A Family of PWM Soft-Single-Switched Converters without Voltage and High Current Stresses

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***Abstract* - The use of switching regulator circuits at high power levels and high frequencies requires careful examination and control of the power dissipation during switching. In this paper it is shown a family of PWM soft-single-switched converters which, having only a single active switch, is able to operate with soft switching in a pulse width modulation way without voltage and high current stresses. In addition such converters can work at high switching frequencies for wide range of load. In order to illustrate the operating principle of these new converters a detailed study, including simulations and experimental test is carried out. The validity of these new converters is guaranteed by the obtained results**.

I. INTRODUCTION

High switching frequencies are necessary to reduce the size and the weight of the DC-DC converters. However, this yields high switching losses and, consequently, low efficiency in hard switching converters.

To solve this problem the quasi-resonant converters (QRCs) were proposed in [1]. 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-modulated quasi resonant converters (PWM-QRC) operate with fixed switching frequency they do not present the control problem like the QRCs [2]. On the other hand they present all the other disadvantages of the QRCs which limits their applications.

Nowadays there are many converters which does not present the limitations described above. An example of such converters is found in [3]. Although this converter presents several advantages, its main switch turns off hard and has high current stress.

The most part of the PWM soft switching converters proposed until now have two active switches and one that has a single active switch, as described in [4], presents high stresses.

To overcome this draw-back, the converter in [5] was proposed. In this paper it will be shown additional aspects of that converter and a converter family derived of it.

II. BOOST AND BUCK PWM SSS CONVERTERS

Fig. 1 shows the Boost PWM soft-single-switched (SSS) converter of the proposed family. The inductor L_{R2} is used to provide ZCS turning on of the switch S_1. L_{ac} is magnetically coupled with L_f. The turn ratio between L_f and L_{ac} must be large enough to induce voltage in L_{ac} making null the current of L_{R2} before the next turning on of the switch S_1, when D_1, D_3 and D_4 are simultaneously conducting.

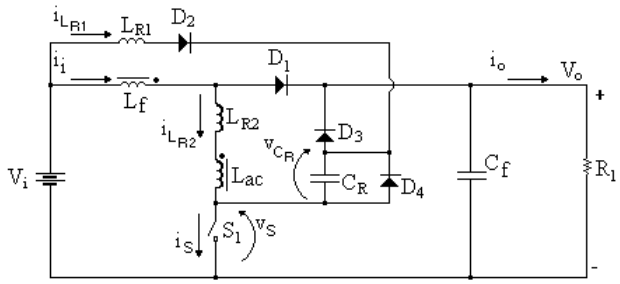


Fig. 1 - Boost PWM soft-single-switched converter.

The branch composed by L_{R1}, D_2 and C_R is used to charge C_R with voltage V_o before the switch S_1 is turned off. Thus, this switch will turn off in a ZVS way.

The operating stages are presented in details in [5]. While diode D_1 is off, the loop V_i-L_{R1}-D_2-C_R-S_1, provides the ZVS of the main switch. When the switch turns off, the energy control loop is initially, V_i-L_f-L_{R2}-L_{ac}-C_R-D_3-C_f until C_R voltage reaches the induced voltage in L_{ac}. Then the loop becomes, L_{R2}-L_{ac}-C_R-D_3-D_1 until C_R is drained to zero volts. Finally the loop becomes, L_{R2}-L_{ac}-D_4-D_3-D_1 until diodes D_4 and D_3 are turned off.

Fig. 2 shows the Buck PWM SSS converter whose operation has strong relationship with the Boost converter of the same family.

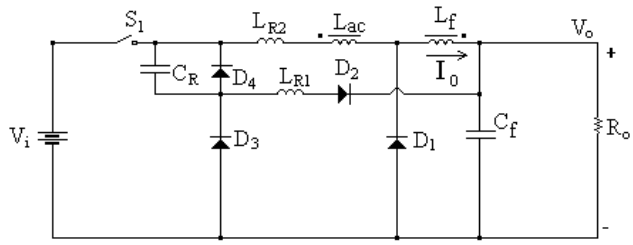


Fig. 2 - Buck PWM soft-single-switched converter.

