AN IMPROVED HPF-BOOST ZCS-PWM PRE-REGULATOR: COMPARATIVE ANALYSIS

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Abstract – **This paper presents a summary of different topological arrangements concerned to a ZCS-PWM cell, based on the analysis of its application in Boost rectifying pre-regulators, controlled by the technique of instantaneous average values of input current, with the purpose to obtain a high input power-factor rectifier, and high efficiency to single-phase applications in telecommunication systems. The main characteristics of each switching cell are described, providing conditions to establish a qualitative comparison among the structures. In addition, experimental results are presented from a prototype of the latest version of the ZCS-PWM Boost rectifier, implemented for processing nominal values of 1200W output power and 400V average output voltage, at 220V rms input voltage and 50kHz switching frequency.**

KEYWORDS

High-power-factor rectifier, soft-switching, ZCS-PWM cell, telecommunication systems.

I. INTRODUCTION

The increasing global demand for electrical energy has emphasized the need for high efficiency and high power factor devices. In this context, single-phase rectifying stages have been analyzed and modified, in order to fit into present requirements. Figure 1 shows a conventional single phase rectifying stage (diode bridge + capacitive filter). Typically, electrical equipments that use this kind of rectifier present a reduced power-factor (usually 0.6), denoting the "waste" of electrical energy.

Several studies have been developed, in the last twenty years, on high frequency switching rectifiers controlled by special control strategies and techniques [1-6], in order to provide alternative solutions to reduce this problem. These control strategies and techniques can minimize the harmonic contents in the input current, and they can also practically eliminate the phase-shift between the input current and the input voltage, resulting in high power factor.

In addition, high operating frequencies permit to decrease the volume and weight of required reactive devices, providing conditions for increasing the power density in these rectifying stages. Because of constraints imposed by international standards, such as IEC 61000-3-2 and IEC 61000-3-4, the Boost converter is one of the most employed converters in single-phase high-power-factor (HPF) rectifying stages, as shown in Figure 2.

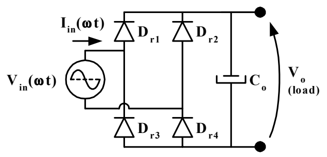


Figure 1 – Conventional single-phase rectifying stage.

The main characteristics that make the Boost converter suitable for this application is its simple circuitry and the presence of an input current filter (L_{in}). Depending on the control technique employed in this converter, it is possible to minimize the required input filter for electromagnetic interference (EMI).

Despite propitiating volume reduction of necessary reactive devices, the operation in high frequencies can result in problems concerned to efficiency, because the switching losses in the semiconductor devices are directly proportional to their operating frequencies. In addition, output voltages of Boost pre-regulators are significantly high (typically 400V), and it requires the use of ultra-fast diodes with high breakdown voltages, resulting in additional losses and problems of electromagnetic interference (EMI), because of their reverse recovery effects.

So, in order to increase the operating frequencies of static converters, without deteriorating their efficiencies, and also because of reverse recovery effects from diodes, soft-switching techniques have been developed [7 until 15]. Basically, the soft-switching techniques can be classified into two distinct groups:

- Zero Voltage Switching (ZVS) and Zero Voltage Transition (ZVT) techniques.
- Zero Current Switching (ZCS) and Zero Current Transition (ZCT) techniques.

Each soft-switching technique is obtained from a new configuration of switching cells. The choice of the soft-switching technique to be employed depends on the technology of active switch(es) used in the converter. For MOSFETs (Metal Oxide Semiconductor Field Effect Transistor), because of their intrinsic capacitances, the ZVS and ZVT techniques are recommended. However, processing high power levels can result in significant conduction losses.

Thus, because of their lower conduction losses, IGBTs (Insulated-Gate Bipolar Transistor) are more attractive than MOSFETs for processing power levels higher than 1kW and/or voltage levels higher than 500V [10-12].

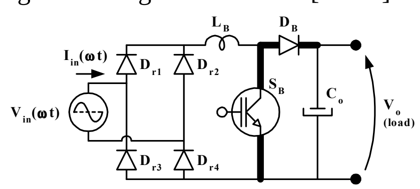


Figure 2 – Single phase High-Power-Factor (HPF) Boost pre-regulator.

Nevertheless, IGBTs present "tail currents" during their turn-off processes, increasing the switching losses. In order to avoid this problem, it is recommended to employ ZCS or ZCT techniques for operations in high frequencies.

