SOFT SWITCHED DC-DC FULL-BRIDGE CONVERTER WITHOUT STRESS

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Abstract – **This paper presents a stressless soft-switched Full-Bridge DC-DC converter. A soft switching cell that eliminates voltage and/or current stresses in the switches is introduced. A mathematical analysis, as well as simulation and experimental results, validate the operation of the studied converter.**

KEYWORDS

Stressless, soft switched.

I. INTRODUCTION

In recent years, the need of power supplies with small size and high power density, which require converters that operate at high switching frequency, has caused several undesirable effects, just as the increase of EMI levels and switching losses.

In order to achieve the minimization of losses, several devices that reduce switches have been proposed [1]-[5]. With the quasi-resonant converters appearance [6], the interest in soft-switching converters with high power and high switching frequency has increased significantly. Such converters present several advantages such as small size, light weight, high frequency of operation, high efficiency, reduced EMI and commutation losses reduction.

With the appearance of soft-switching converters with Zero-Current Switching (ZCS) and Zero-Voltage Switching (ZVS), higher current and/or voltage stresses than that obtained in PWM converters have been observed. Therefore such converters present load limitation due to high current and/or voltage stresses on the switches.

To minimize this drawback, several researches have been carried out, as in [7] and [8]. Based on them, in this paper a stressless soft-switching cell applied to a full bridge converter is proposed.

For higher power levels, the Full-Bridge converter has been widely used. With the application of resonant circuits, converter power levels were limited due to high voltage and/or current stresses.

If a resonant cell that does not submit the switches to a high voltage and/or current stresses is employed, the use of switches with lower voltage and current ratings becomes possible, causing the EMI levels to decrease as well.

This paper proposes a soft-switched Full-Bridge converter using a soft switching cell with the great advantage of eliminating high voltage and/or current stresses in the switches.

II. OPERATION PRINCIPLE

Fig. 1 shows a simplified circuit of the studied Full-Bridge converter. This converter can operate with reduced commutation losses and without voltage and current stress.

In this converter, the auxiliaries switches are turned on in ZCS way and turned off in ZVS way. The main switches are gated on the ZVS-ZCS form and are turned off in ZVS form. Switching is performed so that the main and auxiliary switches are not submitted to voltage and current stresses.

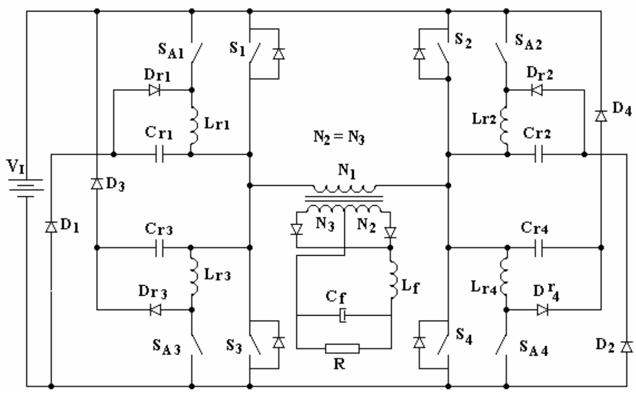


Fig. 1 – Schematic circuit of the Full-Bridge converter.

Only the positive semicycle will be studied to simplify the theoretical analysis, that will be divided in seven topological modes, according to Fig. 2, since the symmetry of both semicycles is considered.

The converter operation stages are as follows:

First Stage: [t_o-t_1]. This stage begins at the instant that switch S_{AUX} is turned on in a ZCS mode, due to the presence of inductor *Lr*, and it finishes when i_{Lr} reaches I_0.

Second Stage: [t_1-t_2]. It begins when i_{Lr} assumes the value I_0. Current I_0 flows through S_A and *Lr*. Before this stage finishes, switch *S1* is turned on in ZCS and ZVS mode. It finishes with S_A turning off in ZVS mode.

