7]
Ninth Stage [t_7,t_8]

Fig. 3 - Stages of Operation.

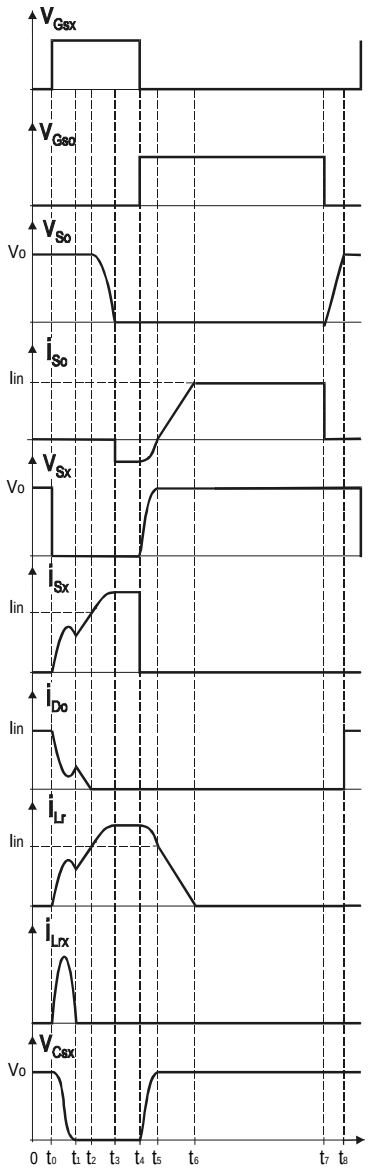


Fig. 4 - Theoretical Waveforms.

IV - DESIGN PROCEDURE

A design procedure for both the ZVT and snubber cell is obtained as follows:

- The resonance frequency between Lr and Cr during the (t_3-t_2) interval time is given by [1]:

$$\omega_r t_r = \frac{\pi}{2} \quad (1).$$

Defining the ZVT resonant time rate as the relation between t_r and the switching period T_s:

$$k_{tr} = \frac{t_r}{T_s} = t_r f_s \quad (2),$$

(1) can be rewritten as:

$$\omega_r = \frac{\pi f_s}{2k_{tr}} \quad (3).$$

- The additional power transferred to the load through the snubber circuit is given by:

$$P_{sx} = \frac{1}{2} C_{sx} f_s V_o^2 \quad (4).$$

The C_{sx} capacitance must be chosen so that the additional power transferred to the load is a fraction of the output power (P_o), in order to maintain the PWM characteristics of the converter. Defining the power transfer rate as the relation between P_{sx} and P_o:

$$k_p = \frac{P_{trans}}{P_o} \quad (5)$$

and using

$$P_o = \frac{V_o^2}{R_o} \quad (6)$$

the C_{sx} capacitance value can be obtained by:

$$C_{sx} = \frac{2k_p}{f_s R_o} \quad (7)$$

- The resonant time interval (t_1-t_0) and the linear increasing current time (t_2-t_0) are given by [7, 8 , 1]:

$$(t_1 - t_0) = \frac{\pi}{\omega_{ron}} \quad (8)$$

$$(t_2 - t_0) = \frac{L_r I_{in}}{V_o} \quad (9).$$

Defining the snubber resonant time rate as the relation between (t_1-t_0) and (t_2-t_0):

$$k_x = \frac{(t_1 - t_0)}{(t_2 - t_0)} \quad (10)$$

and using:

$$I_{in} = mI_o \quad (11)$$

$$m = \frac{V_o}{V_{in}} \quad (12)$$

one can obtain:

$$\omega_{ron} = \frac{\pi R_o}{k_x L_r m} \quad (13).$$

Once $\omega_{ron} = \frac{Z_{ron}}{L_{rx}}$, (13) can be rewritten as:

$$\frac{Z_{ron}}{R_o} = \frac{k_L \pi}{k_x m} \quad (14)$$

where the coupled inductance rate k_L is defined by:

$$k_L = \frac{L_{rx}}{L_r} \quad (15).$$

- In order to achieve proper operation of the ZVT and the snubber cells the designer must guarentee that during the (t_1-t_0) time interval the auxiliary switch current is smaller than the input current. Otherwise the output diode current will reach zero and other stages will occur.