According to this context, a ZCS-PWM (Pulse Width Modulated) cell was proposed in [11], and it was specifically presented in [12] for an application in a HPF Boost pre-regulator, suitable for telecom systems, controlled by the instantaneous average current technique. Several different ZCS-PWM cells have been proposed for applications in Boost pre-regulators, with highlights on cells presented in [13] and [14].

In [13], the proposed soft-switching cell is applied in an interleaved Boost converter, operated in critical conduction mode, in order to minimize reverse recovery effects from Boost diode on main switch. Regarding to the cell analyzed in [14], it presents a resonant inductor in the path of load current, which implies in additional losses in this device. Thus, for applications in continuous current mode, minimizing reverse recovery effects from Boost diode on main switch, the switching cell presented in [11] still represents an adequate choice. In this context, since the proposition of the original cell [11], three different versions were sequentially proposed [15, 16, and 17], where each one of them preserves the main characteristics of soft-switching in the semiconductor devices and brings additional features in each proposed modification, in order to increase the efficiency of the structure and to reduce stresses on semiconductors. In this way, this paper presents the sequence of modifications incorporated in the original ZCS-PWM cell, providing enough information for a detailed comparison among the main characteristics of the different proposed versions, applied in HPF Boost pre-regulators, suitable for telecom systems.

II. ORIGINAL ZCS-PWM CELL

Figure 3 shows the original ZCS-PWM cell [12], applied in a Boost pre-regulator. According to this figure, it is possible to note that the proposed switching cell presents two active switches (S_1 and S_2), two diodes (D_1 and D_2), two small resonant inductors (L_{r1} and L_{r2}) and one resonant capacitor (C_r).

The topological stages for a simplified circuit and main waveforms from this rectifier are shown in Figure 4.

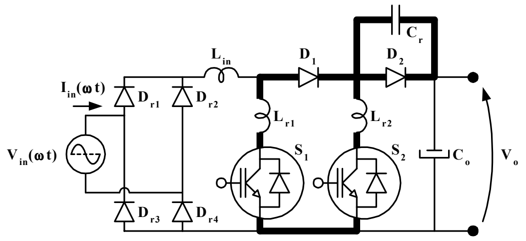
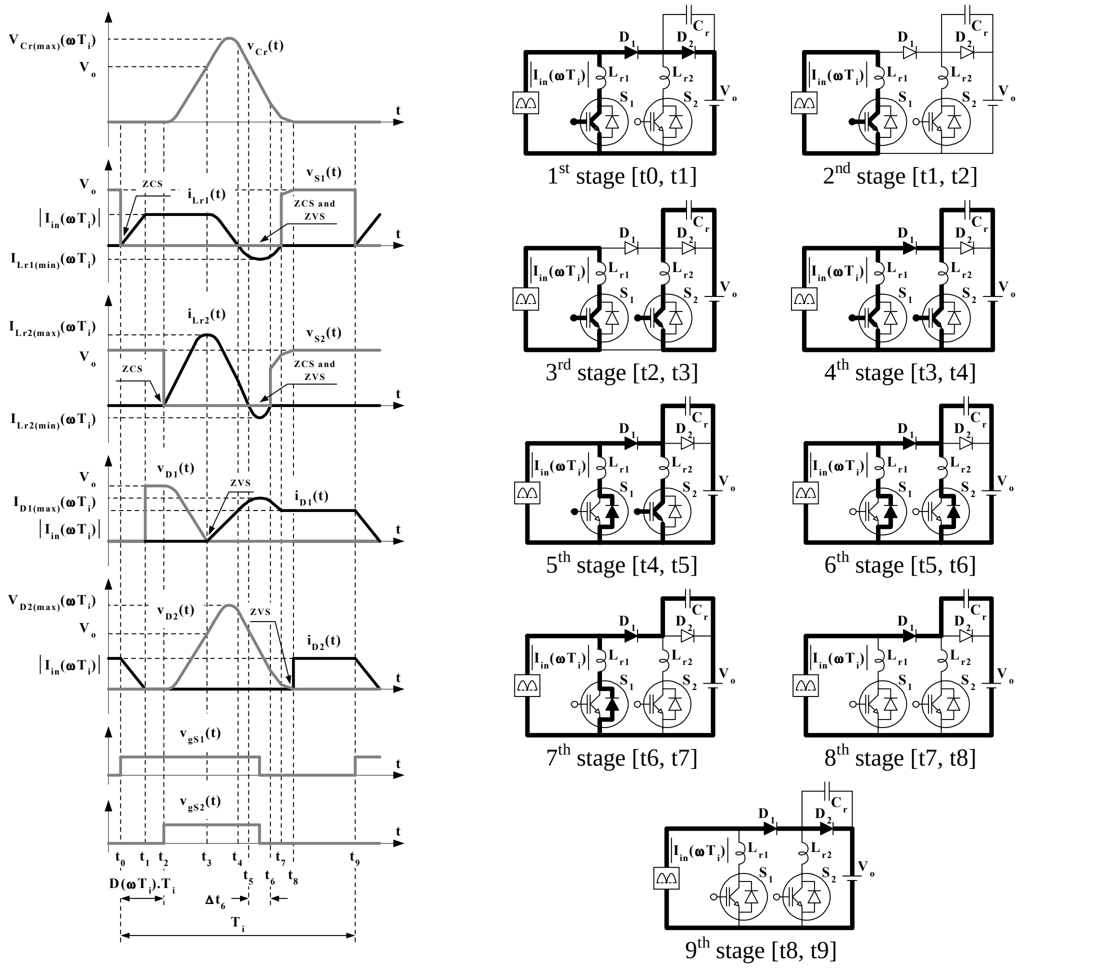