Third Stage: [t_2-t_3]. This is a resonant stage between *Cr, Lr and Dr*, where capacitor *Cr* charges until it reaches V_I, as this stage is finished.

Fourth Stage: [t_3-t_4]. During this stage, the inductor current decreases linearly until it reaches zero. Switch current i_S increases until it reaches load current I_0, and capacitor voltage V_{Cr} remains in V_I.

Fifth Stage: [t_4-t_5]. Energy transference from source to load occurs in this stage. It finishes when switch S_1 is turned off in ZVS mode, as the linear stage of the capacitor begins.

Sixth Stage: [t_5-t_6]. Capacitor linear discharge. It finishes when capacitor voltage V_{Cr} reaches zero.

Seventh Stage: [t_6-t_7]. Freewheeling stage. It starts when the voltage on capacitor *Cr* reaches zero, as the freewheeling stage to the load begins. This stage finishes with the turning on of switches S_A and S_2.

Fig. 3 shows the main waveforms of the operation stages. The phase diagram is shown in Fig. 4, where one can notice the resonant circuit operation.

Fig. 5 shows the operation limits where the converter can operate in soft and hard switching modes.

Considering (1) and (2), the converter operates in soft switching mode for higher loads, as it can be seen in Fig. 5.

If an unity turn ratio transformer is assumed, the following gain expression can be obtained.

$$G = \frac{V_0}{V_I} \tag{1}$$

$$a = \frac{I_0}{V_0}\sqrt{\frac{L_r}{C_r}} \tag{2}$$

$$w_0 = 2p\, f_0 = \frac{1}{\sqrt{L_r \times C_r}} \tag{3}$$

where:

fs – switching frequency;

f_0 – resonant frequency;

a – normalized current load in relation to the resonant current peak value;

w_0 – resonant frequency;

I_0 – load current.

The expressions regarding the operating stages are presented as follows.

A. First Stage [t_o-t_1]

- Initial conditions: $I_{Lr}(t_0) = 0$; $V_{Cr}(t_0) = 0$

$$t_1 = \frac{a}{w_0} \tag{4}$$

B. Second Stage [t_1-t_2]

- Initial conditions: $I_{Lr}(t_1) = I_i$; $V_{Cr}(t_1) = 0$

$$t_2 = t_2 \quad t_1 \tag{5}$$

where t_2 is the instant at which S_A is turned off.

C. Third Stage [t_2-t_3]

- Initial conditions: $I_{Lr}(t_2) = I_0$; $V_{Cr}(t_2) = 0$

$$t_3 = \frac{\sin^{1} \frac{1}{a} \div}{w_0} \tag{6}$$

D. Fourth Stage [t_3-t_4]

- Initial conditions $I_{Lr}(t_3) = \frac{I_0}{a}\sqrt{a^2 \quad 1}$; $V_{Cr}(t_3) = V_i$

