A NEW HPF ZCS-PWM SEPIC RECTIFIER USING PEAK-CURRENT AND AVERAGE-CURRENT MODE CONTROLS – A COMPARATIVE ANALYSIS

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***Abstract* – This paper presents a new high power-factor (HPF) pulse width modulated (PWM) Sepic rectifier, operating in voltage step-down mode. This converter is based on a new soft-commutation cell, which consists of two active switches, two diodes, two small resonant inductors and one resonant capacitor, providing zero-current switching (ZCS) for the active switches.**

This cell provides a zero current (ZC) turn-on and zero-voltage-zero-current (ZVZC) turn-off for the active switches, recommended to IGBTs (Insulated Gate Bipolar Transistors) applications. Moreover, it should be noticed that the diodes D_1 and D_2 are also softly commuted in zero-voltage (ZV), during their turn-on.

In this paper, two different control techniques are employed to the new Sepic rectifier, in order to obtain high power factor. These techniques, known as peak-current mode control and average-current mode control, respectively, provides the input current shaping, allowing the obtaining of low total harmonic distortion (THD) in the input current and resulting in high power-factor.

The principle of operation, the theoretical analysis, a design example, and experimental results from a laboratory prototype rated at 300W, $220V_{rms}$ nominal input voltage, $51V_{dc}$ nominal output voltage, and operating at 20kHz, are reported to provide the comparisons between the power-factor correction techniques proposed, in compliance with IEC 1000-3-2.

I. INTRODUCTION

Nowadays the large application range of switching mode power supplies has been demanding for their reduced size and volume, high efficiency and power quality.

The volume problem can be solved increasing the switching frequency, which reduces the capacitors and inductors size. On the other hand, there is an increasing on the switching losses that is proportional to the switching frequency, as well as an increasing on the current and voltage stresses over the semiconductors and electromagnetic interference (EMI) emission.

The soft-commutation techniques have been developed to reduce the switching losses and EMI emission, facilitating high switching frequency operation, then providing size and volume reduction with high efficiency [1 and 2].

In order to use IGBTs as power switches for high power or high voltage applications (above 500W), due to their smallest conduction losses in relation to MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistor), the zero-current switching (ZCS) or zero-current transition (ZCT) techniques are recommended to reduce switching losses at switching frequencies higher than 20kHz [3].

As known, most of the switching mode power supplies operate as non-linear loads that drain non-sinusoidal currents from the ac system. In general, it becomes in a low power-factor for the structure. Therefore, using different current-mode controls it is possible to emulate a resistive load, consequently obtaining input current with low THD [4 and 5].

Based on these facts, this paper presents a new ZCS-PWM commutation cell, derived from the commutation cell analyzed in [2]. This new ZCS-PWM commutation cell provides a zero-current (ZC) turn-on and a zero-current-zero-voltage (ZCZV) turn-off for the active switches S_p and S_a, besides a zero-voltage (ZV) turn-on for the diodes D_1 and D_2.

A new family of isolated converters can be obtained from this new ZCS-PWM cell as derived Sepic, Buck-Boost and Zeta converters through the inductance of accumulation (L_M). The novel ZCS-PWM Sepic rectifier presented in Figure 1 is a preliminary non-isolated version, adopted to the analysis in this paper.

The peak-current mode and the average-current mode controls are used to provide an experimental comparison to the new ZCS-PWM Sepic rectifier in a voltage step-down application.

The power-factor correction techniques proposed provide high input power-factor for this new Sepic rectifier, in agreement with the main harmonic standards, as IEC 1000-3-2.

Therefore, this new ZCS-PWM voltage step-down Sepic rectifier is able to provide high efficiency for a wide load range, low EMI emission, high power-factor and low THD in the input current.

II. THE NEW TOPOLOGY AND PRINCIPLE OF OPERATION

Figure 1.a shows the new HPF-ZCS-PWM voltage step down Sepic rectifier using peak-current mode control and figure 1.b shows this converter using average-current mode control. Two switches S_p (main switch) and S_a (auxiliary switch), two diodes D_1 and D_2, two small resonant inductors L_{r1} and L_{r2}, and one resonant capacitor C_r compose the commutation cell.