Figure 3 – HPF Boost pre-regulator, employing the original ZCS-PWM cell [12].



(a) (b)

Figure 4 – (a) Main theoretical waveforms, and (b) topological stages of the HPF ZCS-PWM Boost pre-regulator [12], during a generic switching period (T_i).

According to Figure 4, the switches S_1 and S_2 presents ZCS turn-on processes, at $t=t_0$ and $t=t_3$, respectively. This fact occurs due to the presence of inductors L_{r1} and L_{r2}, which limit the di/dt in their respective branches. In addition, S_1 and S_2 are turned off, simultaneously, during the sixth stage (Δt_6), in ZCS and ZVS conditions. Regarding to diodes D_1 and D_2, it can be noted that their turn-on processes occurs in ZVS and their reverse recovery effects on active switches are minimized.

Experimental results presented in [12] show that the power factor correction can be achieved through the instantaneous average current technique, maintaining the soft-switching characteristics at semiconductor devices during an AC system period.

Despite the good performance verified in this topology, the proposed switching cell presents two characteristics that can be considered as drawbacks. Firstly, according to [15], the employment of the original ZCS-PWM cell in Buck-Boost, Sepic and Zeta converters impedes the obtaining of "natural" isolation through the accumulation inductors of these structures. The second drawback can be verified in the Boost converter itself, where it is possible to note that diodes D_1 and D_2 conduce, simultaneously, the current that flows from the AC system supply to the load, during the first and ninth stages. In this way, the conduction losses associated to these devices can become significant, depending on the value of processed current.

III. FIRST VERSION OF THE ZCS-PWM CELL

According to [15], in order to eliminate the drawback concerned to the obtaining of "natural" isolation in Buck-Boost, Sepic and Zeta converters, it is proposed a modification in the original ZCS-PWM cell, resulting in the topology presented in Figure 5. In this structure, when compared to the original cell, the sequence of topological stages is not modified. However, the resonance can be performed without the flow of resonant current through the output voltage filtering capacitor.

The waveforms of this converter are identical to those ones presented for the original cell, excepting the voltage over C_r, which evolves as shown in Figure 6.

Additionally, in this context, in [15] it is presented an application of this modified cell in a Zeta pre-regulator, where it is possible to verify that only diode D_1 conduces the load current.

IV. SECOND VERSION OF THE ZCS-PWM CELL

Due to the application presented in [15] for a Zeta converter, a second version of the original ZCS-PWM cell is proposed in [16]. This new version is employed in a HPF ZCS-PWM Sepic pre-regulator, applied in electronic ballasts for multiple fluorescent lamps. However, this cell requires isolated gate drive circuits, increasing the complexity and costs of this circuitry. In order to solve this problem, in [17], it is proposed a new modification in the structure of this cell, in which the active switches present a single reference point. Because of the similarities between the operation of Sepic and Boost converters, the commutation cell presented in [17] can be directly applied in a HPF ZCS-PWM Boost pre-regulator. Figure 7 presents the circuit of this proposed rectifier.