The main theoretical waveforms are shown in Fig. 3.

It is observed this converter do not contain any voltage stress and S_1 current stress can be reduced by lowering k and by increasing value of L_{R1}. This L_{R1} increasing do not provoke any important disturbance in the circuit, since the branch composed by L_{R1}, D_2 and C_R does not belong to the

principal branch. This capacitor C_R can be charged during all interval that the switch S_1 is conducting.

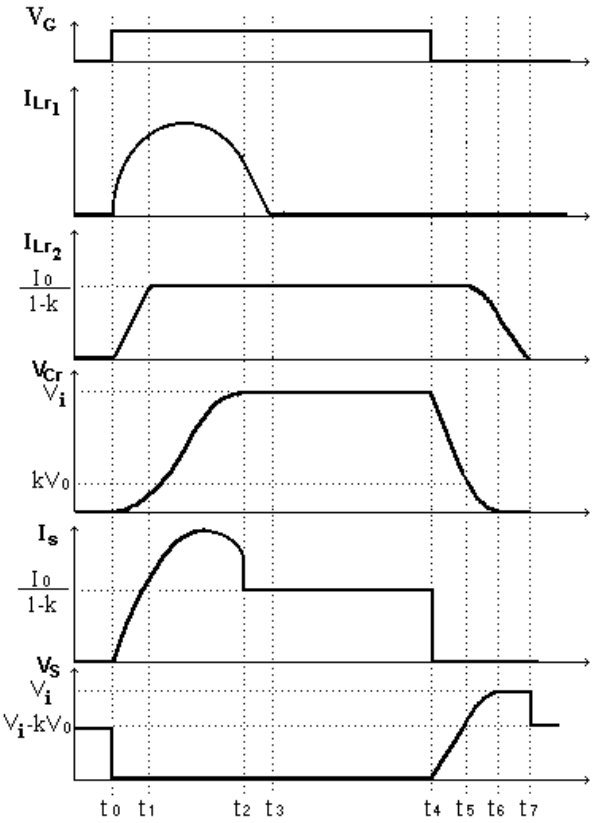


Fig. 3 - Main waveforms for circuit in Fig. 2.

Figs. 4 and 5 shows four different regions of the plane *(α x G)* for the proposed Buck and Boost converters. In the regions 3 and 4, the converters operate hard and in the other two regions they work with soft switching. In the regions 2 and 3 the L_{R2} current becomes zero before the resonant capacitor discharge completely. Despite, the converters operate soft in the region 2.

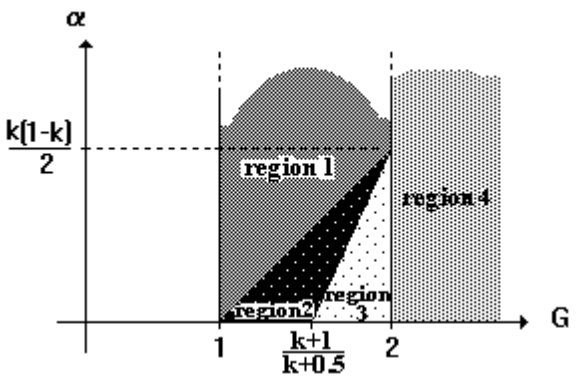


Fig. 4 - Boost Converter operating regions-

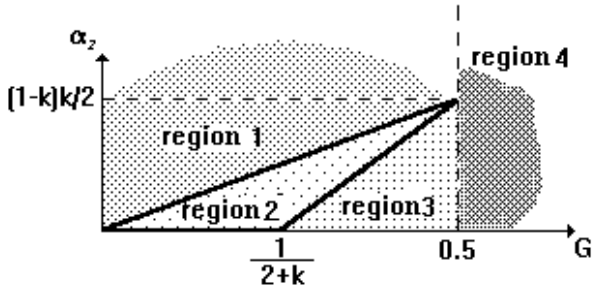


Fig. 5 - Buck Converter operating regions-

III. CIRCUIT ANALYSIS

Figs. 6 and 7 presents the models used for static gain determination.

