DC-DC PWM Converters Using Magnetically Coupled Regenerative Snubbers

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***Abstract* - This paper presents the use of a magnetically coupled regenerative snubber applied to PWM converters operatings in continuous conduction mode (CCM). The operation analysis and design is carried out to the Buck-boost converter, but is easily extensible to the others. The proposed snubber use the main core of the DC-DC converter to build the resonant inductor, reducing components. This is a useful new solution to reduce switching losses by passive snubbers. Experimental results are presented to validate the study.**

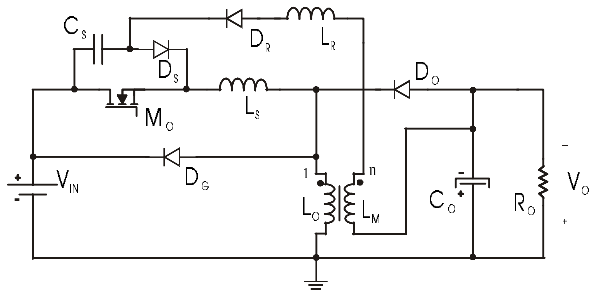
NOMENCLATURE

f_S Switching frequency.
i_{CS} C_S capacitor current.
I_{IN} Rated input current.
i_{LR} L_R inductor current.
I_O Rated output current.
i_{MO} Switch current.
n Coupling turns ratio.
P_O Rated output power.
P_{PER} additional power transferred to the load through the snubber circuit (% rated output power).
R_O Rated output resistance.
t_R C_S capacitor turn-on discharge time.
V_C Maximum turn-off C_S capacitor voltage.
V_{CS} C_S capacitor voltage.
V_{IN} Rated input voltage.
V_{MO} Drain-source voltage of the switch.
V_O Rated output voltage.
Z_{ROFF} Turn-off characteristic impedance.
Z_{RON} Turn-on characteristic impedance.
ω_{ROFF} Resonant turn-off frequency.
ω_{RON} Resonant turn-on frequency.

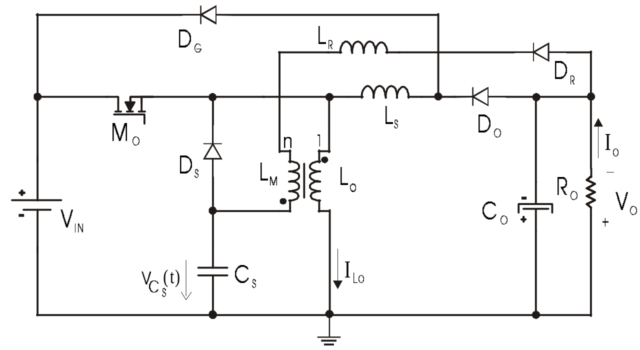
I. INTRODUCTION

Usually, SMPS operate at high switching frequency in order to reduce weight and size of energy-storage components (capacitors and inductors). The penalty is the switching losses increase, which limits the switching frequency operation and/or increase heatsink weight and size. Snubber circuits [1] are used to reduce switching losses, and the regenerative ones [2]-[6] improve efficiency and robustness.

This paper presents a family of PWM converters using a magnetically coupled regenerative snubber. The proposed snubber uses the main core of the DC-DC converter to build the resonant inductor. The Fig. 1 shows two Buck-boost topologies using the proposed snubber.



(a) - Buck-boost #1



(b) - Buck-boost #2

Fig. 1. Magnetically-coupled regenerative snubber applied to the Buck-boost converter: (a) Buck-boost #1, (b) Buck-boost # 2.

II. UNDERSTANDING THE SNUBBER OPERATION

The snubber operation can be understood as follows. The theoretical switch voltage and current waveforms are presented in Fig. 2. At turn-off, the known solution of a parallel capacitor (C_S) for which the current is diverted when the switch is turned off is employed, allowing a soft-transition of the switch voltage (Z*VS - Zero Voltage Switching*). When the switch turns on, the small inductor in series with the switch (L_S) provides soft-transition of its current (ZCS - *Zero Current Switching*), reducing the reverse recovery losses of the output diode (D_O). At this moment, the energy stored in the snubber capacitor (C_S) is transferred to the load by a coupled inductor (L_M) in a resonant way. Any m value (where m is the ratio V_O/V_{IN}) has a respective n turns-ratio, which leads to the correct snubber operation. Ideally the leakage inductance of the coupled inductor should be the L_R inductance, in order to obtain a compact structure.