The auxiliary switch current during (t_1-t_0) is given by:

$$i_{Sx}(t) = \frac{V_o}{L_r}(t - t_0) + \frac{n^2 V_o}{Z_{ron}} sin[\omega_{ron}(t - t_0)] \quad (16).$$

From (16) one can observe that the maximum $i_{Sx}(t)$ value occurs when:

$$(t - t_0) = \frac{\pi}{2\omega_{ron}} \qquad (17).$$

Using the condition $i_{Sx}(t) \le I_{in}$ and (17) in (16) gives:

$$\frac{\pi V_o}{2\omega_{ron} L_r} + \frac{n^2 V_o}{Z_{ron}} \le m.I_o \qquad (18).$$

Using (8), (9) and (10), (18) can be rewritten as:

$$\frac{Z_{ron}}{R_o} \ge \frac{2n^2}{m(2 - k_{tx})} \qquad (19).$$

Fig. 5 shows the design graphics obtained from (3) and (7), whereas Fig 6 shows the graphics obtained from (14) and (19). One can easily choose the component values for both the ZVT and snubber cells from them, taking into account the limit of the auxiliary switch current presented by (19) that is represented by the dotted curve in Fig. 6. The design proceeding is described bellow:

- Knowing the switching frequency (f_s), choose a ZVT resonant time rate value (k_{tr}). Then the ZVT resonant frequency (ω_r) can be obtained by Fig. 5a;
- Knowing the switching frequency and output resistance product (f_sR_o), choose a power transfer rate value (k_p). Then the snubber capacitance value (C_{sx}) can be obtained by Fig. 5b;
- Knowing the converter voltage gain m, choose a snubber resonant time rate (k_{tx}) and a coupled inductance rate (k_L). Then the normalized turn-on impedance value (Z_{ron}/R_o) can be obtained by Fig. 6a, b or c (pay attention to work with curves over the dotted one);
- The snubber resonant inductance is obtained as:

$$L_r = C \quad Z_{ron} \qquad (20);$$

- The resonant inductance is given by (15);
- The resonant capacitance is obtained using:

$$C_r = \frac{1}{L_r \omega_r^{\,2}} \qquad (21)$$

V - Design Example

Table I shows the design specifications for a ZVT boost converter using the proposed snubber.

TABLE I
DESIGN SPECIFICATIONS

Input Voltage (V_{in})	120V
Output Voltage (V_o)	300V
Output Power (P_o)	500W
Switching frequency (f_s)	100kHz

Choosing $k_{tr} = 0.07$, from Fig. 5.a, the ZVT resonance frequency is:

$$\omega_r = 2.15 \times 10^6 \, (rad/s).$$

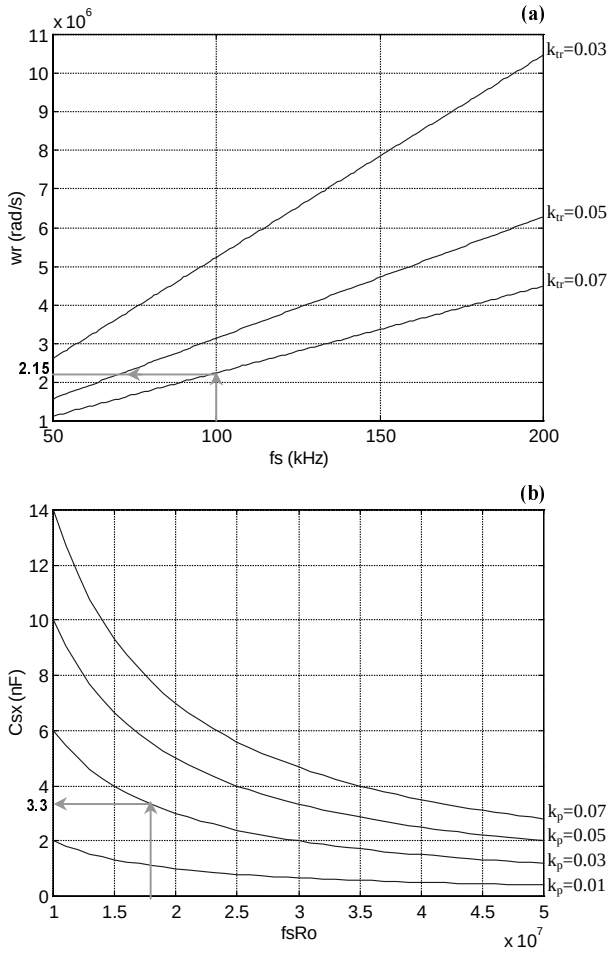


Fig. 5 – Design Graphics (a) ω_r and (b) C_{sx}.

The output resistance is obtained from (6):

$$R_o = 180(\Omega)$$

The switching frequency and output resistance product is:

$$f_s R_o = 1.8 \times 10^7 \, (rad \times \Omega / s)$$

Choosing $k_p = 0.03$, from Fig. 5.b, the snubber capacitance value is:

$$C_{sx} = 3.3(nF)$$

From (12) the converter voltage gain is:

$$m = 2.5$$

Choosing $k_{tx} = 0.035$ and $k_L = 0.0625$, from Fig. 6.b, the normalized turn-on impedance value is:

$$\frac{Z_{ron}}{R_o} = 0.22$$

The L_{rx} and L_r values are obtained by using (20) and (15) respectively:

$$L_r = 5.17(\mu H) \qquad L_r = 82.8(\mu H)$$

The resonant capacitance is obtained by using (21):

