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

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Abstract – **This paper presents a ZVT DC-DC Boost converter that uses a magnetic coupling to reduce the total losses of the auxiliary switch. Its great advantage is that the auxiliary inductor is incorporated in the main one, reducing the number of magnetic components of the circuit. A design procedure as well as a design example is shown. Experimental results obtained from a 300V-500W-100kHz prototype are presented and confirm the operation of the proposed converter and the benefits obtained by its use.**

KEYWORDS

Zero Voltage Transition, Magnetic Coupling, Switching Losses

I. INTRODUCTION

High switching frequency (fs) operation of pulse width modulation (PWM) converters allows weight and size reduction of their reactive components, but switching losses and electromagnetic interference (EMI) emissions increase along with operation frequency increase. The switching losses can be minimized by using active snubbers that allow to increase the power density of DC-DC converters without exceeds the semiconductor thermal restrictions.

Among several solutions available, the Zero Voltage Transition (ZVT) cell [1] is one of the most robust and simplest. It enables the main switch to be turned on and off at zero voltage, besides reducing its turn-on capacitive losses due to the intrinsic capacitance discharge of the switch. Its main drawback is the improper turn-off commutation of the auxiliary switch, which is dissipative.

Many others topologies, based on the ZVT technique, have been presented in the last years [2-8] that do not have the drawback of the original ZVT converter [1]. The converter presented in [7] and shown in Fig. 1.a is one of the most efficient and simplest ones. In spite of all its advantages, the converter has an operation restriction: soft switching is achieved only if the output voltage is greater than twice the input voltage.

This paper presents a novel topology based on the BOOST converter presented in [7] that uses a magnetic coupling to improve the total losses of the auxiliary switch, as presented in Fig. 1.b. The introduction of the magnetic coupling in the circuit allows obtaining the minimum losses in the auxiliary switch. Section II describes the principle of operation of the proposed converter and Section III presents the design equations and procedure. Section IV shows a design example that illustrates the design procedure presented. Section V presents the experimental results obtained from a prototype, whereas Section VI gives a conclusion.

II. THE PROPOSED IMPROVED TOPOLOGY

The improved converter proposed in this paper can be seen in Fig. 1.b. It allows the main switch to be turned on and off at zero voltage as well as the auxiliary switch to be turned on and off at zero current. Besides, the magnetic coupling permits the auxiliary switch current to be reduced, which also reduces its conduction losses. In counterpart, it also increases the voltage across the auxiliary switch, increasing its turn-on capacitive losses. Despite this, an adequate turns ratio value choice can lead to the minimum auxiliary switch losses. A compact structure is obtained if Lr is the secondary leakage inductance of the magnetic coupling. In this case there's no necessity of the additional magnetic core presented in [7], once all the inductors can be built in the same core. The stages of operation as well as the theoretical waveforms of the proposed structure are shown in Figs. 2 and 3, respectively. To the analysis, an equivalent circuit, shown in Fig. 2, replaces the magnetic coupling. The stages of operation can be described as follows:

First Stage ($t_0 - t_1$)
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 ($t_1 - t_2$)
At t_1, the auxiliary switch is turned on and L_r current starts to increase linearly until it reaches the output diode (D_o) current value.

Third Stage ($t_2 - t_3$)
At t_2, D_o turns off and begins the resonance between L_r and C_r. At the end of this stage, the current across the resonant inductor is equal to I_r.

(a)

(b)