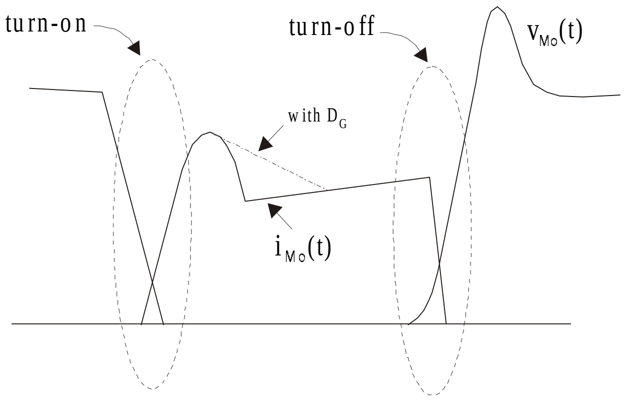


Fig. 2. Expected switch voltage and current.

The output diode current i_{Do} decreases at a low di/dt rate due to the turn-on snubber inductor influence (L_S). At the end of the process, the recovery charge is low. After the diode turns off, the connection point of L_S and D_O (Fig. 1) becomes floating. Without the D_G diode, a resonance between the equivalent diode capacitance and L_S occurs, until the connection point voltage settles at V_{IN}. This resonance appears in the D_O voltage as an overvoltage. This voltage stress is not normally high, but must be considered in the diode selection (e.g., considering the diode reverse voltage equal to V_{IN} + V_O as a start point). The output diode does not present any current stress. To overcome the D_O overvoltage problem, the diode D_G is used clamping the output diode voltage to V_{IN} + V_O [7,8].

III. Turn-On and Turn-Off Analysis

In the following analysis, the switch output capacitance (*Coss*) was neglected. This assumption can be made since its value is small if compared with the auxiliary capacitance C_S. One should pay special attention on the cases that Coss value is close to C_S one. In these cases, its value must be included in the analysis and design equations of the circuit devices.

The following analysis is carried out to the Buck-boost #1 (Fig.1-(a)), but is easily extensible to the Buck-boost #2 and other converters.

A. Turn-Off Switching

Initially, the C_S capacitor voltage is zero. During the turn-off, the capacitor charges with constant current until its voltage reaches the value V_{IN} + V_O. At this moment, the output diode D_O starts conducting and a resonance between capacitor C_S and inductor L_S occurs. The turn-off resonant circuit is shown in Fig. 3, in the *s* domain.

From the analysis of Fig. 3, one can obtain the voltage across and the current through the capacitor during the resonance as

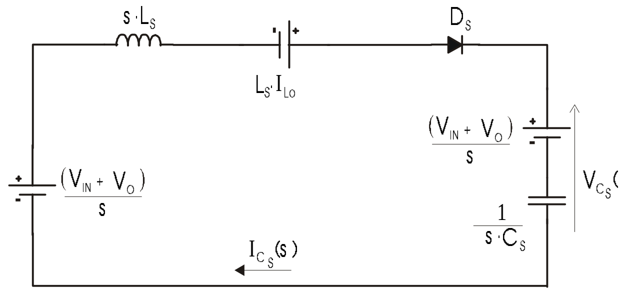


Fig. 3. Turn-off resonant circuit.

$$v_{C_S}(t) = (V_{IN} + V_O) + Z_{ROFF}\ I_{L_O}\ \sin(\omega_{ROFF}\ t) \tag{1}$$

$$i_{C_S}(t) = I_{L_O}\ \cos(\omega_{RON}\ t) \tag{2}$$

where:

$$Z_{ROFF} = \sqrt{(L_S / C_S)} \tag{3}$$

$$\omega_{ROFF} = 1/\sqrt{L_S \cdot C_S} \tag{4}$$

Depending on the capacitor voltage value, the auxiliary diode D_R starts conducting. If it happens, two additional resonant stages can occur. Their analysis is complex and the effects caused by them establish some operation limits (such as switch overvoltage and limitations on the converter duty cycle) [9]. To ensure that the auxiliary diode D_R will not conduct, the maximum capacitor voltage (V_C) must be limited as

$$V_C \le V_{IN} + V_O\ (n+1) \tag{5}$$

where:

$$V_C = (V_{IN} + V_O) + Z_{ROFF}\ I_{L_O} \tag{6}$$

B. Turn-On Switching

During the turn-on, the auxiliary capacitor C_S will discharge through the auxiliary inductor L_R and the auxiliary diode D_R into the load. Usually, the L_S inductor is smaller than the L_O one; then, the voltage drop across L_S can be neglected. Considering this, the turn-on resonant circuit is shown in Fig. 4, in the *s* domain. The initial capacitor voltage at turn-on is equal to V_C (the final value of the capacitor voltage at the last resonant stage during turn-off).