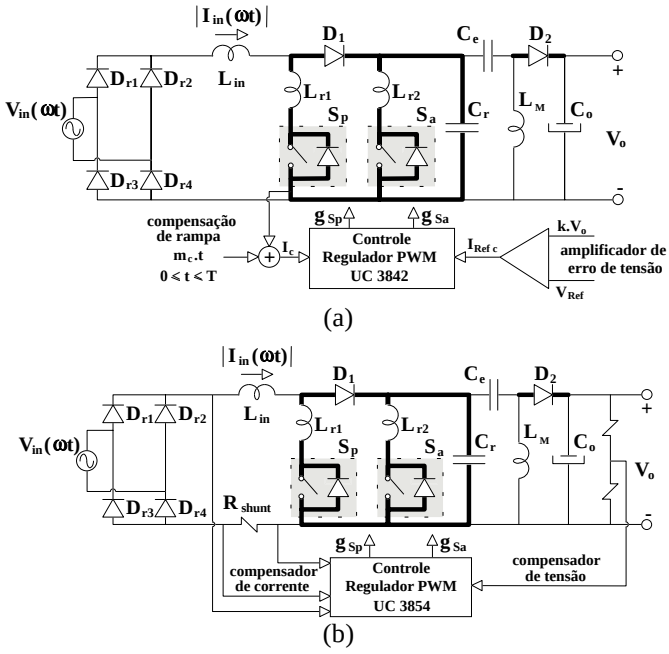


Fig. 1 – New HPF ZCS-PWM step-down Sepic rectifier.
(a) peak-current mode control with slope compensation.
(b) average-current mode control.

In order to explain the operation of this new converter and quantify its behavior, the following conditions are assumed:

- all components are ideal;
- the switching frequency (f_s) is much higher than the ac system frequency (f_{line}), so the input voltage can be considered practically constant during one switching period (T_s);
- the input voltage ($V_{in}(\omega t)$) is considered sinusoidal, and the output voltage (V_o) is constant;
- the input filter (L) associated with the input rectifier (D_{r1} until D_{r4}) is approximated by an input rectified current source ($|I_{in}(\omega t)|$), and it is considered constant ($|I_{in}(\omega T_i)|$) during a generic switching period ($T_i = T_s$);
- the accumulation inductor (L_M) is large enough to be approximated by a constant current source ($I_M = I_{o\ nom}$), where $I_{o\ nom}$ is the nominal value of the output current;
- the accumulation capacitor (C_e) is replaced by a constant voltage source (V_{Ce}), during a generic switching period (T_i);
- the peak-current reference of control ($I_{Ref\ c}$) is considered constant during an ac system period (T_{line}) in the peak-current mode control.

Figure 2 shows the main ideal waveforms and the topological stages obtained from the analysis of the proposed rectifier, for both control modes used, during a generic switching period.

It can be seen in Figure 2.a that the main switch S_p turns on at $\omega t = \omega t_0$, and the auxiliary switch S_a at $\omega t = \omega t_2$, both in zero-current switching (ZCS). Both switches are turned off simultaneously, during the seventh stage ($\Delta t_7 = \omega t_7 - \omega t_6$), in zero-current and zero-voltage (ZCZV). It should be noticed that the diodes D_1 and D_2 are also softly commuted in zero-voltage (ZVS) in their turn-on processes, at $\omega t = \omega t_4$ and $\omega t = \omega t_9$, respectively.

It should be noticed that the current through the main switch ($|Iin(\omega t)|$) is smaller than that observed in the conventional Sepic converter ($|I_{in}(\omega t) + I_o|$),reducing the conduction losses in this semiconductor device.

In the peak-current mode control, the auxiliary switch S_a turns on at $\omega t = \omega t_2$ when $i_c(\omega t)$ is equal to $I_{Ref\ c}$.