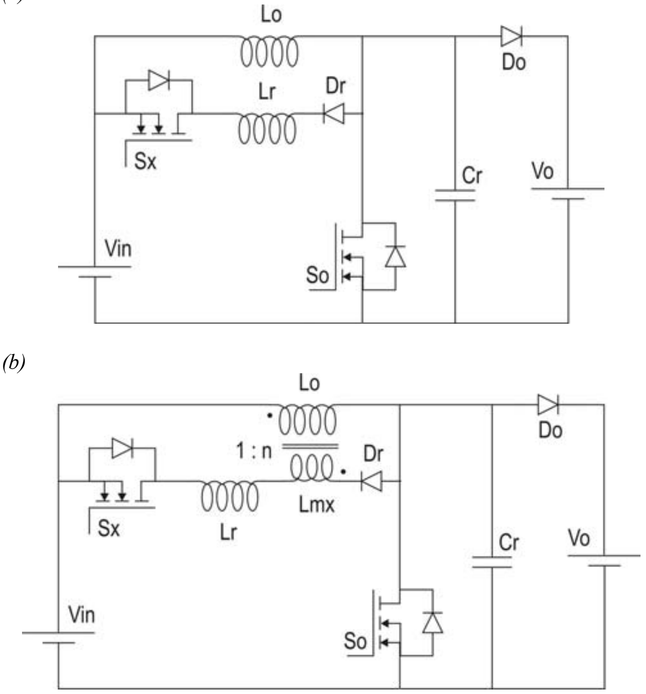

Figure 1 – (a) Self-Resonant BOOST Converter presented in [7] and (b) Improved Converter Proposed.

Fourth Stage (t_3 – t_4)
When v_{Cr} reaches zero the body diode of the main switch conducts. Now S_o is turned on at zero voltage. During this stage the L_r current decreases linearly until reaching zero.

Fifth Stage (t_4 – t_5)
At t_4 the auxiliary switch S_x is turned off and the conventional charging stage of the boost converter takes place.

Sixth Stage (t_5 – t_6)
At t_5 the main switch 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.

III. DESIGN EQUATIONS AND PROCEDURE

The design procedure presented was obtained in order to achieve the minimum losses in the auxiliary switch.

The resonant inductor L_r is obtained in order to limit the di/dt of the output diode D_o during its reverse recovery process:

$$L_r = \frac{(V_o - V_{in})}{di_{Do,\max}/dt} \tag{1}$$

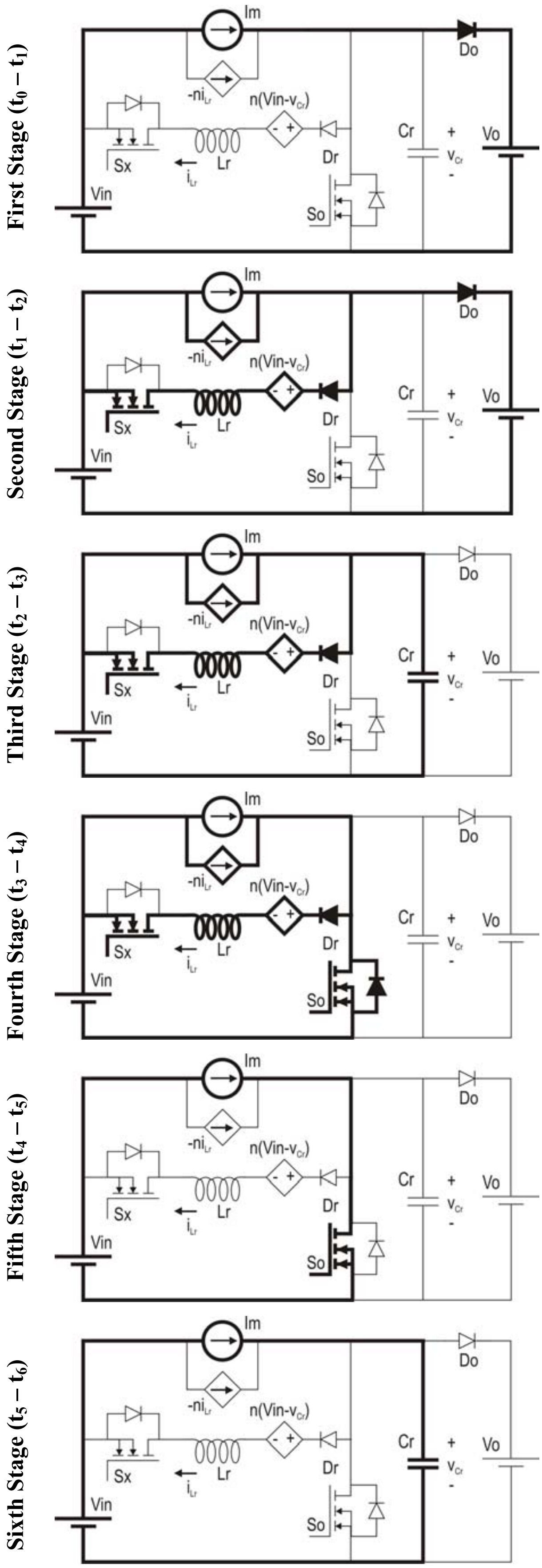

Figure 2 – Stages of Operation of the Proposed Converter.