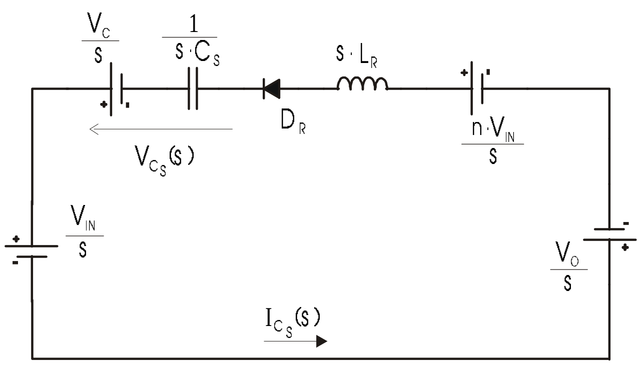


Fig. 4. Turn-on resonant circuit.

From the analysis of Fig. 4, one can obtain the voltage across and current through the capacitor during the resonance as

$$v_{C_S}(t) = \Gamma + (V_C - \Gamma)\cos(\omega_{RON}\, t) \tag{7}$$

$$i_{C_S}(t) = \left((V_C - \Gamma)/Z_{RON}\right)\sin(\omega_{RON}\, t) \tag{8}$$

where:

$$\Gamma = V_O + V_{IN}\,(1-n) \tag{9}$$

$$Z_{RON} = \sqrt{(L_R / C_S)} \tag{10}$$

$$\omega_{RON} = 1/\sqrt{L_R \cdot C_S} \tag{11}$$

IV. Design Equation

The desired capacitor voltage and current at the end of the turn-on resonance are zero. Applying this condition in (7), one can obtain the turns ratio n of the coupled inductor as

$$n = \left(2\,(V_{IN} + V_O) - V_C\right)/(2\,V_{IN}) \tag{12}$$

The auxiliary resonant inductance value is chosen from the desired resonance time t_R, which is obtained doing $\omega_{RON}\, t_R = \pi$. Therefore,

$$L_R = (1/C_S)\,(t_R/\pi)^2 \tag{13}$$

It is important to remember that, in practice, L_R will be the leakage inductance of the coupled inductor itself.

The turn-on snubber inductance L_S is chosen so that it reduces the reverse recovery losses of the output diode D_O. It is obtained by limiting the switch *(di/dt)on* [1]. Thus,

$$L_S = (V_{IN} + V_O)/(di_{MO}/dt) \tag{14}$$

The capacitance C_S must be chosen so that (5) is satisfied.

Defining

- converter voltage gain

$$m = V_O / V_{IN} \tag{15}$$

- C_S capacitor voltage gain

$$M_{VC} = V_C / (V_{IN} + V_O) \tag{16}$$

- M_{SW} is the switch overvoltage respect its original value, without snubber (is the ratio $V_{MO,snubber} / V_{MO,original}$). For the Buck-boost #1 converter, $M_{SW} = M_{VC}$.

- normalized turn-off impedance

$$Z_P = Z_{ROFF} / R_O \tag{17}$$

Using (15) e (16), the limit established by (5) can be defined as

$$M_{VC} \le \left(2\,m^2 + 2\,m + 2\right)/\left(m^2 + 3\,m + 2\right) \tag{18}$$

From (6), M_{VC} can be given by

$$M_{VC} = 1 + (m\, Z_P) \tag{19}$$

Eq. (18) and (19) are, together, boundary conditions for the M_{VC} value. Plotting both in the same curve, Fig. 5 is generated. The upper limit represents the maximum value given by (18) that assures the no-conduction of D_R during turn-on. The lower limit is obtained doing $Z_P = 0$ in (19). The shadowed area of Fig. 5 shows the operational region of the proposed snubber applied to the Buck-boost #1 converter. The converter design in the mentioned area avoids undesirable conduction of D_R. Furthermore, the acceptable switch overvoltage, M_{VC}, is established.