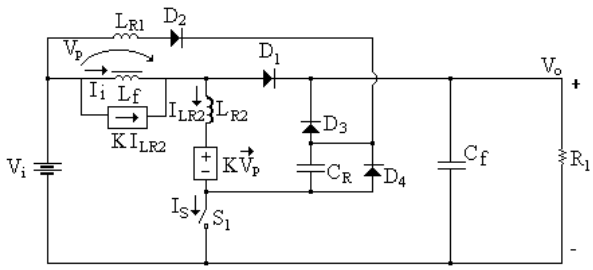


Fig. 6 - Boost converter model for static gain determination.

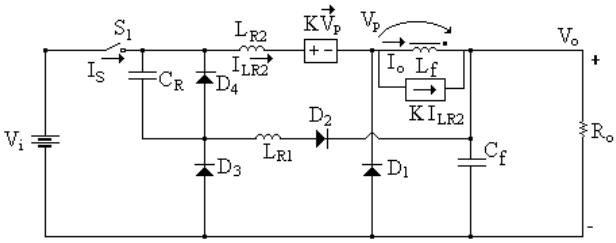


Fig. 7 - Buck converter model for static gain determination.

To determine the static gain of the PWM converters presented in this paper, the following considerations have been made:

- the current I_i and voltage V_o of the Boost converter, and the current I_0 and the voltage V_o of the Buck converter are ripple-free.
- all components and switches are ideal.

Furthermore the following definitions were used:

$$\omega_o = \left(\frac{1}{L_{R2}C_R}\right)^{1/2} \tag{1}$$

$$\alpha = \frac{I_i}{V_0}\left(\frac{L_{R2}}{C_R}\right)^{1/2} \tag{2}$$

$$\alpha_B = \frac{I_0}{V_i}\left(\frac{L_{R2}}{C_R}\right)^{1/2} \tag{3}$$

$$K = \frac{N_{ac}}{N_f} \tag{4}$$

$$G = \frac{V_o}{V_i} \tag{5}$$

.

where

N_f = L_f turns
N_{ac} = L_{ac} turns

Using these definitions and several equations which were developed for all stages, we can determine the static gain, as given by the following equations.

Boost Converter

$$G = \frac{1}{1 - \left(\frac{D}{1-k}(1 - \frac{k}{G}) + \frac{1}{T\omega_0}(-\frac{\alpha}{(1-k)^2} + \frac{(1-\frac{k}{G})^2}{2\alpha}) \right)} \tag{6}$$

Buck Converter

$$G = \frac{D}{1-k}(1-kG) + \frac{1}{T\omega_0}(-\frac{\alpha_B}{(1-k)^2} + \frac{(1-kG)^2}{2\alpha_B}) \tag{7}$$

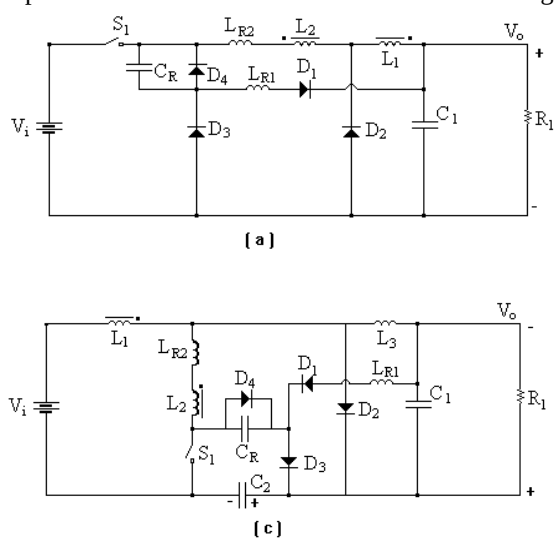
.