$$C_r = 2.61(nF)$$

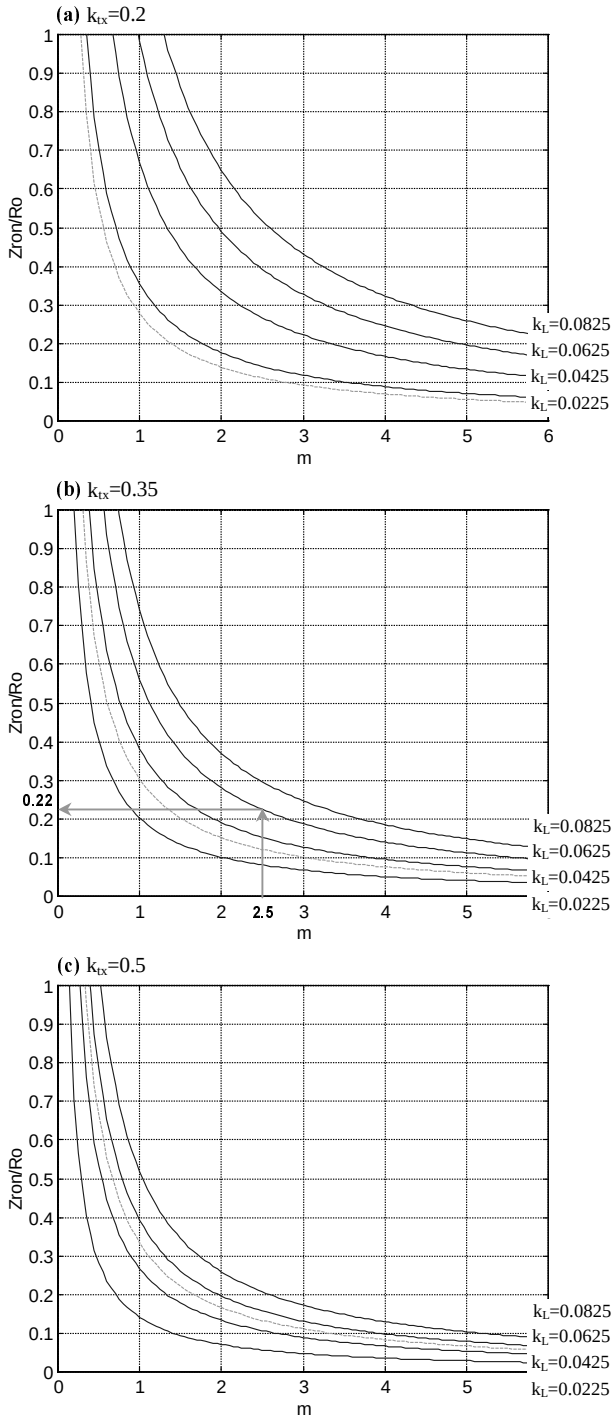


Fig. 6 – Design Graphics Z_{ron}/R_o for (a) k_{tx}=0.2, (b) k_{tx}=0.35 and (c) k_{tx}=0.5.

VI - EXPERIMENTAL RESULTS

In order to compare the efficiency, both ZVT-PWM boost DC-DC converters were implemented: the conventional ZVT and the proposed one. Their rated values are presented in Table I.

Table II presents the components used in both prototypes.

The switches' commutations for the conventional converter are shown in Fig. 7 and 8, whereas Fig. 9 and 10 show the waveforms for the improved converter. One can observe the improvement in the turn-off process of the auxiliary switch.

TABLE II
PROTOTYPE COMPONENTS

Component	*Value / Model*
Main Switch (S_o)	IRFP360
Auxiliary Switch (S_x)	IRF740
Auxiliary Diode (D_x)	FES8HT
Resonant Diode (D_r)	FES8HT
Snubber Diode (D_{sx})	FES8HT
Snubber Resonant Diode (D_{rx})	FES8HT
Output Diode (D_o)	FES8HT
Boost Inductor (L_o)	940 µH
Resonant Inductor (L_r)	80 µH
Snuber Resonant Inductor (L_{rx})	5 µH
Resonant Capacitor (C_r)	2.7 nF
Snubber Capacitor (C_{sx})	3.3 nF
Output Capacitor (C_o)	47 µF

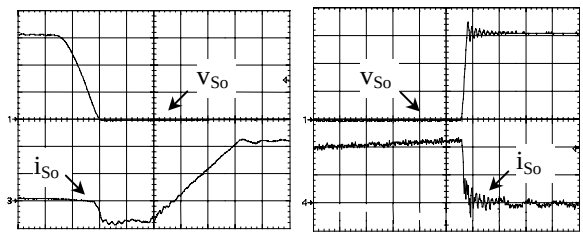


Fig. 7 - Conventional converter (a) turn-on and (b) turn-off of the main switch.
Scales:100V/div – 2A/div – 500ns/div

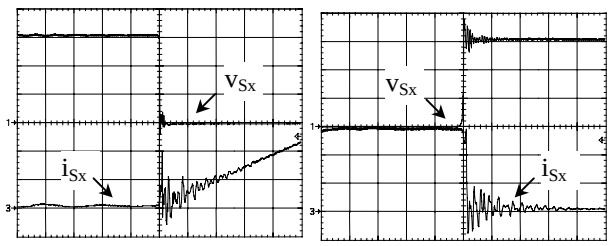


Fig. 8 - Conventional converter (a) turn-on and (b) turn-off of the auxiliary switch.
Scales:100V/div – 2A/div – 250ns/div

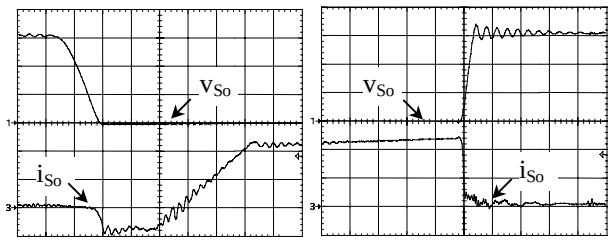


Fig. 9 - Proposed converter (a) turn-on and (b) turn-off of the main switch.
Scales:100V/div – 2A/div – 500ns/div