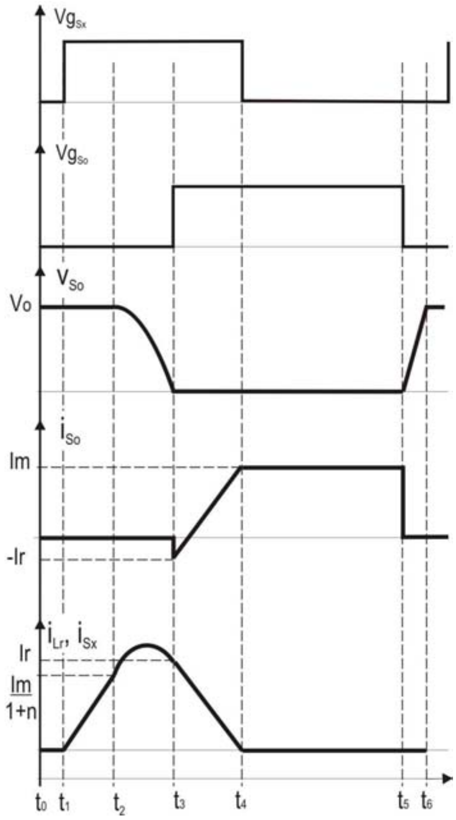

Figure 3 – Theoretical Waveforms of the Proposed Converter.

and the resonant capacitor C_r is designed to minimize the turn-off losses of the main switch S_o:

$$C_r = \frac{I_m \times t_f}{2 \times V_f} \tag{2}$$

where: t_f is the current fall time of the main switch

V_f is the final voltage across the main switch after its fall time period.

The current through the auxiliary switch (i_{Sx}), its conduction ($P_{Sx,ON}$) and turn-on capacitive losses (P_{Coss}) are given by:

$$i_{Sx}(t) = \begin{cases} \dfrac{(1+n)\times(V_o - V_{in})}{L_r} \times (t - t_1), \text{ for } t_1 \le t \le t_2 \\ \dfrac{I_m}{1+n} + \dfrac{(V_o - V_{in})}{(1+n)\times Z_r} \times sin\left[\omega_r \times (t - t_2)\right], \text{ for } t_2 \le t \le t_3 \\ I_r - (1+n)\times\dfrac{V_{in}}{L_r} \times (t - t_3), \text{ for } t_3 \le t \le t_4 \end{cases} \quad (3),$$

$$P_{Sx,ON} = R_{DSon} \times I_{Sx}^{\ 2} \tag{4}$$

and

$$P_{Coss} = 1/2 \times f_S \times C_{oss} \times \left[(1+n)\times(V_o - V_{in})\right]^2 \quad (5),$$

where I_{Sx} is the RMS value of i_{Sx}.

From (3), (4) and (5), one can obtain the total loss on the auxiliary switch (P_{Sx}) as:

$$\begin{aligned} P_{Sx} = P_{Sx,ON} + P_{Coss} = \frac{1}{2} \times C_{oss} \times f_S \times \left[(1+n)\times(V_o - V_{in})\right]^2 + \\ + R_{Dson} \times f_S \times \Bigg\{ \frac{L_r \times I_m^{\ 3}}{3\times(1+n)^4 \times (V_o - V_{in})} + \frac{L_r \times I_r^{\ 3}}{3\times(1+n)\times V_{in}} + \\ + \frac{2\times V_o \times I_m}{Z_r \times \omega_r \times (1+n)^2} + \frac{\Phi_r}{\omega_r \times (1+n)^2} \times \left[I_m^{\ 2} + \frac{(V_o - V_{in})^2}{2\times Z_r^{\ 2}} \right] + \\ - \frac{sin(2\times\Phi_r)}{4\times\omega_r} \times \left[\frac{(V_o - V_{in})}{Z_r \times (1+n)}\right]^2 \Bigg\} \end{aligned} \tag{6}$$

where:

$$Z_r = \frac{1}{1+n} \times \sqrt{\frac{L_r}{C_r}} \tag{7}$$

$$\omega_r = \frac{1+n}{\sqrt{L_r \times C_r}} \tag{8}$$

$$I_r = i_{Lr}(t_3) = \frac{I_m}{1+n} + \frac{(V_o - V_{in})}{(1+n)\times Z_r} \times sin\Phi_r \tag{9}$$

and

$$\Phi_r = \arccos\left(\frac{-V_{in}}{V_o - V_{in}}\right) \tag{10}$$

It will be shown, in the next section, from (6), that an appropriate choice of the magnetic coupling turns ratio (n) leads to the minimum losses on the auxiliary switch.