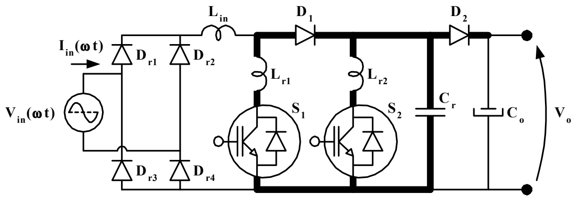


Figure 5 – HPF Boost pre-regulator, employing the first version of ZCS-PWM cell [15].

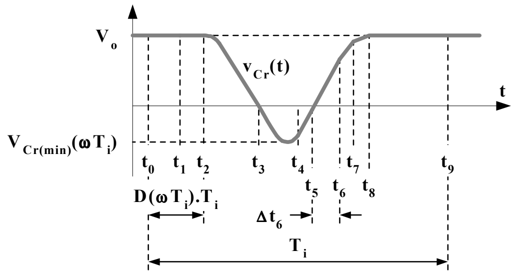


Figure 6 – Theoretical waveform of voltage over the resonant capacitor, in the first version of ZCS-PWM cell [15], during a generic switching period (T_i).

Figure 8 shows the theoretical waveforms of voltages and currents in diodes D_1 and D_2. The other waveforms are identical to those ones presented in the first version of this ZCS-PWM cell.

The topological stages of the ZCS-PWM Boost pre-regulator showed in Figure 7 are presented in Figure 9.

When comparing the topological stages from Figure 9 with the stages of its predecessor Boost rectifier, showed in Figure 4, it is possible to observe that there are significant differences in the topological stages. In addition, it is important to observe that the transference of energy to the load occurs during the first and ninth stages, for the second version, where the ninth stage is responsible for the major

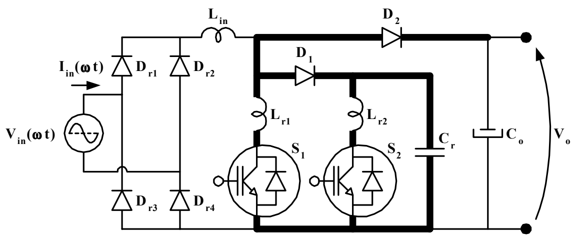


Figure 7 – HPF Boost pre-regulator, employing the second version of ZCS-PWM cell [17].

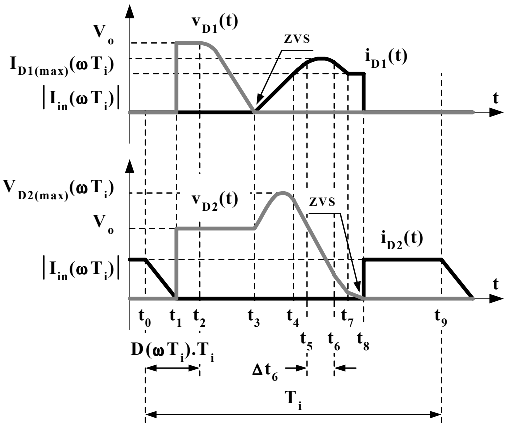


Figure 8 – Theoretical waveforms of D1 and D2 switching processes, from the second version of the ZCS-PWM cell [17], during a generic switching period (Ti).