Where:

$$D = \frac{(t_4 - t_0)}{T} \tag{8}$$

$$T = t_7 \tag{9}$$

It can be seen there is a strong relationship between the static gain of the two converters. Both static gain depend on: the turn ratio *(K)* between L_f and L_{ac} , the duty-cycle *(D)*, resonant frequency *(w_o)*, the normalized current *(α)* and the switching period. If the term *(kG)* on the Buck converter gain is replaced by *(k/G)*, the new obtained expression will be included in the Boost converter gain.



(a)

(c)

Figs. 8 and 9 show how voltage gain varies with normalized current (α, α_B) for five different values of duty cycle. As it can be seen, these converters, except for light loads, behaves almost like the conventional converters.

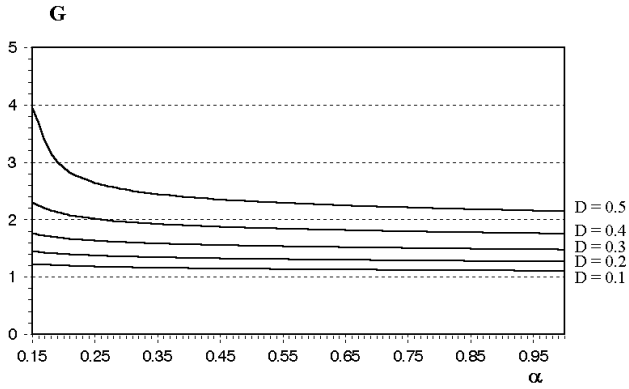


Fig. 8 - Curves of Boost static gain characteristic vs. normalized input current, when duty cycle varied.

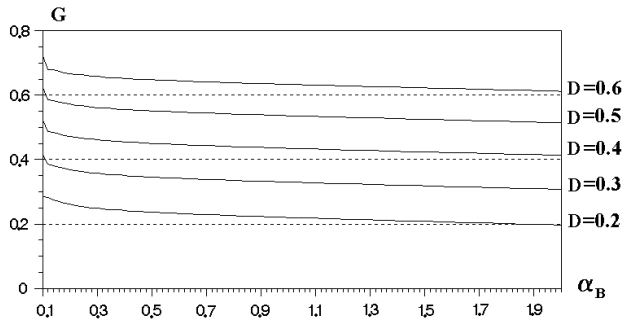
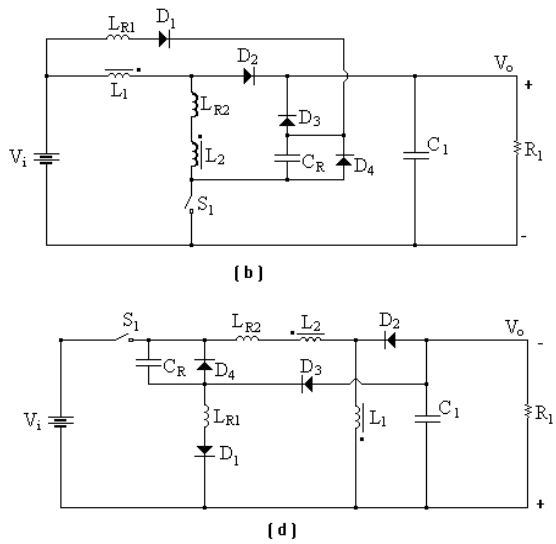


Fig. 9 - Curves of Buck static gain characteristic vs. normalized input current, when duty cycle varied.