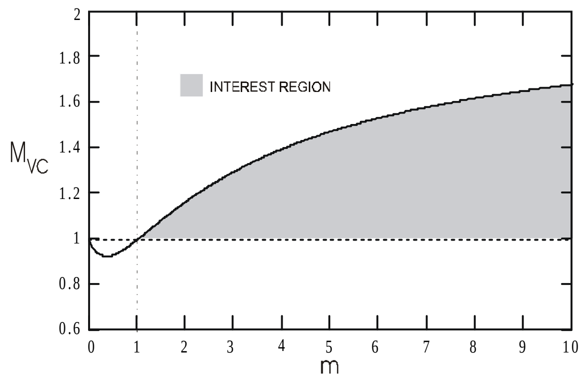


Fig. 5. The operation region for the Buck-boost #1converter using the proposed snubber – M_{VC} x m graphic.

From Fig. 5, one can see that the Buck-boost #1 converter only works for m>1 (boost characteristic). (This limitation does not occur for the Buck-boost #2, as will be seen soon.)

Besides this, the additional power transferred to the load through the snubber circuit (P_{PER}) must be controlled in order to maintain the pulsewidth modulation (PWM) characteristics of the converter. This additional power is a function of L_S and C_S which, for the Buck-boost #1 converter, are given by (17) and (20):

$$\frac{1}{\sqrt{L_S\, C_S}} = \left(\frac{100\, f_S\, M_{VC}}{Z_P\, P_{PER}}\right)\left(\frac{m+1}{m}\right) \tag{20}$$

The L_M inductance is given by:

$$L_M = L_O\, n^2 \tag{21}$$

A. Design Procedure

The proceeding is as follows.

- Knowing the converter vo1tage gain m, choose a gain M_{VC} in the interest region of the Fig. 5. It stablishes the switch overvoltage. Lower M_{VC} value leads to higher C_S value and its charge-discharge time;
- using (19), the Z_P value is obtained;
- choose the additional power transferred to the load, P_{PER} [try to work with values below 10% of P_O, to keep the PWM characteristic of the converter];

- the L_S and C_S values are obtained from (17) and (20). The *(di/dt)on* value must be verified from (14). If it results unadequated (*(di/dt)on* > 200 A/µs) [1], another M_{VC} value must be chosen and the procedure must be restarted;
- the turns ratio n is obtained by (6) and (12).

The L_O and C_O values are designed using the conventional method for PWM converters.

Using a similar analysis for the Buck-boost #2 converter, its operational region can be found. Fig. 6 (a) and (b) shows its M_{VC} and M_{SW} gain, respectively. This topology works for any m gain. Its M_{VC} definition is the same for the first solution (16), but its M_{SW} definition is given by:

$$M_{SW} = (V_C + V_{IN})/(V_{IN} + V_O) = M_{VC} + 1/(m+1) \quad (22)$$

Design equations can be easily obtained, and therefore:

$$M_{VC} = \left(\frac{m}{m+1}\right) + m\, Z_P \quad (23)$$

$$M_{VC} \leq (2\,m^2 + 3\,m)/(m^2 + 3\,m + 2) \quad (24)$$

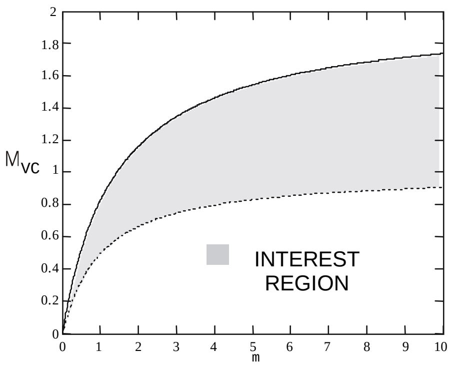
$$\frac{1}{\sqrt{L_S\, C_S}} = \left(\frac{100\, f_S}{2\, Z_P\, P_{PER}}\right)\left(\frac{(M_{VC}\,(m+1))^2 - 1}{m^2}\right) \quad (25)$$