IV. DESIGN EXAMPLE

Following, there is an example that illustrates the design procedure presented before. Table 1 shows the specifications used in this example and Table 2 shows the component values obtained.

TABLE I
Design Example Specifications

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

TABLE II
Component Values Obtained

Component	Value/Model
Main Inductor (L_o)	870μH
Resonant Inductor (L_r)	6μH
Resonant Capacitor (C_r)	1.5nF
Magnetic Coupling Turns Ratio (n)	0.55
Main Switch (S_o)	IRFP360
Auxiliary Switch (S_x)	IRF830
Diodes (D_o and D_r)	MUR850

The conventional boost devices were designed following the traditional way [9].

Limiting the current variation rate at diode D_o in 30A/µs, from (1) one can obtain:

$$L_r = 6\mu H .$$

Assuming the main switch current fall time (t_f) equal to 67ns (IRFP360) and its final voltage (V_f) equal to 50V, from (2) one obtain:

$$C_r = 2.8nF .$$

Considering that the C_r value calculated incorporates the output capacitance of the main switch (IRFP360 – $C_{oss} = 1.1nF$) the resonant capacitance used was:

$$C_r = 1.5nF .$$

The graphic shown in Fig 4 is obtained by using the L_r and C_r values in (6) and shows the total losses in the auxiliary switch. Observing the graphic, it can be seen that choosing a magnetic coupling turns ratio (n) equal to 0.55 permits to obtain the minimum auxiliary switch losses.

V. EXPERIMENTAL RESULTS

In order to verify the operation of the proposed converter, a 300V-500W-100kHz prototype of the BOOST converter was built. Fig. 5 and Fig. 6 presents the experimental results obtained from the prototype.

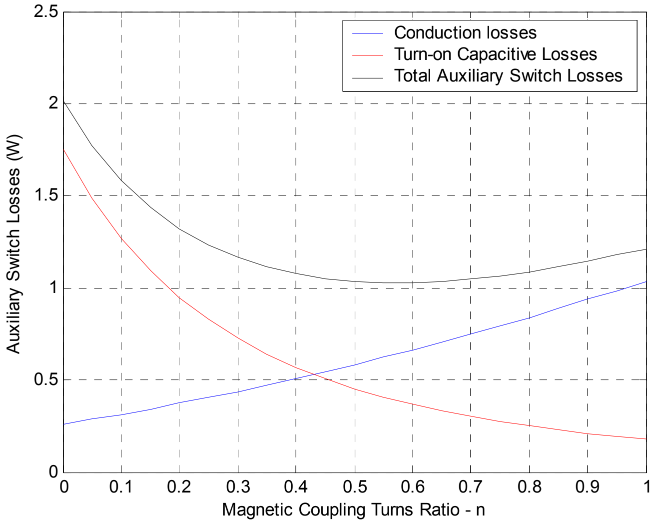

Figure 4 – Auxiliary Switch Losses.

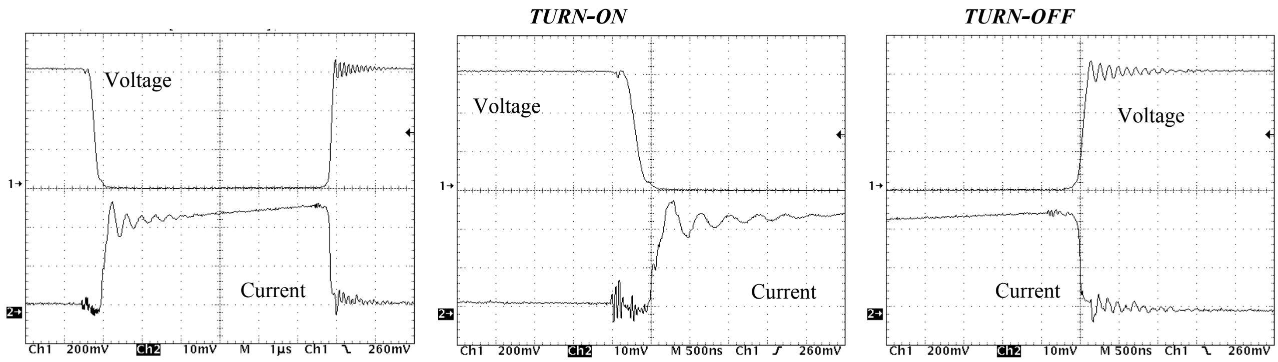

Figure 5 – Main Switch Voltage and Current.