Figure 2.b shows the topological stages for the new HPF-ZCS-PWM Sepic rectifier during a generic switching period. These stages are described as follows:

- 1st stage: The main switch is turned on in ZC, due to the presence of the resonant inductor L_{r1}. The current through L_{r1} (i_{Lr1}) rises linearly from zero up to $|I_{in}(\omega T_i)|$, when the diode D_1 is turned-off.
- 2nd stage: The current i_{Lr1} remains constant and flowing through S_p. This time interval is used to regulate the output voltage;
- 3rd stage: The auxiliary switch is turned-on at ZC, due to the presence of the resonant inductor L_{r2}. The current through L_{r2} (i_{Lr2}) rises linearly from zero up to I_M, when the diode D_2 turns off;
- 4th stage: The resonance between C_r and L_{r2} starts (the voltage across C_r decreases and the current i_{Lr2} increases). When the voltage across C_r becomes zero, the current i_{Lr2} reaches its maximum value $I_{Lr2max}(\omega t)$, and the diode D_1 turns on in ZV;
- 5th stage: The resonant inductors L_{r1} and L_{r2} are connected in parallel. Then, the currents through them decrease. This stage finishes when the current through L_{r1} becomes zero at $\omega t = \omega t_5$;
- 6th stage: The current i_{Lr1} flows through the anti-parallel diode of S_p. This stage finishes when the current through the auxiliary switch becomes zero;
- 7th stage: The current i_{Lr1} is still flowing through the anti-parallel diode of S_p and the current through L_{r2} flows through the anti-parallel diode of S_a. During this time interval both switches are turned off in ZCZV. When the current through the anti-parallel diode of S_a becomes zero, the next stage starts;
- 8th stage: The current i_{Lr1} flows through the anti-parallel diode of S_p. At $\omega t = \omega t_8$, i_{Lr1} reaches zero and this diode turns off;
- 9th stage: The voltage across C_r increases linearly, and its value becomes $V_o + V_{Ce}$, at $\omega t = \omega t_9$. At this time, the diode D_2 turns on in ZV;
- 10th stage: The major part of the power is transferred to the load during this stage, when diodes D_1 and D_2 are on. This stage finishes when S_p is turned on at $\omega t = \omega t_{10}$, starting the next switching period of operation.

