NEW CLASS OF ZCZVT PWM CONVERTERS WITH MAGNETICALLY COUPLED AUXILIARY CIRCUIT WITH LOW REACTIVE ENERGY.

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***Abstract* – This paper proposes and analyses a new class of Zero-Current Zero-Voltage Transition (ZCZVT) PWM Converters. This new class makes use of a non-resonant auxiliary circuit to control the current flow between main and auxiliary circuits. With the non-resonant auxiliary circuit, the reactive energy, commonly significant in ZCZVT converters, can be kept at lower levels, ensuring higher efficiency and lower current stresses. Moreover, this new Class of converters brings a new expectation about the ZCZVT technique and its advantages, mainly in IGBT and other minority carrier based converters. To verify the feasibility of the proposed class a novel ZCZVT boost converter is implemented and experimental results are obtained from a laboratory prototype rated at 1.0 kW, 50 kHz.**

***Keywords* - ZCZVT, Resonant Transition Technique.**

I. INTRODUCTION

Nowadays, the development of novel semiconductor materials and packaging technologies have resulting in an ever increase improvement of the semiconductor devices. These developments have leading to devices whose switching conditions approaching the ideal conditions, with low losses and stresses, which permit high power and high switching frequency operation. Nonetheless, the uncertainty concerning the popularity of new technologies is dependent of factors such as, cost, simplicity, large scale usage by industry, and the improvement of competing technologies that could provide better characteristics.

An alternative to avoid the market uncertainties and take advantages of using well-established semiconductor device technologies (as Silicon based MOSFETs and IGBTs) is to employ soft-switching techniques that can improve the switching conditions of the semiconductor devices enabling power conversion with higher efficiencies and power density.

In the last decades the soft-switching techniques have been a trendy subject among researchers around the world and after a dozen of years some of them proved to be best suited for such given application. An example of it is the suitability of the ZVT technique to majority carrier devices. The MOSFET based ZVT (ZVS) converters can operate at high frequencies with lower switching losses when compared to other soft-switching techniques. Further improvements to efficiency gain in ZVT converters are accomplished by means of circuit modifications that have been proposed during last years [1-6] and have been contributing to the ZVT technique to become a well-established soft-switching technique, which is demonstrated by the interest of some power supplies manufacture companies [18-21], and also by ASICs manufacture companies, that provides ICs [22-26] devoted to ZVT and ZVS converters for DC-DC and PFC applications.

Nevertheless, the power MOSFET presents two major limitations: (i) the first concerns the on state resistance that is proportional to the device breakdown voltage and thus can result in high conduction losses in applications above 500V reverse blocking voltages; (ii) the other constraint concerns the physical size limitation imposed by the lower current capability of the device compared to bipolar-based device technologies, such as thyristor derived devices, IGBTs, etc.. Therefore it is expected that or by the limitations imposed by current capability or by the conduction losses, the minority carrier devices will substitute the majority carrier devices (high power levels).

In contrast, an intrinsic characteristic of IGBTs (and other minority carrier devices) is the existence of a residual current after the device turn-off (tail current). This current tail is one of the largest sources of the switching losses of the device and it is also a limiting factor to the maximum operation frequency of power converter. As the ZVT techniques enhance the commutation conditions just during the turn-on process and only reduce the current and voltage overlapping during the turn-off process, this technique is no longer the best to be applied to minority carrier devices. Actually the effectiveness of the ZVT technique is extended for fast switching IGBT. However, the IGBT technologies present a trade-off between the switching and conduction losses [7-8], which results in fast-switching devices with higher on state voltage drop. Additionally, the cost of the device is associated with its switching transition times, leading to more expensive faster switching IGBTs. As an alternative to the ZVT technique was presented in [9] named Zero-Current Transition, ZCT. This technique eliminates the current and voltage overlapping completely during the turn-off process, providing favorable conditions independently of the switching speed of the minority carrier type device. The concept of this technique has its origin in the circuits of forced commutation [10]. Although this approach is suited to minimize the turn-off losses, the main switch turn-on process happens in a way similar to the hard-switched PWM converters, i. e., the reverse recovery losses still present. For these reasons, in [11] two distinct ZCT converters were presented. These converters provided improved main switch turn-on conditions and reduced losses associated to the main diode recovery freewheel were reduced.