Scales: 100V/div – 2A/div – 1µs/div (500ns/div – turn-on and turn-off)

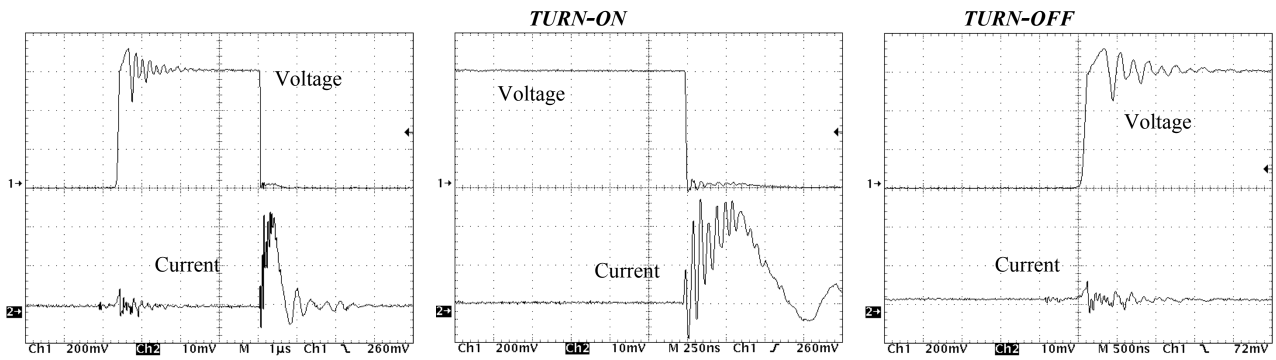

Figure 6 – Auxiliary Switch Voltage and Current.

Scales: 100V/div – 2A/div – 1µs/div (250ns/div – turn-on and 500ns/div – turn-off)

Analyzing the figures, it can be seen that the main switch is turned on and off at zero voltage and the auxiliary switch is turned on and off at zero current as expected.

Fig 7 shows the efficiency of the proposed converter. It can be seen that the converter presents efficiency higher than 95% for all the output power range analyzed and equal to 95.5% at rated output power.

VI. CONCLUSION

This paper presented a ZVT converter using a magnetic coupling to reduce the total losses of the auxiliary switch.

The proposed converter allows the main switch to be turned on and off at zero voltage and the auxiliary switch to be turned on and off at zero current. A compact structure can be achieved if only the main inductor core of the converter is employed to get both the magnetic coupling and the resonant inductor.

A design procedure was presented which permits to obtain the optimal turns ratio “n”, leading to the minimum losses on the auxiliary switch. Experimental results validate the operation of the proposed converter and demonstrate the improvement achieved by using the proposed enhancement.

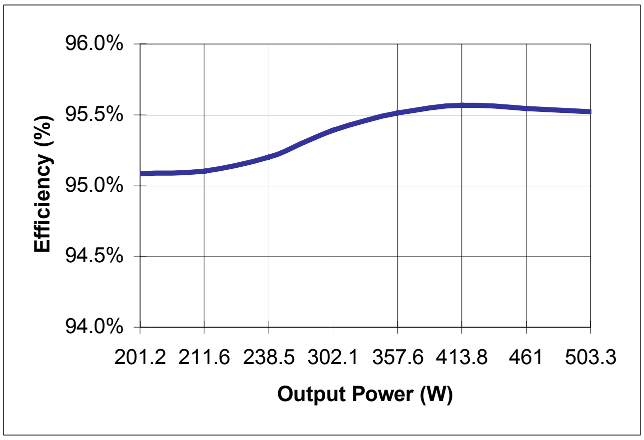

Figure 7 – Efficiency of the Proposed Converter.

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