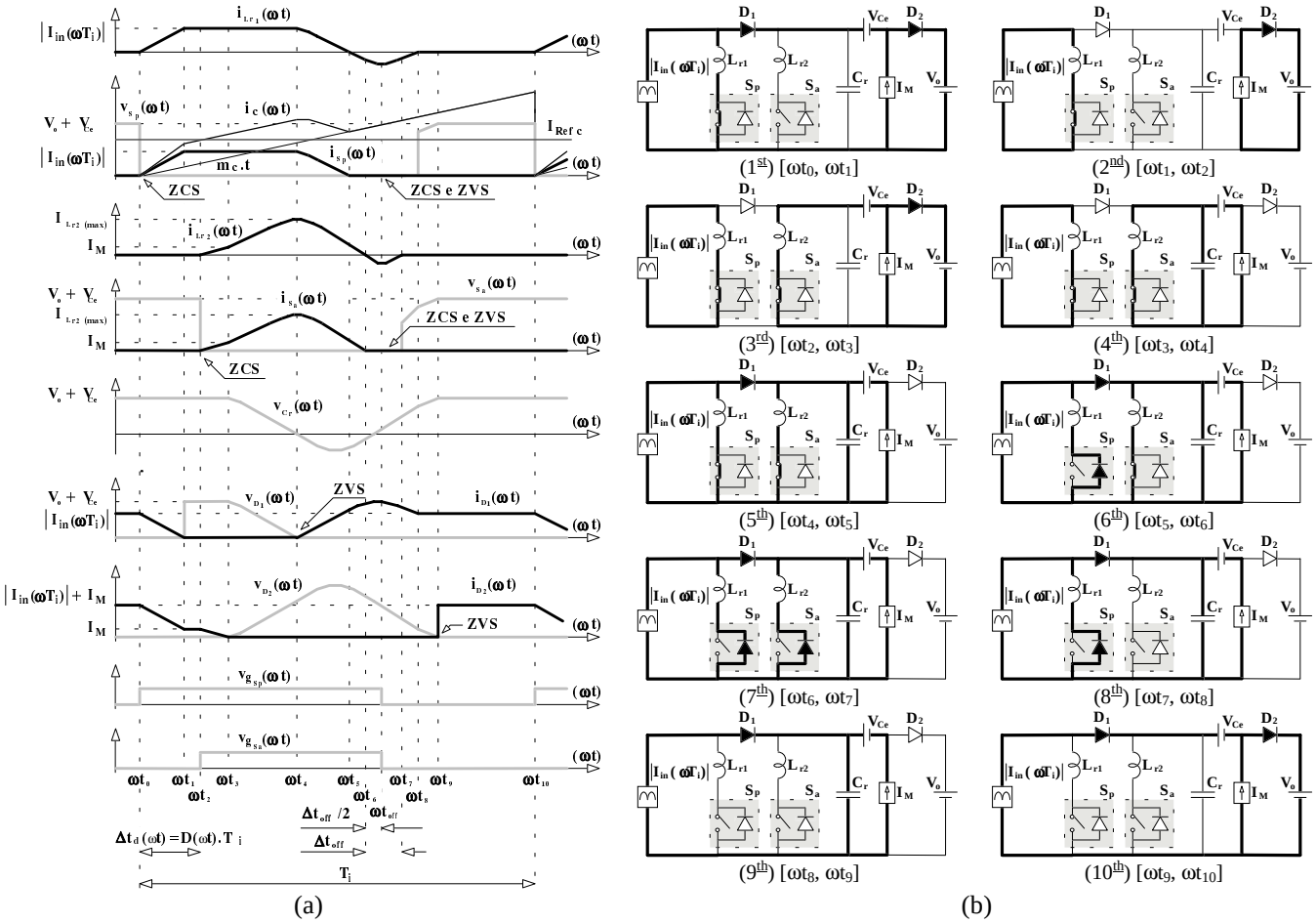


Figure. 2 - (a) Main ideal waveforms and (b) Topological stages for the new HPF ZCS-PWM Sepic rectifier, during a generic switching period (T_i).

III. Analysis of Commutation

In order to achieve soft-commutation at zero-current switching for both active switches (S_p and S_a) as described above, the constraints (1), (2) and (3) should be satisfied:

$$\beta = \frac{L_{r2}}{L_{r1}} < 1; \quad (1)$$

$$\alpha_{1max} < \beta.(1+\alpha_{2max}); \quad (2)$$

$$\alpha_{2max} < \frac{(1-\beta)}{(1+\beta)}. \quad (3)$$

where:

$$\alpha_{1max} = \frac{I_p}{(V_o + V_{Ce})} \cdot \sqrt{\frac{L_{r2}}{C_r}}; \quad (4)$$

$$\alpha_{2max} = \frac{I_{onom}}{(V_o + V_{Ce})} \cdot \sqrt{\frac{L_{r2}}{C_r}}; \quad (5)$$

$$I_p = \frac{\sqrt{2}.P_{onom}}{\eta \cdot (V_{in\,rms} - 0{,}15 \cdot V_{in\,rms})}; \quad (6)$$

P_{onom} = nominal output power;
η= minimum value of efficiency;
I_{onom} = nominal output current;
I_p = peak value of input current;
$V_{in\,rms}$ = rms value of input voltage.

The time interval available to turn off the switches S_p and S_a simultaneously is given by (7). Then, the time interval for the auxiliary switch control is defined by (8).

$$\Delta t_{off} = \Delta t_7 = \frac{2}{\omega_{02}} \cdot \left(\frac{\pi - a\cos(-(\beta + \alpha_2.(1+\beta)))}{\sqrt{1+\beta}} \right). \quad (7)$$

$$\Delta T = \frac{1}{\omega_{02}} \cdot \left[\alpha_2 + \frac{\pi}{2} + \frac{\pi}{\sqrt{1+\beta}} \right]. \quad (8)$$

where:

$$\omega_{02} = \frac{1}{\sqrt{L_{r2}.C_r}}. \quad (9)$$

The dc voltage conversion ratio (q) for the new HPF ZCS-PWM Sepic rectifier is given by equation (10), and it is shown in Figure 3.