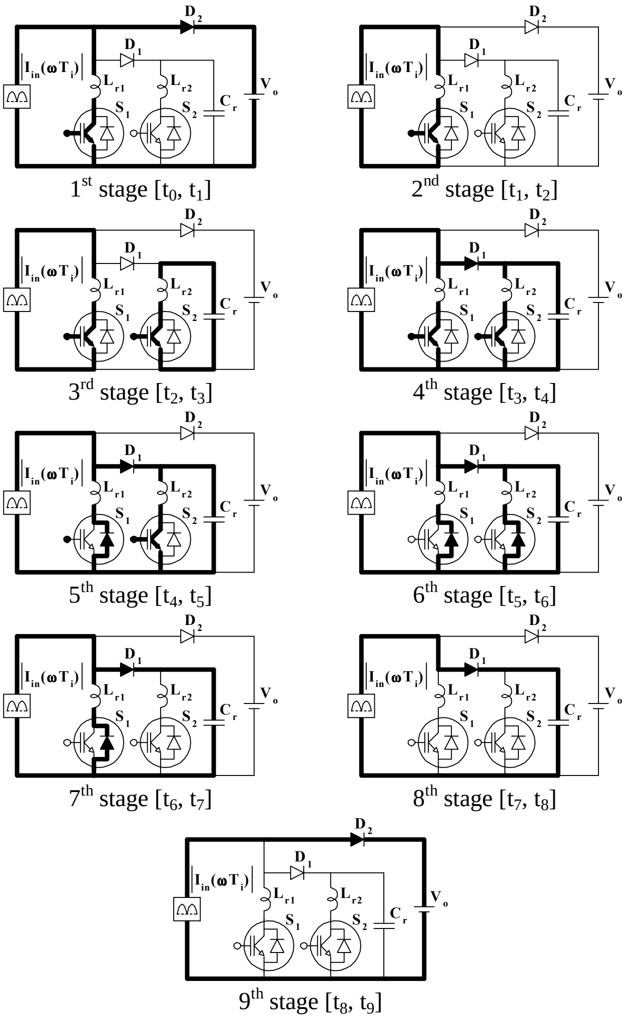


Figure 9 – Topological stages of the Boost pre-regulator, employing the second version of ZCS-PWM cell [17], during a generic switching period (T_i).

part of this transference. Thus, the elimination the serial connection between diodes D_1 and D_2, in the version showed in Figure 7, represents a significant advantage concerned to the minimization of conduction losses associated to D_1.

Table I shows a summarized comparison among the main characteristics of the analyzed ZCS-PWM cells. According to this table, it is easy to verify the evolution in the topology of the proposed cell, permitting the "natural" isolation of Buck-Boost, Sepic and Zeta converters, and the elimination of serial connection between D_1 and D_2, without the flow of resonant current through the output filter.

III. DESIGN EXAMPLE AND EXPERIMENTAL RESULTS

In order to validate the developed analysis, a prototype of the Boost rectifier presented in Figure 7 was implemented, employing a control circuit based on IC UC3854 [5], dedicated to the instantaneous average current technique.

A. Design Example of the new HPF ZCS-PWM Boost Pre-regulator

The design of this ZCS-PWM Boost rectifier is developed according to the input and output data presented in Table II.

TABLE I
Main Characteristics of the Analyzed ZCS-PWM Cells

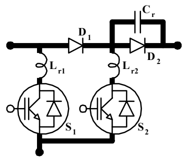
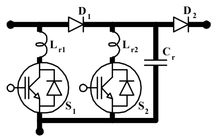
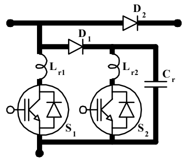
Characteristic / Cell	Resonant Current flows through the Load	"Natural" Isolation of Buck-Boost, Sepic e Zeta	Serial Connection between Diodes
 Original Cell	Yes	No	Yes
 First Version	No	Yes	Yes
 Latest Cell	No	Yes	No

TABLE II
Input and Output Data for the ZCS-PWM Boost Rectifier

rms input voltage ($V_{in(rms)}$)	220V ± 15%
AC system frequency (f_{CA})	60Hz
ZCS-PWM Boost switching frequency (f_B)	50kHz
average value of the DC output voltage (V_o)	400V
nominal output power (P_o)	1200W
adopted minimum efficiency (η%)	95%

The resonant devices are obtained after adopting the following parameters:

$$\beta=0{,}625\ ;\quad f=0{,}147\ \text{and}\quad \alpha_{max}=0{,}51.$$

The resonant parameters were specified as:

$$C_r=22nF\ ;\quad L_{r1}=16\mu H\ \text{and}\quad L_{r2}=10\mu H.$$

The input filter (L_{in}) is designed to limit the input current ripple into 10% of its nominal peak value. Regarding to the output filter (C_o), it is determined to ensure that the output voltage ripple will not exceed 2% of its nominal average value. So, these filters are:

$$L_{in}=3mH\ \text{and}\quad C_o=680\mu F.$$

The design of external parameters of UC3854 follows the methodology proposed in [5]. The driving logic for switches S_1 and S_2 is developed according to the blocks diagram showed in Figure 10.

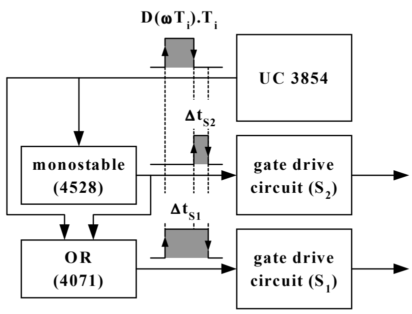


Figure 10 – Blocks diagram of the driving logic for S1 and S2.