In spite of providing promising characteristics for the use of minority carrier devices, the ZCT technique presents some characteristics, such as large amount of reactive energy, more complex switching strategy and high rate of change of the voltage (dv/dt) across the semiconductor devices, that reduce the converter efficiency gain and the converter EMI has few improvement compared to the PWM converters. These disadvantages are overwhelmed for the majority of the voltage-mode switching techniques and, consequently, these characteristics offset the benefits achieved by the ZCT technique and corroborate with the lack of acceptance of this technique by the industry.

The search for alternatives suitable for the minority carrier devices led to a new commutation concept, the Zero-Current Zero-Voltage Transition, simultaneously, ZCZVT, where both commutation take place assisted by the auxiliary circuit. The first topology [12] has its basis on the ZCT converter proposed in [9, 11]. This topology make use of two auxiliary switches for a single unidirectional PWM pole. In [13], a new attempt to develop the ZCZVT technique was presented. This topology uses a simple auxiliary circuit with only an auxiliary switch per main switch. It maintain all the characteristics of the resonant transition converters, nevertheless, it presents operation under limited convertion voltage ratio and with high reactive energy. In [14-16] novel converters were proposed, however all of them make use of resonant processes to achieve the soft-transition conditions in both, turn-on and turn-off. The resonance produces high stresses, reactive energy and more complex switching strategies.

In a companion paper [17], a novel synthesis methodology for resonant transition converters allowed the derivation of a new class of ZCZVT converters, named Class A ZCZVT converters. The new ZCZVT converters makes possible the reduction of the reactive energy maintaining the advantages of the ZCZVT such as, zero-current and zero-voltage switching for the main pole semiconductors with controlled dv/dt and di/dt, good suitability for for both, majority and minority carrier devices, etc..

The aim of this paper is to analyze in details this New Class of converters in order to identify its merits and its limitations.

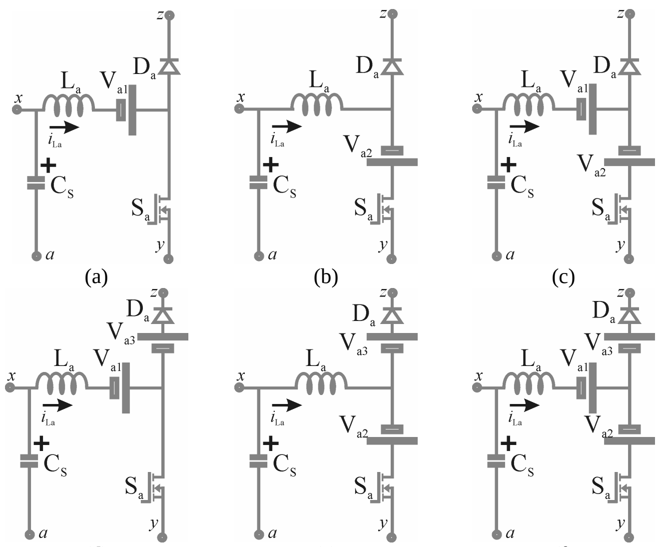


Fig. 1 – Proposed ZCZVT auxiliary circuits for PWM converters.

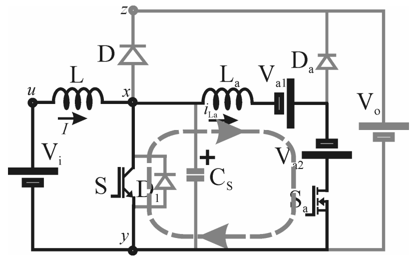


Fig. 2 – Proposed ZCZVT auxiliary circuits.

II. NEW CLASS OF ZCZVT PWM CONVERTERS

The auxiliary circuit of the new class of ZCZVT PWM converters is comprised by a commutation inductor, L_a, an auxiliary pole (S_a ,D_a) and a set of auxiliary voltage sources (V_{a1}, V_{a2} and/or V_{a3}), as shown in Fig. 1, where a set of unidirectional auxiliary circuits are depicted.