$$q(\alpha_{1rms}, \alpha_2, \beta, f, D_{rms}, V_{Ce}) = \frac{V_o}{V_{in\,rms}} \quad (10)$$

where:

$$\alpha_{1rms} = \frac{I_{in\,rms}}{(V_o + V_{Ce})} \cdot \sqrt{\frac{L_{r2}}{C_r}}, \quad (11)$$

$$f = \frac{f_s}{f_{02}}, \quad (12)$$

$$f_{02} = \frac{1}{2 \cdot \pi \sqrt{L_{r2} \cdot C_r}}, \quad (13)$$

and: D_{rms} = rms duty cycle of control;
$I_{in\ rms}$ = rms value of input current.

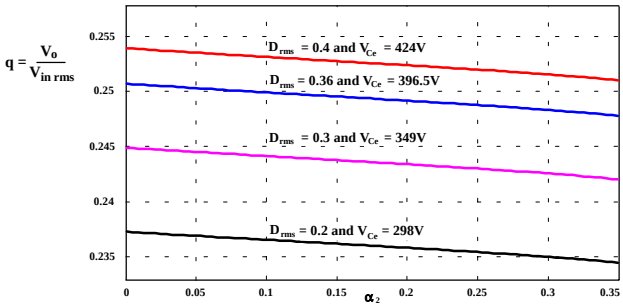


Figure 3 – Dc voltage conversion ratio,
considering α_{1rms}=0.101, α_{1max}=0.144, β=0.4 and f=0.15.

From the analysis of Figure 3, we recommend the step-down operation of the new HPF ZCS-PWM Sepic rectifier only for q lower than 1/3, due to the higher voltage stresses over the semiconductors when operating above this limit.

IV – Experimental Results

Figure 4 shows the implemented power circuit for the new HPF ZCS-PWM Sepic rectifier rated at:

$V_{in\ rms}$ = 220V ± 15%; f_{line} = 60Hz; V_o = 51V;
P_o = 300W; η% = 95%; f_s = 20kHz;
and: δ = 0.94 (maximum duty cycle of control, in peak-current mode control).

Figure 5 shows the test unities for the new HPF ZCS-PWM Sepic rectifiers using peak-current mode control (Figure 5a) and average-current mode control (Figure 5b).

Figure 6 shows the experimental efficiencies obtained for both tested rectifiers. It can be seen that the efficiencies are higher than 89%, over a wide range of load.

The measured efficiency for peak-current mode control was 95%, and for average-current mode control was 94.8% at full load. For nominal load, the measured efficiency in average-current mode control is lower than that in peak-current mode control, due to higher conduction losses in the current sense.

On the other hand, for output power lower than 260W, the average-current mode control has an efficiency better than the peak-current mode control, due to discontinuous current mode operation in peak-current mode control, and input current cross-over distortion with additional harmonic distortion for low power levels.

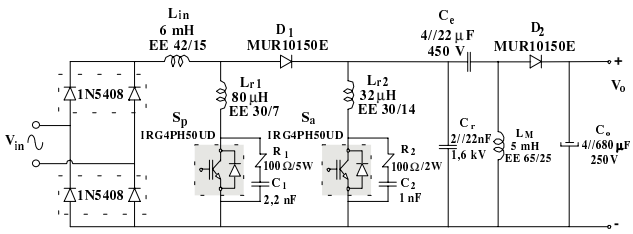
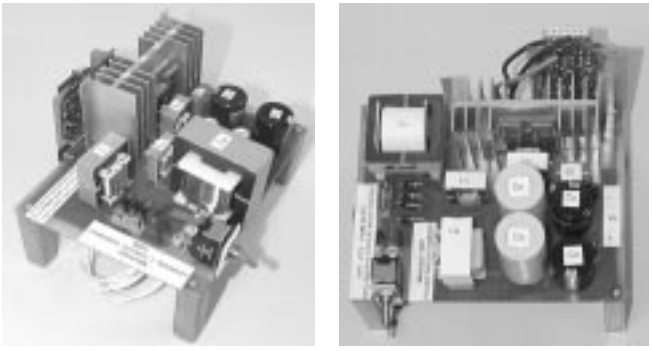


Figure 4 – Implemented power circuit
for the new ZCS-PWM Sepic rectifier.