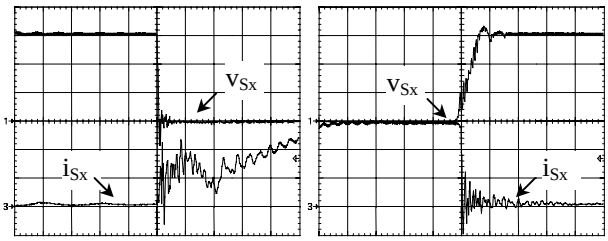


Fig. 10 - Proposed converter (a) turn-on and (b) turn-off of the auxiliary switch. Scales:100V/div – 2A/div – 250ns/div

It is observed from Fig. 8a. and 10a. that a spike occurs in the S_x current during the turn-on. This is due to the reverse recovery of D_x. At S_x turn-off, v_{Csx} grows to V_o and D_x conducts until the complete linear discharge of the L_r current. When the diode D_x stops conducting, a charge equilibrium among real and parasitic capacitances occurs, and v_{Csx} goes down to a value below the output voltage V_o. When the main switch is turned off and its voltage becomes greater than v_{Csx}, D_x starts to conduct again and D_o conducts the difference between the input current and the L_r current. The auxiliary switch S_x is turned on with D_x conducting. The reverse recovery of D_x then causes the spike in the i_{Sx} current. It's important to mention that this also occurs in the conventional ZVT-PWM converter, as can be seen in Fig. 8a.

The resonant evolution of v_{Csx} and i_{Lrx} are shown in Fig. 11. As can be noted, during the turn-on process, the energy stored in C_{sx} is transferred to the load. Fig. 12 shows the efficiency of both converters.

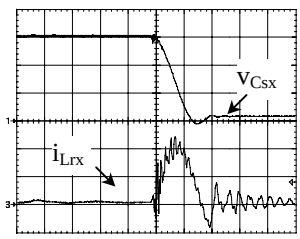


Fig. 11 - Resonant evolution of v_{Csx} and i_{Lrx}. Scales:100V/div – 2A/div – 250ns/div

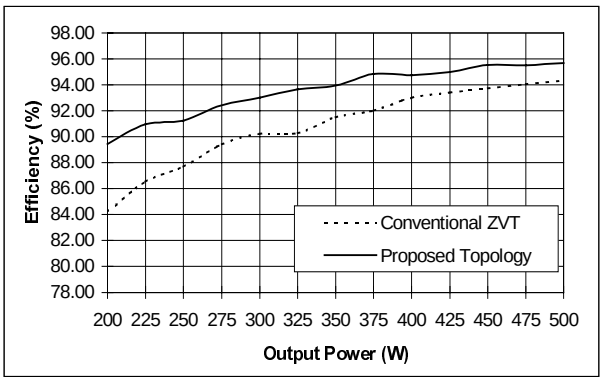


Fig. 12 - Efficiency comparison between both converters.

VII – CONCLUSION

This paper has presented a simple solution to improve the efficiency of a ZVT DC-DC boost converter. Such improvement is achieved by using a regenerative snubber applied to the auxiliary switch. Besides the main switch ZVS turn-on and ZVT turn-off, and the auxiliary switch ZCS turn-on, the proposed snubber also achieves the auxiliary switch ZVT turn-off.

A family of curves were presented, making easy the design process. A compact structure can be achieved if only the resonant inductor core of the original ZVT converter is employed to get both the magnetic coupling and the snubber resonant inductor.

A prototype of 500 W/100 kHz was implemented in order to compare the topology behavior with and without the snubber. The experimental waveforms and efficiency results demonstrate the improvement achieved using the proposed enhancement.

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