IV. A FAMILY OF PWM SSS CONVERTERS

As it can be seen, the Boost PWM-SSS converter is consisted of the conventional Boost PWM converter added by the resonant network composed by the elements L_{R2}, L_{ac}, L_{R1}, D_2 , D_3 and D_4 which are connected as shown in fig.1



(b)

(d)

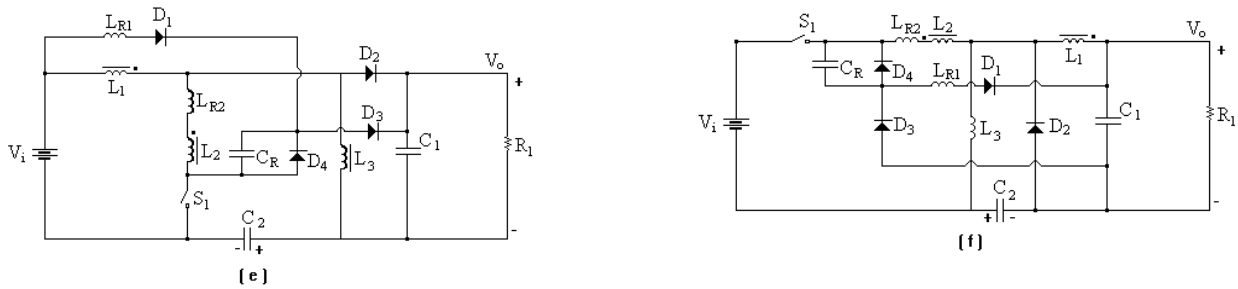


Fig. 10 - The family of PWM SSS converter.(a)Buck (b)Boost (c)Cuk (d)Buck Boost (e)Sepic (f)Zeta.

The other converters of the family which is being proposed are obtained in similar way, as shown in fig. 10.

Some researchers thought this non dissipative commutation cell could not be applied to a family. However, after lots of researches this application became possible.

Table 1 - Values of parameters shown in Fig.11

Converter	$I_a\sqrt{\frac{L_{R1}}{C_R}}$	V_a	V_P
Buck	V_i-V_0	V_i	V_0
Boost	V_i	V_0	V_0-V_i
Cuk	V_0	V_i+ V_0	V_0
Buck-Boost	V_i	V_i	V_0
Sepic	V_i	V_i +V_0	V_0-V_i
Zeta	V_i-V_0	V_i-V_0	V_0

As it well known, all converters of a family have state planes with the same shape and voltage gains which are easily derived from each other, as it can be observed from expressions (6) and (7).

Fig. 11 shows the normalized state plane for PWM soft-single-switched converters. Although the state plane of each one of these converters shapes like that, the values of I_a, V_a e V_D are different for all converters as shown in tab.1.

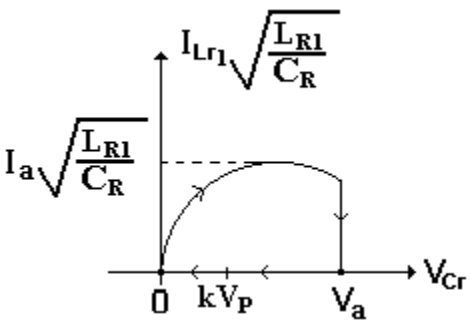


Fig. 11 - State plane for PWM soft-single-switched converters.

V. SIMULATION RESULTS

In order to illustrate the feasibility and operation of the converters of the proposed family, the Buck converter, have been simulated with the following parameters: V_i = 120 V (input voltage), V_0 = 50 V (output voltage), L_f = 162 μH (filter inductor), k= 0.25 , L_{R1} = 20 μH (resonant inductor 1), L_{R2} = 4.52 μH (resonant inductor 2), C_f = 220 μF (output filter capacitor), C_R = 6.2 nF (resonant capacitor), f = 100 kHz (switching frequency).

The semiconductor components are considered ideal. A sample of waveforms obtained by simulation are shown in Fig. 12.