(a) (b)

Figure 5 – Test unities of the new HPF Sepic rectifier using: (a) peak-current mode control with slope compensation and (b) average-current mode control.

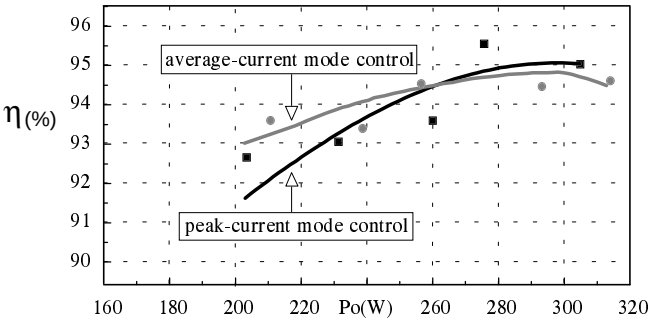
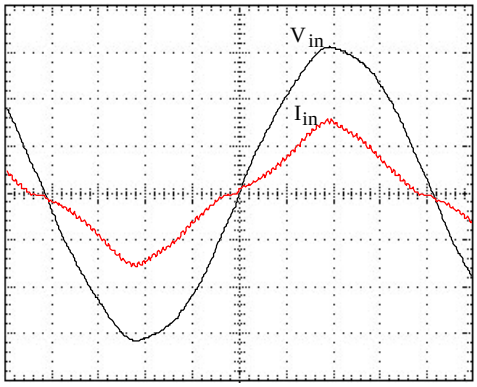
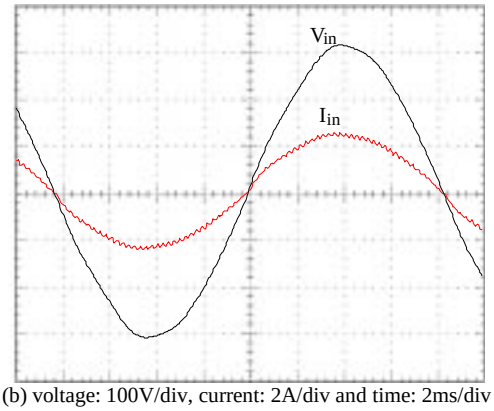


Figure 6 – Experimental efficiencies
for the new HPF ZCS-PWM Sepic rectifiers.

Figure 7 shows the input voltage and current for both tested controls, at full load.



(a) voltage: 100V/div, current: 2A/div and time: 2ms/div



(b) voltage: 100V/div, current: 2A/div and time: 2ms/div

Figure 7 – Input voltage and input current, at full load, using:
(a) peak-current mode control and (b) average-current mode control.

From the analysis of Figure 7, the measured THD of input voltage (THD_{Vin}) was about 1.61%, while the THD of input current (THD_{Iin}) was 17.92% for the peak-current mode control. For the average-current mode control these values were 1.42% and 3.88%, respectively. It should be noticed that no additional input filters were used in both cases. The THD and the reactive energy in circulation are smaller in the average-current mode control, as well as PF and phase displacement. These results are summarized in Table 1.

Table 1 – Power Factor (PF), phase displacement (ϕ) and THD of the input voltage and input current for the new HPF ZCS-PWM Sepic rectifiers tested.

NEW HPF-ZCS-PWM SEPIC RECTIFIER				
Mode control	THD V	THD I	ϕ	PF
Peak-current	1.61%	17.92%	4.98°	0.983
Average-current	1.42%	3.88%	3.21°	0.999

Table 2 summarizes a comparison among the rms values of the main harmonic input-current components obtained from the analysis of Figure 7 and the IEC 1000-3-2 standards. It is noticed that both converters obey the IEC 1000-3-2 but the harmonic currents for the average-current mode control are smaller than those obtained for the peak-current mode control.

Table 2 – Comparison between IEC 1000-3-2 absolute current limits and the experimental harmonic input-current components at full load.