$$n = (2\,(V_O) + V_{IN} - V_C)/(2\,V_{IN}), \quad (26)$$

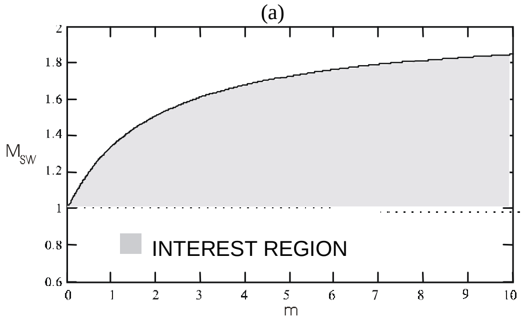
where:

$$V_C = V_O + Z_{ROFF}\, I_{LO} \quad (27)$$

Equations (13), (14), (17) and (21) also applies to the Buck-boost #2 converter.



(a)



(b)

Fig. 6. Buck-boost #2, operation region:
(a) M_{VC} x m ; (b) M_{SW} x m.

V. PWM Converters Using the Proposed Snubber

The main solutions of the proposed snubber applied to the PWM family can be seen in Figs. 7-10 [9]. The Boost converter of the Fig. 7 was formerly presented by Menegáz [10] without the D_G diode.

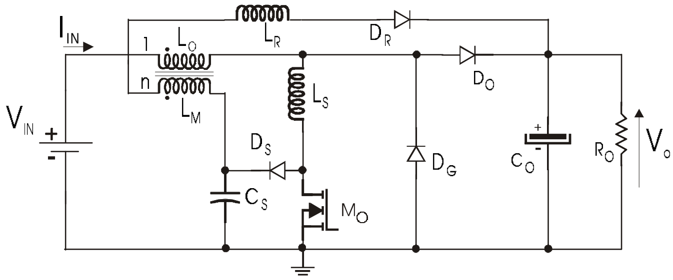


Fig. 7. - Boost converter with the proposed snubber;

The proposed snubber applied to a Buck converter is shown in Fig. 8.

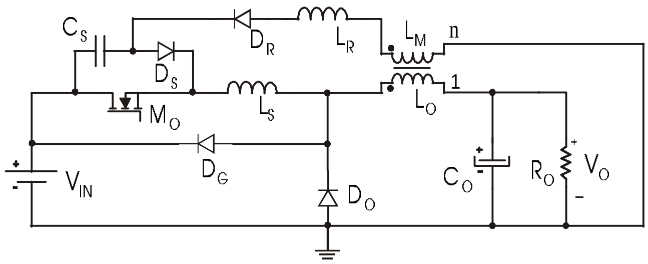


Fig. 8. - Buck converter with the proposed snubber;

As occurs for the Buck-boost converter, the Sepic, Cuk and Zeta converters present more than one possible solution, but in general only one is applied to any m converter gain. Their respective M_{VC} and M_{SW} definition are given by (16) and (22), respectively. The Sepic converter is presented in Fig. 9. Its drawback is that an inductor is introduced in the earth line. The effective resonant in inductor L_R is the sum of L_R^* plus L_S.

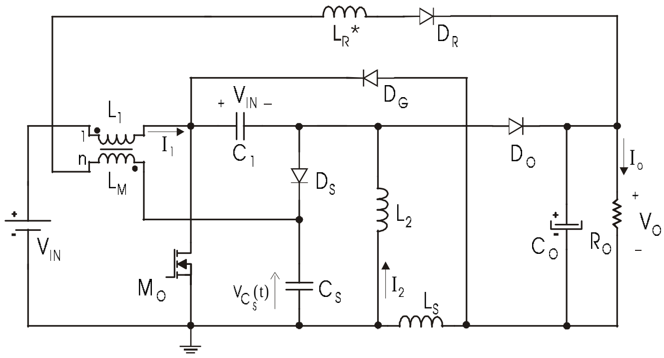


Fig. 9. - Sepic converter with the proposed snubber

For the Cuk converter, the solution is shown in Fig. 10. The switch overvoltage is similar to that obtained for the Sepic converter. For the Zeta converter (Fig. 11), no solution for the D_G position was found clamping the output diode to $V_O + V_{IN}$.