B. Experimental Results

Experimental results obtained from a prototype of the Boost rectifier showed in Figure 7 are presented in the following. The semiconductor devices employed in the prototype are specified in Table III.

The input current and input voltage waveforms, for nominal operating conditions, are shown in Figure 11.a. Figure 11.b shows the frequency spectrum of the input current, where its THD is equal to 3.27% and the measured power factor of this structure is about 0.986, when the input voltage THD is equal to 2.10%.

Figure 12 shows the switching details from the semiconductor devices employed in the ZCS-PWM Boost rectifier. These results were obtained for situations where the instantaneous value of input voltage is near to zero ($V_{in}(\omega t) \cong 0$) and near to its peak value ($V_{in}(\omega t) \cong V_{in(p)}$), for nominal conditions.

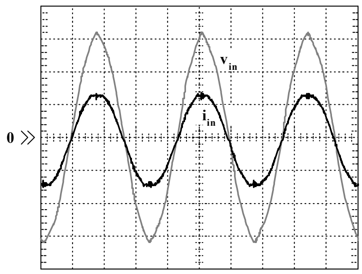
According to Figure 12, it can be observed that switches S_1 and S_2 present ZCS turn-on, and ZCS and ZVS turn-off. In addition, it is possible to conclude that these switching characteristics are preserved during an AC system period.

Additionally, from Figure 12, it can be observed that diodes D_1 and D_2 do not present a serial connection, reducing the conduction losses associated to D_1, in comparison to the other versions of this ZCS-PWM cell. Due to this fact, the efficiency of this structure should result significantly high.

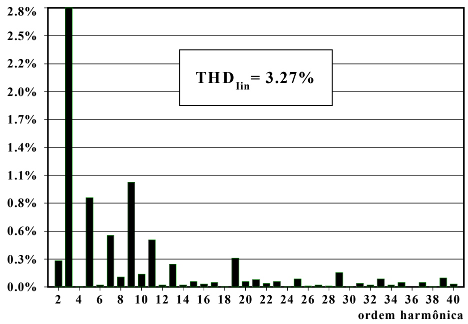
Figure 13 shows a comparison among measured efficiency values, from implemented prototypes of Boost pre-regulators employing three different switching cells, namely: hard-switching cell, first version of this ZCS-PWM cell [15], and latest version of this ZCS-PWM cell [17]. All prototypes were implemented according to the data provided in Tables II and III.

TABLE III
Semiconductor Devices employed in the Prototype

Diode Bridge	D_{r1}, D_{r2}	SKR25/06
	D_{r3}, D_{r4}	SKN25/06
Main Switch	S_1	IRG4PH50UD
Auxiliary Switch	S_2	IRG4PC50UD
Auxiliary Diode	D_1	MUR8100E
Boost Diode	D_2	MUR8100E

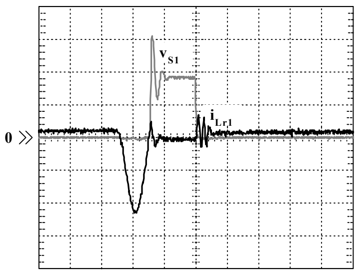


i_{in}: 5A/div; 5ms/div
v_{in}: 100V/div; 5ms/div
(a)

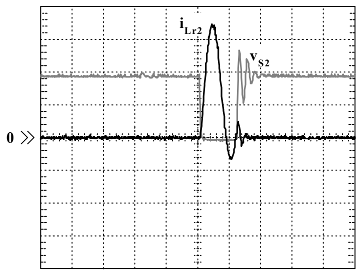


(b)

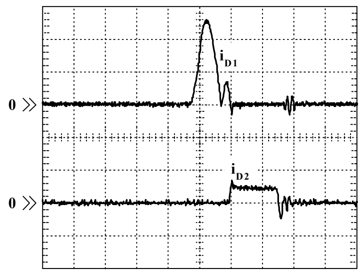
Figure 11 – (a) Input voltage and input current, and (b) frequency spectrum of I_{in}, at nominal load.