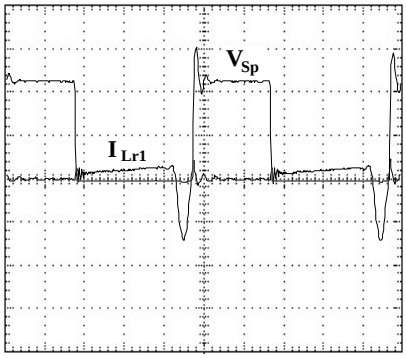
Harmonic Order	Maximum current per harmonic order (rms values)			
	Relative (mA/W) 1000-3-2	Absolute (A) 1000-3-2	Peak-Current Control (A)	Average Current Control (A)
2			0.012	0.0052
3	3.4	1.02	0.316	0.0524
4			0.001	0.0019
5	1.9	0.57	0.037	0.026
7	1.0	0.3	0.031	0.027
9	0.5	0.15	0.012	0.0075
11	0.35	0.105	0.014	0.0109
13	0.296	0.0888	0.009	0.0061
15	0.256	0.0468	0.004	0.0064

Figures 8, 9, 10 and 11 show the commutation details for both switches, S_p and S_a, and it is noticed that the soft-switching are achieved during all the ac system period, with ZC turn-on and ZVZC turn-off for both rectifiers. In both control modes the current through L_{r2} remains practically constant during the ac system period if the output voltage is considered constant.

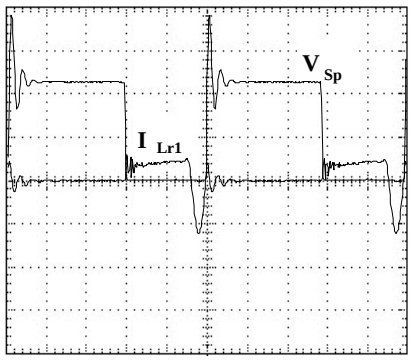
V – CONCLUSIONS

The most important aspects of these new HPF-ZCS-PWM Sepic rectifiers are:

- The converter is regulated by the conventional PWM technique, at constant frequency;
- The soft-commutations for both active switches are achieved in ZC turn-on and ZVZC turn-off;

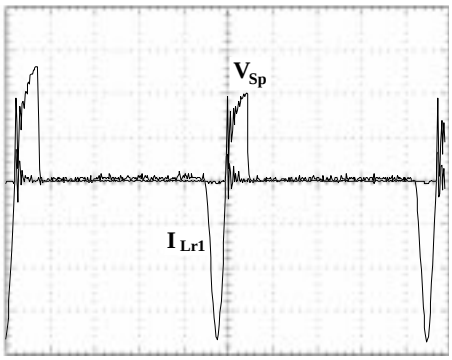


(a) voltage: 200V/div, current: 2A/div and time: 10μs/div.

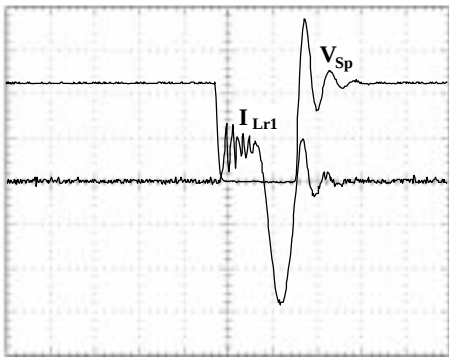


(b) voltage: 200V/div, current: 2A/div and time: 10μs/div.

Figure 8 – HPF ZCS-PWM Sepic rectifier using peak-current mode control. Commutation detail for the main switch: (a) near $V_{in}(\omega t)=0$, and (b) near $V_{in}(\omega t)=V_p$, at full load.

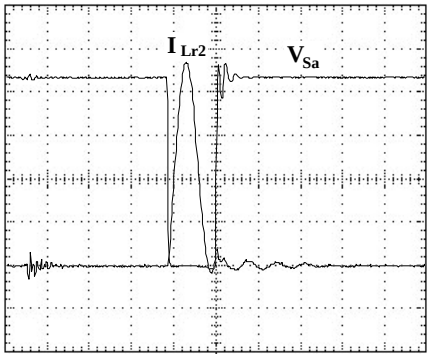


(a) voltage: 100V/div, current: 2A/div and time: 10μs/div.