A. Auxiliary Circuit Definition.

The goal of the auxiliary circuit is to provide conditions to commutate the main diode or the main switch at any time without using the resonant approach common to ZCTs and other ZCZVTs. In order to achieve such conditions it is make necessary the use of an auxiliary semi-controlled pole and a set of auxiliary voltage sources (V_{a1}, V_{a2}, V_{a3}), where at least V_{a1} or V_{a2} must be non-zero and positive. This way, even when the main switch is on, the auxiliary circuit is capable to generate conditions to charge the commutation inductor, L_a, Fig. 2.

Six distinct families of ZCZVT converters can be derived introducing each one of the ZCZVT auxiliary circuits presented in Fig. 1 to the basic six types of non-isolated DC-DC converters. It will result in third six (36) non-isolated DC-DC converters.

Aiming to simplify the analysis of all topologies, the common equivalent circuit of DC-DC converters (basic PWM cell) proposed in [25] can be assessed. Since the common equivalent circuit permit to the non-isolated DC-DC converters to share the same structure, the connection of the ZCZVT auxiliary circuits become straightforward, terminals '*x*' '*z*' and '*y*' shown in Fig. 1 are connected to the homonymous terminals of the common equivalent circuit, Fig. 3. On the other hand, terminal '*a*' (Fig. 1) can be connected to terminals 'u', '*z*' or '*y*' (Fig. 3).

To obtain the ZCZVT DC-DC topologies from Fig. 3 it is only required to interchange the input and output voltages and the storage capacitor (when required) among terminals '*x*' '*z*' and '*y*'.

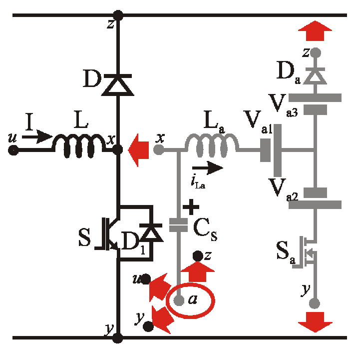


Fig. 3 – The common equivalent circuit of DC-DC converters and ZCZVT auxiliary circuit connection.

B. Principle of Operation.

In order to analyze the operation principle of the new class of ZCZVT PWM converters the boost converter with the auxiliary circuit of Fig. 1(a) have been chosen. The main theoretical waveforms for this converter is shown in Fig. 4.

In steady state operation the ZCZVT boost converter present twelve circuit modes, Fig. 5.

1) Turn-on Process

Mode 1. (t_0,t_1): In this mode the auxiliary inductor is charged linearly from zero until it reaches the load current I, (Fig. 5(b)).

Mode 2. (t_1,t_2): At t_1, i_{La} is equal to I, thus the current through L_a resonates discharging the capacitance C_s, (Fig. 5(c)).

Mode 3. (t_2,t_3): At t_2, v_{Cs} reaches zero and the body diode of main switch conducts. Current i_{La} increases linearly due to the presence of the voltage V_{a1} across L_a, (Fig. 5(d)).

Mode 4. (t_3,t_4): This mode starts when the auxiliary switch S_a is turned off. The main switch can be turned on during this mode under zero current and voltage, simultaneously. At this moment current through L_a starts to ramp down until it reaches the input current I, (Fig. 5(e)).

Mode 5. (t_4,t_5): At t_4, main switch body diode turns off and current I deviates from L_a to main switch S linearly until it reaches zero through the auxiliary circuit, (Fig. 5(f)).

Mode 6. (t_5,t_6): In this mode the auxiliary circuit is off and the converter operates as it PWM counterpart, governed by the PWM modulation, (Fig. 5(g)).

2) Turn-off Process:

Mode 7. (t_6,t_7): At t_6 the auxiliary switch S_a is turned on again. In this mode the auxiliary inductor is charged linearly from zero until it reaches the load current I, (Fig. 5(h)).

Mode 8. (t_7,t_8): In this mode current increases linearly through main switch body diode until the auxiliary switch be turned off, (Fig. 5(i)).

Mode 9. (t_8,t_9): At t_8 the auxiliary switch S_a is turned off and current decreases linearly through main switch body diode until it reaches zero, (Fig. 5(j)).

Mode 10. (t_9,t_{10}): In this mode i_{La} resonates with v_{Cs} until C_s be fully charged to V_{zy} (t_{10a}) or until the current i_{La} reaches zero (t_{10b}), (Fig. 5(k)).