$$t_4 = \frac{1}{w_0} \times \sqrt{a^2 \quad 1} \tag{7}$$

E. Fifth Stage [t_4-t_5]

- Initial conditions: $I_{Lr}(t_4) = 0$; $V_{Cr}(t_4) = V_i$

$$t_5 = DT \quad t_4 \tag{8}$$

F. Sixth Stage [t_5-t_6]

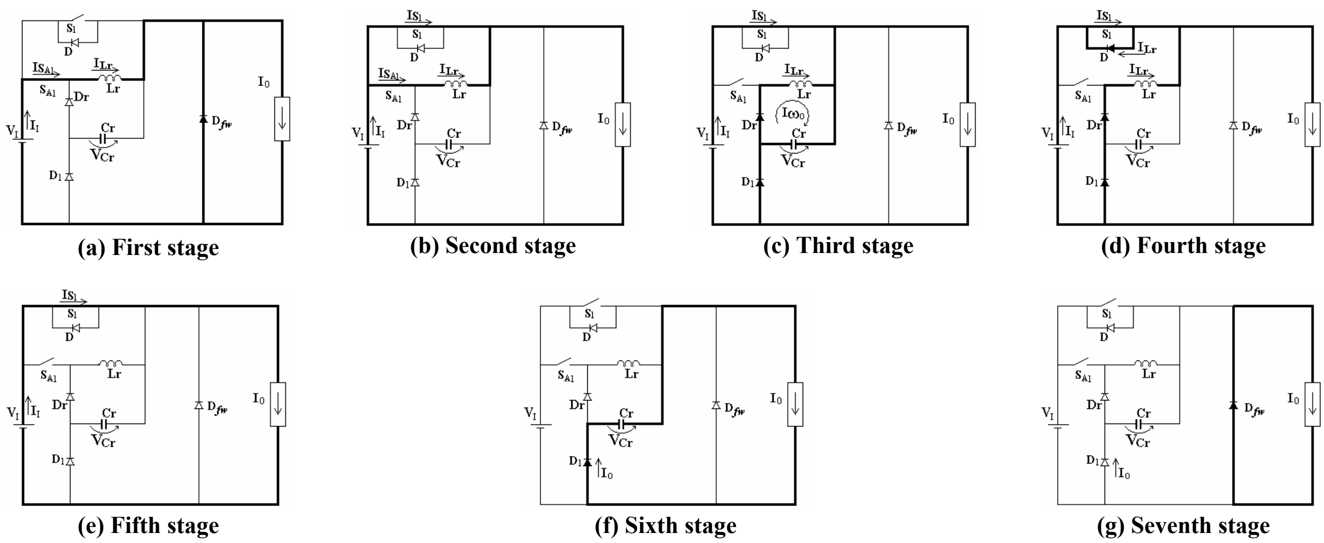
- Initial conditions: $I_{Lr}(t_5) = 0$; $V_{Cr}(t_5) = V_i$

$$t_6 = \frac{1}{a \times w_0} \tag{9}$$

G. Seventh Stage [t_6-t_7]

Initial condition: - $I_{Lr}(t_6) = 0$; $V_{Cr}(t_6) = 0$

$$t_7 = T \quad t_6 \tag{10}$$



(a) First stage **(b) Second stage** **(c) Third stage** **(d) Fourth stage**

(e) Fifth stage **(f) Sixth stage** **(g) Seventh stage**

Fig.2 – Operating stages of the proposed converter.

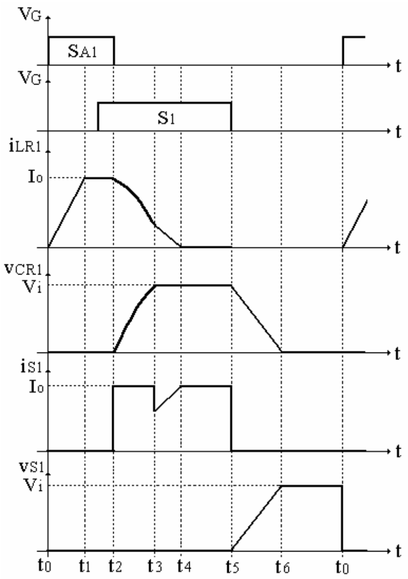


Fig.3 – Main waveforms of the soft- switched converter.

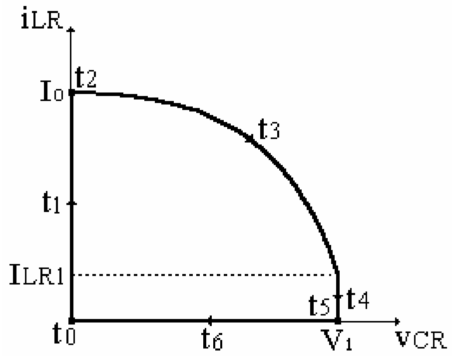


Fig.4 – Phase diagram.