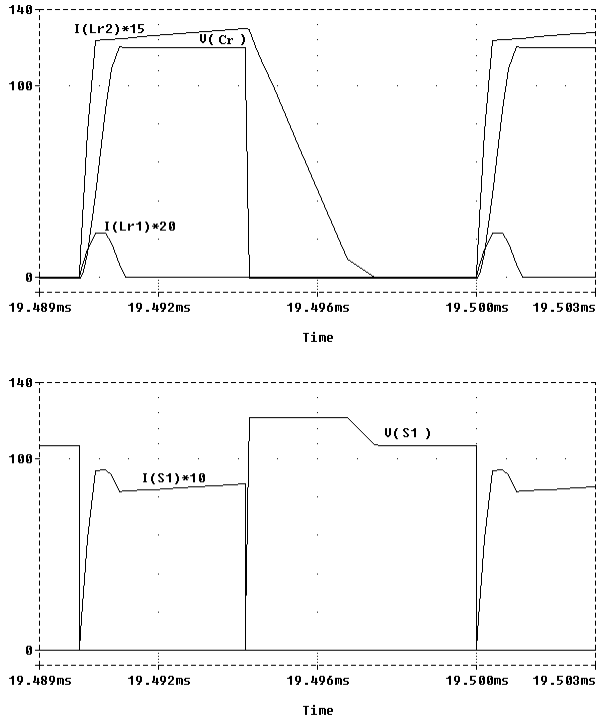


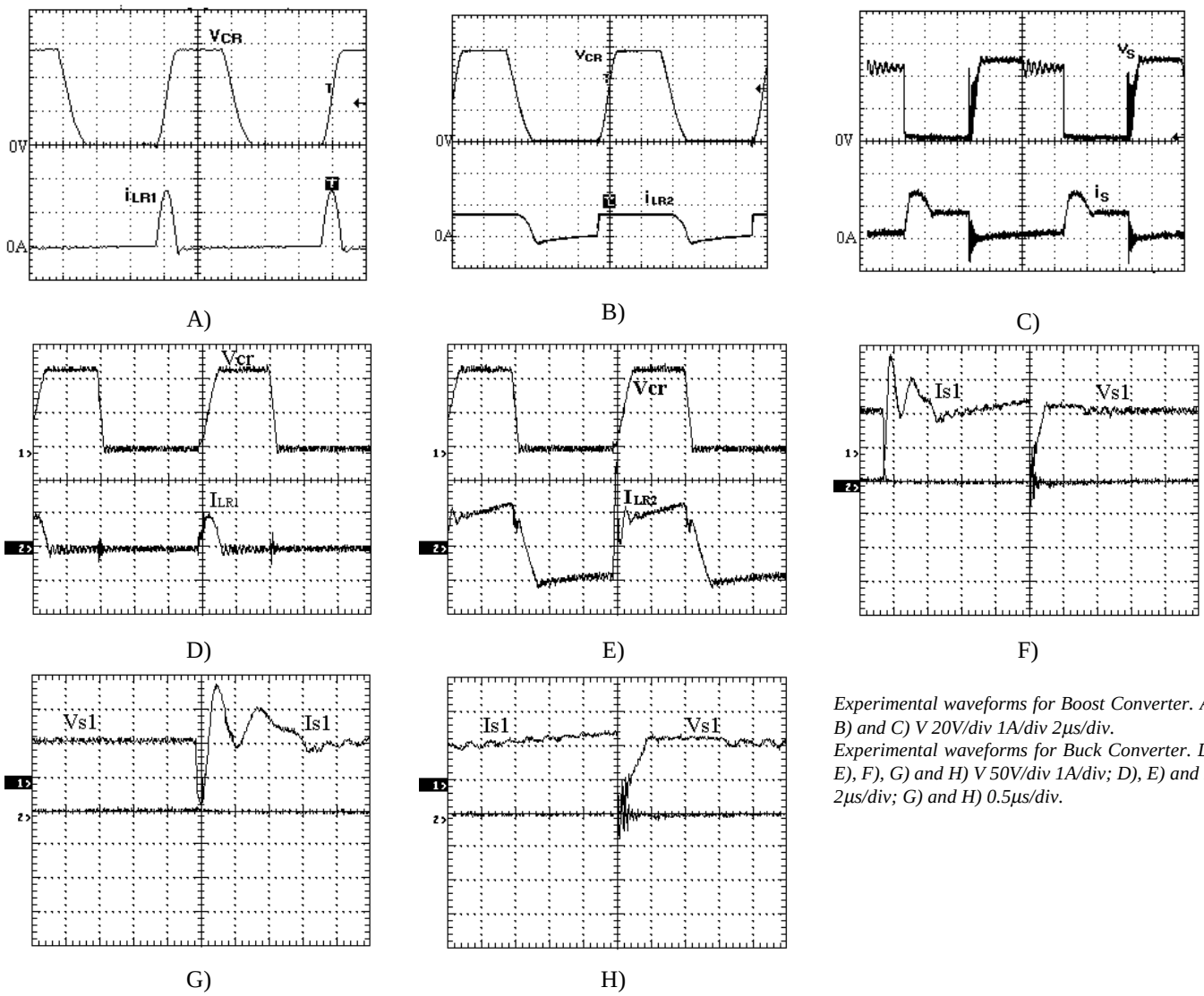
Fig. 12 - Simulation results for the PWM soft-single-switched converter.