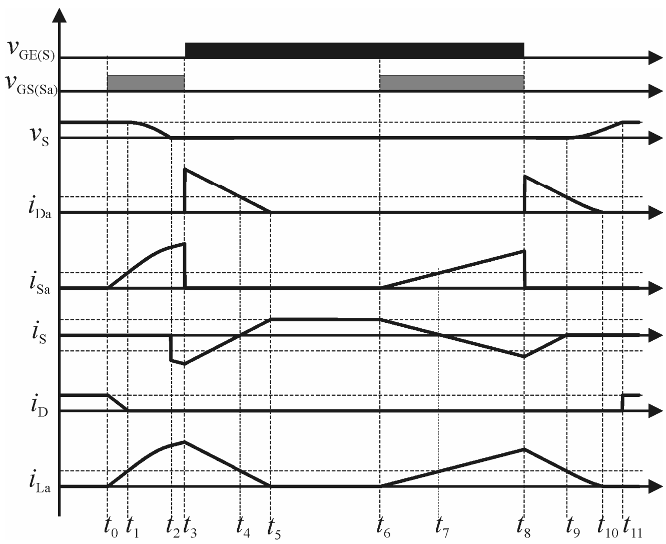


Fig. 4 – Theoretical waveforms.

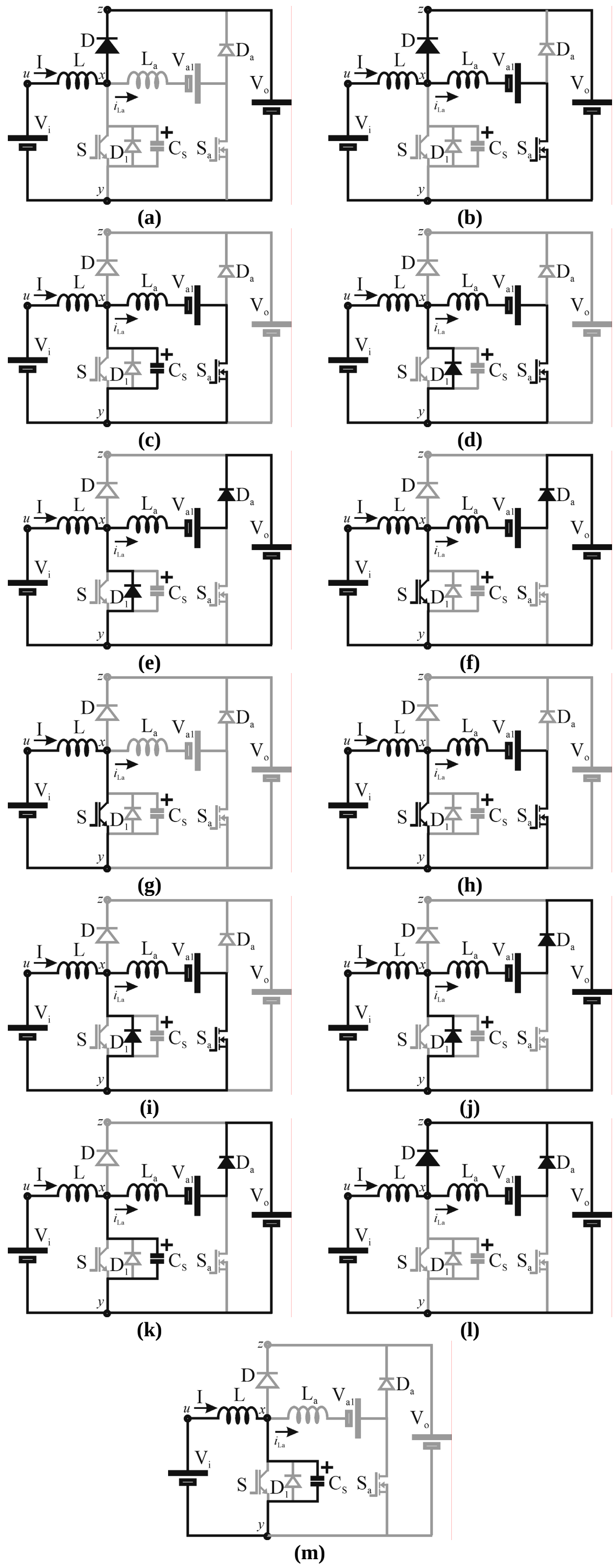


Fig. 5 – New ZCZVT boost converter circuit modes.