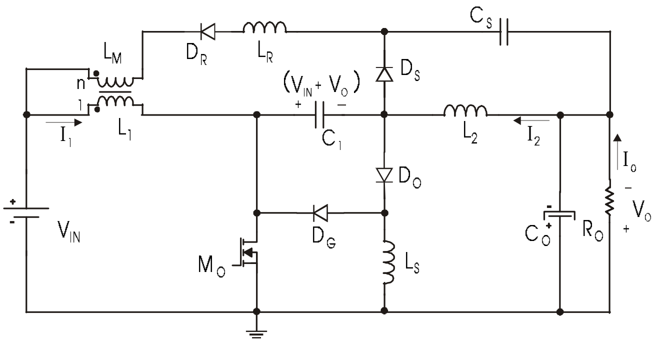


Fig. 10 - Cuk converter with the proposed snubber.

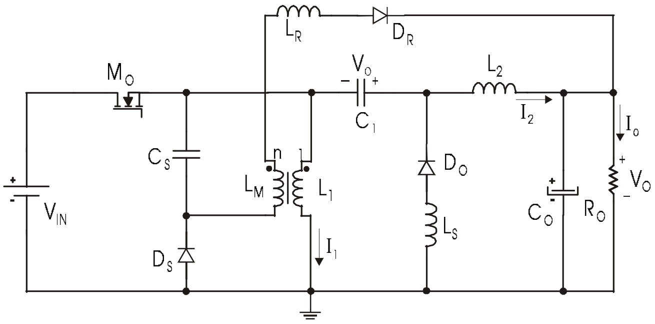


Fig. 11 - Zeta converter with the proposed snubber.

A. *Comparing to some other snubbers*

The proposed snubber can be compared to other important known snubber solutions. The Table I summarizes the comparison, considering extra components required.

TABLE I
COMPARING SOME NON-DISSIPATIVE SNUBBERS

Reference	Number of Components		
	Inductors	Capacitors	Diodes
[5]	3	1	3
[11]	1	2	3
[6]	3	1	3
Proposed Snubber	2*	1	2 or 3

*(1 sharing the main inductor core)

Most of the cases the main inductor will not present a size increase due to the magnetic coupling; in the few occasions this occurs the use of this snubber must be re-evaluated.

VI. DESIGN EXAMPLE FOR THE BUCK-BOOST #1 CONVERTER

Table II shows the design specifications for a Buck-boost #1 converter using the proposed snubber.

TABLE II
DESIGN SPECIFICATIONS

Input Voltage	48 V
Output Voltage	200 V
Output Power Range	40 - 200 W
Additional Power Transferred to the Load	10 %
Switching Frequency	50 kHz

The switching frequency used in this prototype is limited to 50 kHz because the magnetic core available in our laboratory presents high magnetic losses above this frequency.

Once V_O = 200 V and V_{IN} = 48 V, the converter voltage gain can be obtained by (15) as

$$m = 4.17 \tag{25}$$

The converter duty cycle is

$$D = V_O / (V_{IN} + V_O) = 0.8 \tag{26}$$

and the output current is given by

$$I_O = P_O / V_O = 1 \text{ A} \tag{27}$$

The L_O inductor current is given by

$$I_{LO} = I_O / (1 - D) = 5.17 \text{ A} \tag{28}$$

Choosing an L_O inductor current ripple of 20%,

$$\Delta i_{LO} = 0.2\, I_{LO} = 1 \text{ A} \tag{29}$$

Finally, the Buck-boost inductance value is given by

$$L_O = \frac{V_O\,(1 - D)}{f_S\ \Delta i_{LO}} = 750\ \mu\text{H} \tag{30}$$

The snubber components are designed using the proceeding mentioned before.

Choosing M_{VC} = 1.4 and using (19), the normalized turn-off impedance value is obtained as

$$Z_P = 0.096 \tag{31}$$

Choosing P_{PER} = 10 % and solving the equations system formed by (17) and (20), the L_S and C_S values are obtained as:

$$L_S = 2.1\ \mu\text{H} \qquad C_S = 5.76\ \text{nF} \tag{32}$$

Finally, the turns ratio n can be obtained by (6) and (12) as

$$n = 1.55 \tag{33}$$

VII. EXPERIMENTAL RESULTS FOR THE BUK-BOOST #1 CONVERTER

A Buck-boost #1 converter with the proposed snubber was built according to the developed methodology. Table III shows the device characteristics of the implemented prototype.