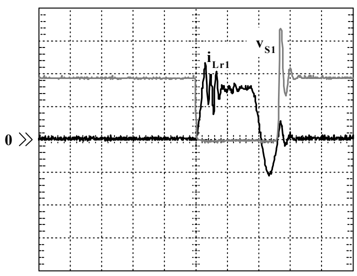
i_{Lr1}: 5A/div; 2µs/div
v_{S1}: 200V/div; 2µs/div
(a) Main Switch, $V_{in}(\omega t) \cong 0$



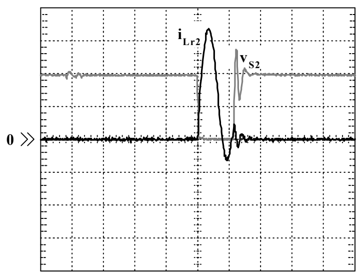
i_{Lr2}: 5A/div; 2µs/div
v_{S2}: 200V/div; 2µs/div
(b) Auxiliary Switch, $V_{in}(\omega t) \cong 0$



i_{D1}: 5A/div; 2µs/div
i_{D2}: 5A/div; 2µs/div
(c) Diodes D_1 e D_2, $V_{in}(\omega t) \cong 0$



i_{Lr1}: 5A/div; 2µs/div
v_{S1}: 200V/div; 2µs/div
(d) Main Switch, $V_{in}(\omega t) \cong V_{in(pk)}$



i_{Lr2}: 5A/div; 2µs/div
v_{S2}: 200V/div; 2µs/div
(e) Auxiliary Switch, $V_{in}(\omega t) \cong V_{in(pk)}$

i_{D1}: 5A/div; 2µs/div
i_{D2}: 5A/div; 2µs/div
(f) Diodes D_1 e D_2, $V_{in}(\omega t) \cong V_{in(pk)}$

Figure 12 – Voltage and current waveforms through the semiconductor devices, operating at nominal conditions.

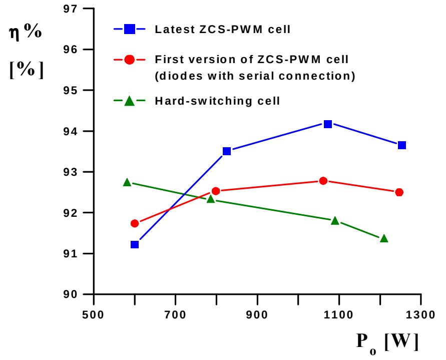


Figure 13 – Comparison among values of measured efficiencies.

According to the results showed in Figure 13, it is possible to note that the latest version of the ZCS-PWM cell provides a higher efficiency to the pre-regulator stage, when it is operated in nominal conditions. In the ZCS-PWM cells analyzed in this paper, the energy used in the resonance is constant. So, the efficiency of these ZCS-PWM pre-regulator stages denotes a tendency to decrease when light loads are connected to their outputs.

The Boost pre-regulator employing the hard-switching cell presents an opposite tendency, because the connection of light loads provides lower current stresses and, consequently, lower conduction losses, resulting in higher values of efficiency when operating in these conditions.

V. CONCLUSIONS

This paper presented a summary concerned to the evolution of one ZCS-PWM switching cell applied to Boost pre-regulator stages with high power factor.

The main characteristics of each switching cell were presented and discussed, providing enough information to the development of a detailed comparison among the proposed topologies.

The original ZCS-PWM cell does not permit the obtaining of "natural" isolation in Buck-Boost, Sepic and Zeta converters through their accumulation inductors. In addition, this cell presents topological stages where the current from the input AC system supply flows through two diodes, connected in series. The subsequent versions of this ZCS-PWM cell were proposed to eliminate these drawbacks, maintaining the soft-switching characteristics performed by the employed semiconductors devices.

A prototype employing the latest version of the ZCS-PWM cell was implemented in order to verify the developed analysis. From the experimental results, it is possible to conclude that the proposed structure provides the obtaining of soft switching in the semiconductors devices, and the elimination of the serial connection between D_1 and D_2.

The instantaneous average current technique was successfully implemented in the proposed ZCS-PWM Boost pre-regulator, resulting in reduced THD and negligible phase-shift in the input current, when compared to the AC input voltage, resulting in a high power factor.

Regarding to the efficiency of this structure, the results obtained for nominal conditions, and compared to other implemented Boost pre-regulators, permit to conclude that this latest version of this cell presents a good performance.

Finally, the obtaining of high efficiency and high power factor denotes the optimized use of electrical energy.

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