Mode 11a. (t_{10a},t_{11}): At t_{10a} main diode starts conduct and i_{La} decreases linearly due to the voltage V_{a1} applied across L_a, (Fig. 5(l)).

Mode 11b. (t_{10b},t_{11}): At t_{10b} i_{La} reaches zero and capacitor C_s is charged linearly by current I, (Fig. 5(m)).

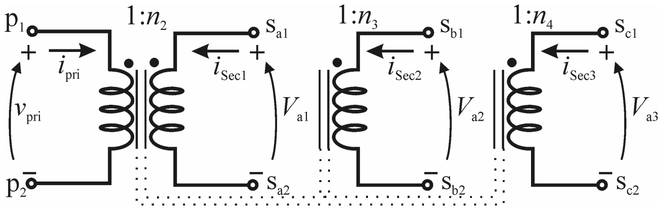


Fig. 6 –Coupled inductor diagram.

Table I – Configurations for the primary winding connection.

Config.		Primary winding connections	
		Terminal "p2"	Terminal "p1" (dot)
1	*b*	*y*	-- *u*
	c	*y*	-- *x*
	d	*y*	-- *z*
2	*c*	*u*	-- *x*
	d	*u*	-- *z*
3	*d*	*x*	-- *z*

Mode 12. (t_{11},t_{12})*:* At t_{11} the auxiliary circuit is off and converter operates as its PWM counterpart, (Fig. 5(a)).

It must be noticed that the circuit modes described above are valid for all auxiliary circuit configurations applied to a CC-CC PWM converter with the exception of configuration 2 (Fig. 1(b)) whose operation does not allowed the circuit mode 11a.

C. Auxiliary Voltage Source Implementation.

As can be seen by Fig. 1, the main point of the new class of ZCZVT PWM converters is the realization of one or more constant voltage sources. A constant voltage source can be implemented basically by means of a large capacitance or by means of the magnetic coupling among two or more winding wrapped in the same core. The magnetic coupling implementation presents as main advantages the flexibility and the efficiency. Additionally, the magnetic integration can provide a good alternative to obtain the auxiliary voltage source and also can provide a reduction on the total magnetic volume of the converter. For these reasons the magnetic coupling is choose to implement the required constant auxiliary voltage source. Considering that the secondary winding is disposed in the auxiliary circuit (forming the actual constant voltage source), the primary winding connection can be made according Table 1, where the terminals of the winding are given by 'p1' and 'p2'(Fig. 6); and the connection correspond to the terminals of the basic PWM cell, 'u', 'x', 'y' and 'z'(Fig. 2).

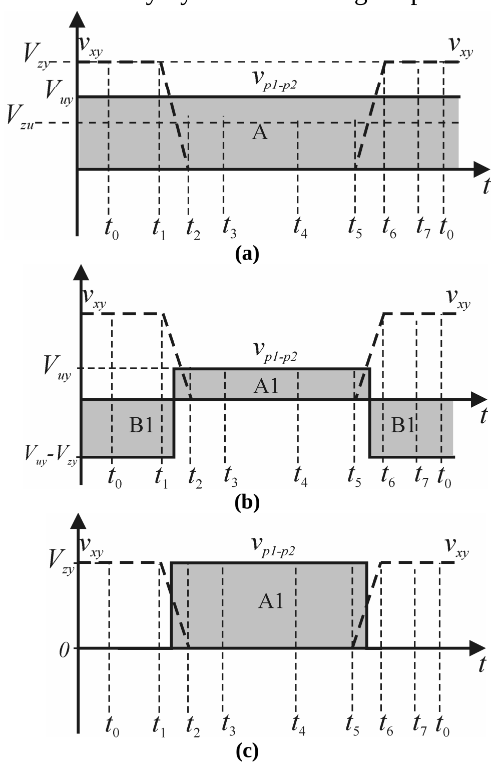


Fig. 7 – Primary winding voltage waveform for different configurations.

All configurations with no connections with the terminal 'x' of the basic PWM cell (Fig. 3) will provide an invariant voltage value to the secondary winding, Fig. 7(a). On the other hand, the configurations with a connection with the terminal 'x' will produce a variable voltage value to the secondary winding, Fig. 7(b) and 7(c).