TABLE III
EXPERIMENTAL PROTOTYPE DEVICES

Device	*Value/Model*
Main Inductor (L_O)	750 μH
Auxiliary Inductor (L_M)	1.8 mH
Turn-on Inductor (L_S)	2.1 μH
Output Capacitor (C_O)	22 μF
Turn-off Capacitor (C_S)	5.7 nF
Switch (M_O)	IRFP360
Output Diode (D_O)	HFA08TB60
Turn-off Diode (D_S)	HFA08TB60
Auxiliary Diode (D_R)	HFA08TB60
Clamp Diode (D_G)	HFA08TB60

Fig. 11 shows the MOSFET voltage and current, whereas Fig. 12 shows the output diode voltage and current. One can observe that soft-transition is achieved in the switch, and that the output diode voltage is clamped to $V_{IN} + V_O$.

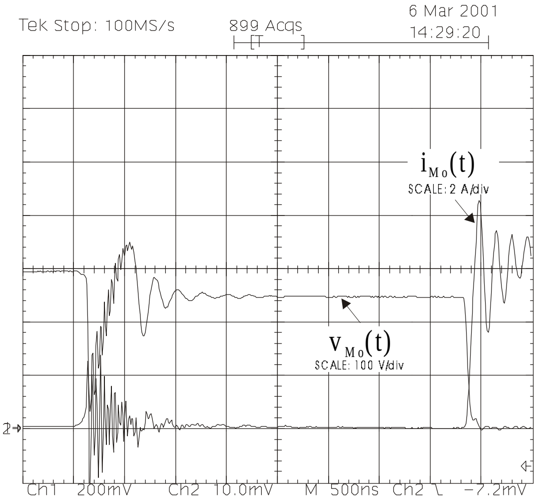


Fig. 11. MOSFET voltage and current.

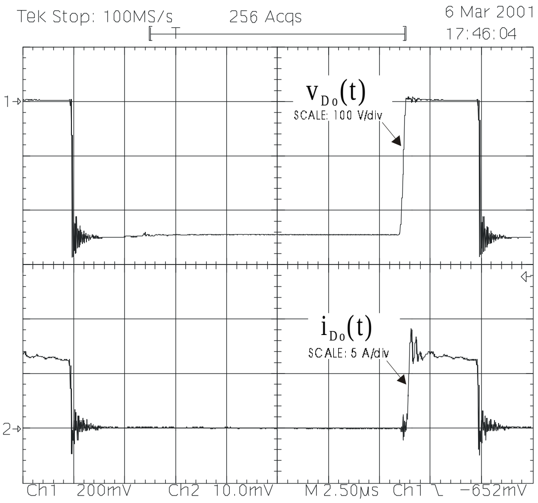


Fig. 12. Output diode voltage and current.

The Fig. 13 shows the converter efficiency employing the proposed snubber, confirming the good behaviour of the snubber.

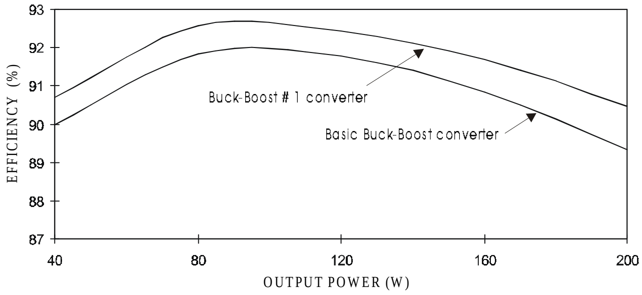


Fig. 13. Converter Efficiency.

CONCLUSION

A new regenerative turn-on and turn-off snubber applied to the PWM family was presented in this paper (the converters were analised at the continuous conduction mode – CCM). Its advantage is that it applies to any *m* converter ratio because the *n* turns ratio guarantees the correct snubber operation. Design equations were obtained to the Buck-boost converter from the analysis of the operation stages equivalent circuits, but is easily extensible to others converters. Its main characteristic is that a magnetic coupling is used to regenerate the snubber energy. This new structure requires only one additional magnetic core, to limit the *di/dt* when the switch turns on. This magnetic core is smaller than the main inductor, so its losses can be neglected. Experimental results for the Buck-boost #1 converter show that soft turn-on and turn-off transitions are obtained. Furthermore, using D_G diode eliminates the overvoltage on the output diode.

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