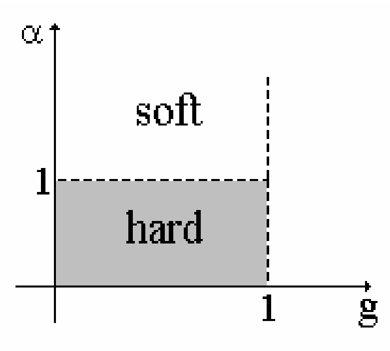


Figure 5 – Operation limits.

From the preceding equations, the static gain can be determined as follows.

$$V_0 = \frac{1}{T}\int_0^T V_I(t)\,dt \qquad (11)$$

Therefore, from (11), the gain is given as:

$$G = D + \frac{1}{\omega_0 \cdot T}\left(\frac{1}{2\cdot\alpha} - \alpha\right) \qquad (12)$$

Where:

$$D = \frac{(t_5 - t_0)}{T}$$

$$T = t_7 - t_0$$

Fig. 6 shows the voltage gain variation with normalized current (α) for four different values of duty cycle (D). As it can be seen, this converter, except for light loads, behaves almost as the conventional PWM converters.

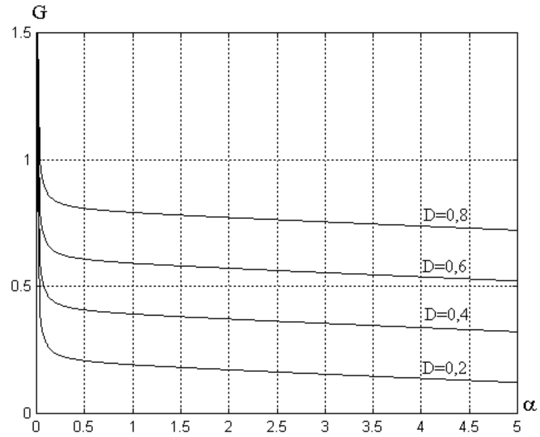


Fig. 6 – Curves of the static gain characteristic as a function of the normalized input current, when duty cycle varies.

III. SIMULATION AND EXPERIMENTAL RESULTS

In order to illustrate the operation of the stressless soft-Switched Full-Bridge converter, simulation tests were performed using the following parameters set: V_I = 100 V_{DC}; *Lf*=1 mH; *Cl*=330 µF; *Cr*=6.8 nF; *Lr*=7 µH; *fs*=50 kHz. Switches used are MOSFET's IRF740 and diodes are MUR1560 and UF5404.

Figs. 7 and 8 shows simulation results. As it can be observed, the converter operates softly and without stress.

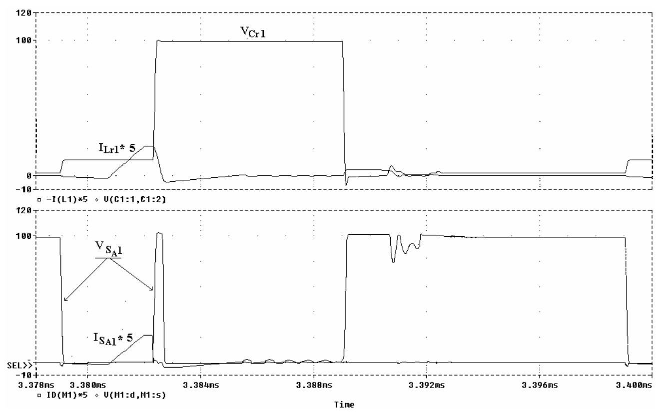


Fig. 7 – Simulation results:
Upper: capacitor voltage (V_{Cr}) and inductor current(I_{Lr});
Lower: auxiliary switch voltage (V_{SA1}) and current (I_{SA1}).