As it is observed from Fig. 12, in this situation S_1 operates under soft switching conditions. It is turned on under zero-current and turned off with zero-voltage. The maximum voltage in this switch is equal to the input voltage.

VI. EXPERIMENTAL RESULTS

Experiments with the proposed soft-switching Boost and Buck Converters, whose result sample is shown in Fig. 13 are useful to verify theoretical operation principles.

The experimental values of L_f, L_{ac}, L_{R1}, L_{R2}, C_0, C_R, and f are the same as those specified in simulation, but for the Boost converter output voltage is 60V and input voltage is 30V. The used switch was the MOSFET IRF740, and diodes D_1, D_2,, D_3 and D_4 were the HFA15TB60.



Experimental waveforms for Boost Converter. A), B) and C) V 20V/div 1A/div 2µs/div.
Experimental waveforms for Buck Converter. D), E), F), G) and H) V 50V/div 1A/div; D), E) and F) 2µs/div; G) and H) 0.5µs/div.

Fig. 13 - Experimental waveforms for PWM SSS Converters

Notice, in proposed converters the voltage stress across the switch is the same as in the hard switched converter. When the switch turns on the inductor L_{R1} sets the C_R capacitor voltage to provide zero-voltage turn off. Fig. 13(G) shows L_{R2} effect to slow the switch current at turn on. Fig. 13 (H) shows how slow the switch voltage rises at turn off due to capacitor C_R charge.

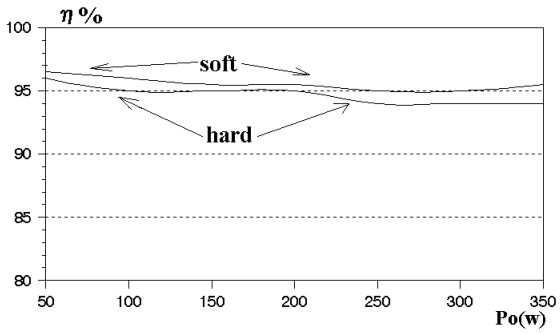


Fig. 14 -Experimental efficiency versus output power of the Buck Converter.

Fig. 14 shows the efficiency versus output power of the Buck converter. It can be seen the commutation cell provokes an increment of the converter efficiency around 2% at the rated load condition.

VII. CONCLUSION

A new Family of PWM Soft-Single-Switched Converter has been presented . These converters with only a single switch can operate in a soft switching way in a wide load range without voltage and high current stresses. As an example, Boost and Buck soft-switching converter are studied and the obtained results, validate the proposed converter family.

VIII. REFERENCES

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