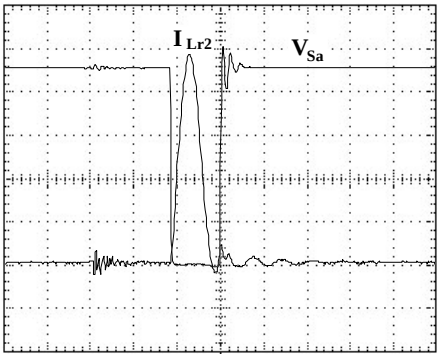


(b) voltage: 200V/div, current: 2A/div and time: 10μs/div.

Figure 9 – HPF ZCS-PWM Sepic rectifier using average-current mode control. Commutation detail for the main switch: (a) near $V_{in}(\omega t)=0$, and (b) near $V_{in}(\omega t)=V_p$, at full load.

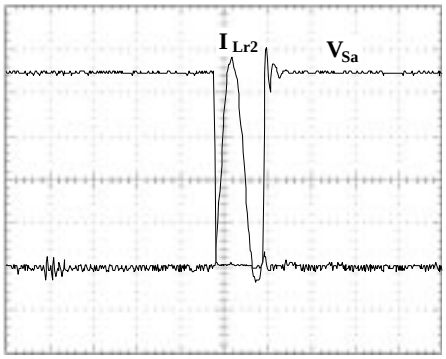


(a) voltage: 100V/div, current: 5A/div and time: 5μs/div.

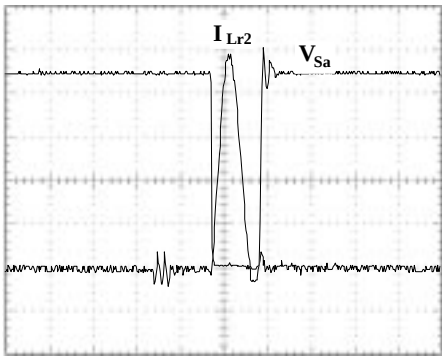


(b) voltage: 100V/div, current: 5A/div and time: 5μs/div.

Figure 10 – HPF ZCS-PWM Sepic rectifier using peak-current mode control.Commutation details for the auxiliary switch: (a) near $V_{in}(\omega t)=0$, and (b) near $V_{in}(\omega t)=V_p$, at full load.



(a) voltage: 100V/div, current: 5A/div and time: 5μs/div.



(b) voltage: 100V/div, current: 5A/div and time: 5μs/div.

Figure 11 – HPF ZCS-PWM Sepic rectifier using average-current mode control. Commutation details for the auxiliary switch: (a) near $V_{in}(\omega t)=0$, and (b) near $V_{in}(\omega t)=V_p$, at full load.

- The diodes D_1 and D_2 are softly commuted in ZV, during their turn-on processes;
- The current that flows through the main switch ($|I_{in}(\omega t)|$) is smaller than that observed in the conventional Sepic converter ($|I_{in}(\omega t)| + I_o$), resulting in lower conduction losses in this semiconductor device;
- High efficiency for wide load range, and high power-factor (low total harmonic distortion with small phase displacement) were obtained;
- Possibility of a new isolated ZCS-PWM rectifiers family;
- Application limited for $q < 1/3$ (dc voltage conversion ratio), due to the additional voltage stresses over the semiconductors.

The peak-current control technique with slope compensation has an intrinsic over-current protection for the main switch, as well as a simple command circuitry due to the absence of the current compensator. Its operation is restricted to a strict input voltage variation, and a stable operation is achieved using slope compensation.

The average-current mode control is more accurate and stable than peak-current mode control, presenting a current compensator and a voltage compensator.

Analyzing the results of the proposed rectifier, using both power-factor correction techniques, it is noticed that the average-current mode control presents a better performance than the peak-current mode control. In this technique a PF near the unity, a small phase displacement, a small THD in compliance with the IEC 1000-3-2 and the spread of possible applications make this active power-factor correction into the best solution to minimize the world wide waste of energy.

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