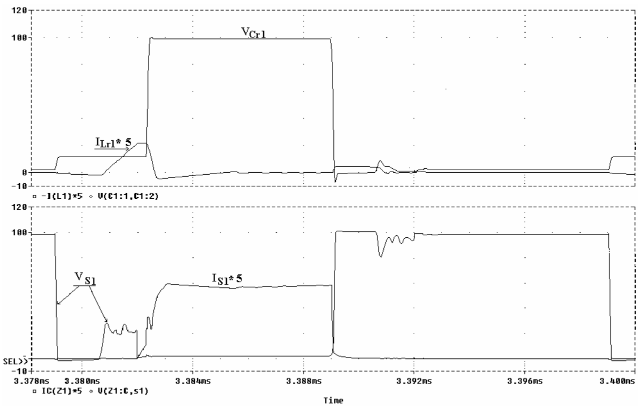


Fig. 8 – Simulation results:
Upper: capacitor voltage (V_{Cr}) and inductor current(I_{Lr});
Lower: main switch voltage (V_{S1}) and current (I_{S1}).

A prototype of the stressless soft-switched Full-Bridge converter was built using the following parameters set: V_I=400V_{DC}; Lf=1 mH; Cl=330 F; Cr=6.8 nF; Lr=7 H; fs=50 kHz. Switches used are MOSFET's IRF740 and diodes are MUR1560.

Experimental results are presented in Figs. 9 and 10, which demonstrate the fundamental operation principles. As it can be seen, the switching occurs with reduced losses and without current and/or voltage stresses.

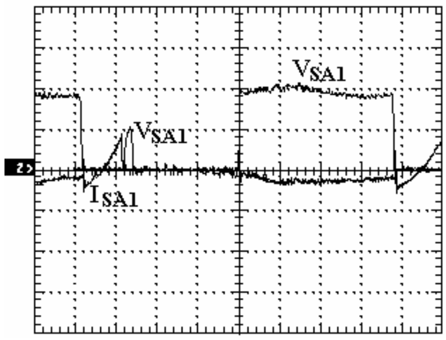


Fig. 9 – Auxiliary Switch Voltage V_{SA1} (200V/div.) and current I_{SA1} (2A/div.) – (time: 2.5 ms/div.).

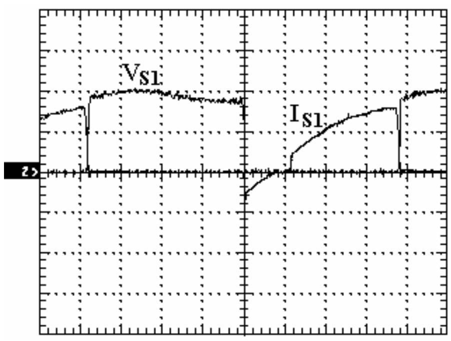


Fig. 10 – Main switch voltage V_{S1} (200V/div.) and current I_{S1} (5A/div.) – (time: 2.5ms/div.).

Fig. 11 shows the converter efficiency as a function of the output power. As it can be seen, the proposed converter achieves similar performance compared to the conventional one for low power, but for higher power the soft converter is better than conventional one.

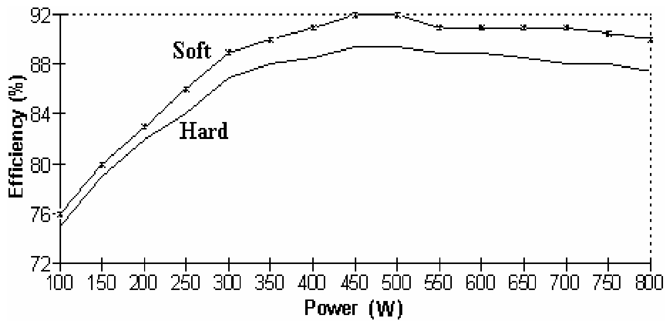


Fig. 11 – Efficiency as a function of the output power.

IV. CONCLUSION

The DC-DC Full-Bridge Converter using a stressless soft switching active cell has been presented. The main and auxiliaries switches operate softly and without voltage and/or current stresses. The operation and performance of the converter were verified by PSPICE simulation results, which confirm the soft commutation in ZVS and ZCS modes in all switches. Theoretical results have been verified experimentally on a laboratory prototype.

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