To further enhance the benefits of the magnetically coupling voltage source, the primary winding is choose in such way that it can be the own filter inductor, i. e., 'p2' is connected to terminal 'u' and 'p1' to terminal 'x'.

III. DERIVED TOPOLOGIES

The concept of the new ZCZVT technique can be extended to any switched-mode conversion-inversion topology. To illustrate it, Fig. 8 shows the six basic single-ended non-isolated topologies of the new ZCZVT converters with configuration 1 of the auxiliary voltage sources (Fig. 1(a)), magnetically implemented. The converters in Fig. 8 are represented in their usual form. Nevertheless they are derived from the permutation of input and output among the common equivalent circuit of DC-DC converters.

The principle of operation of the new ZCZVT converters is similar to that of the ZCZVT boost converter shown in previous section.

A variation of the auxiliary voltage sources (Fig. 1(b)) generates other topologies, as shown in Fig. 9.

Fig. 10 shows some isolated single-ended topologies of the new class of ZCZVT PWM converters. Likewise the ZVT PWM converters, the disadvantage of the new ZCZVT PWM converters is that they do not make use of the leakage of the power transformer and, this way, the transformer should be design in such way to minimize its leakage inductance. One way to minimize the leakage is using the interleaving technique for the winding strategy, at the consequence of the increase of the windings capacitance. In spite of it, the winding capacitances are absorbed by capacitance C_s and both are softly discharged by the auxiliary circuit without any augmentation on the switching losses.

IV. EXPERIMENTAL RESULTS

In order to verify the theoretical analysis, a laboratory prototype for the new ZCZVT boost converter has been implemented. The parameters of prototype are described in Table II as well as the diagram of the prototype in Fig. 11.

The obtained experimental results for ZCZVT boost

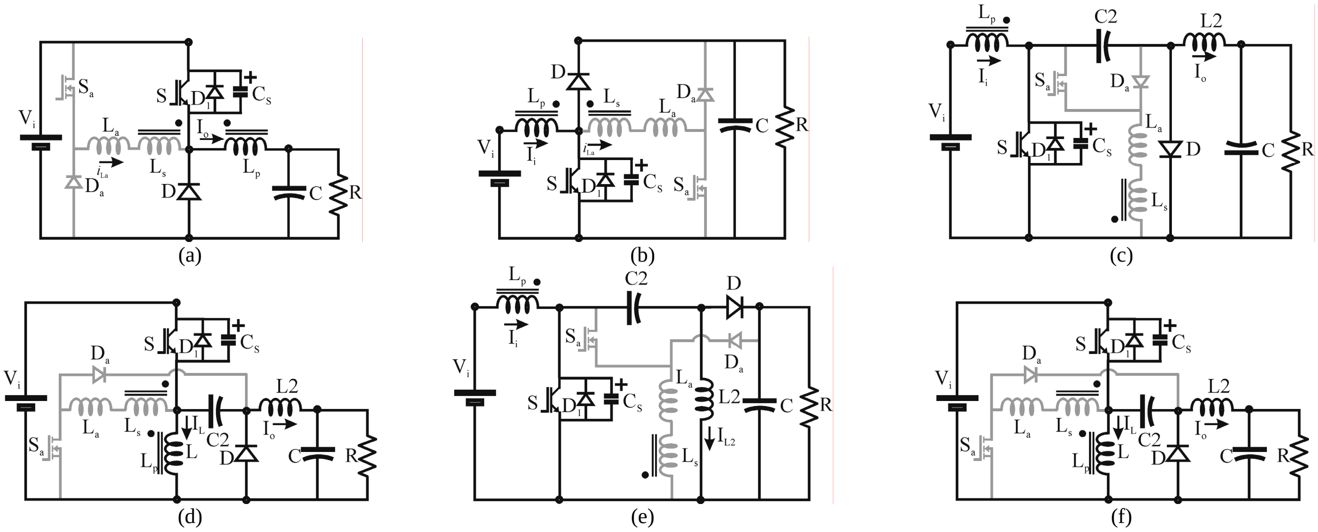


Fig. 8 – New non-isolated single-ended ZCZVT PWM converters. (a) Buck; (b) Boost; (c) Cük; (d) Buck-boost; (e) SEPIC; (f) Zeta.

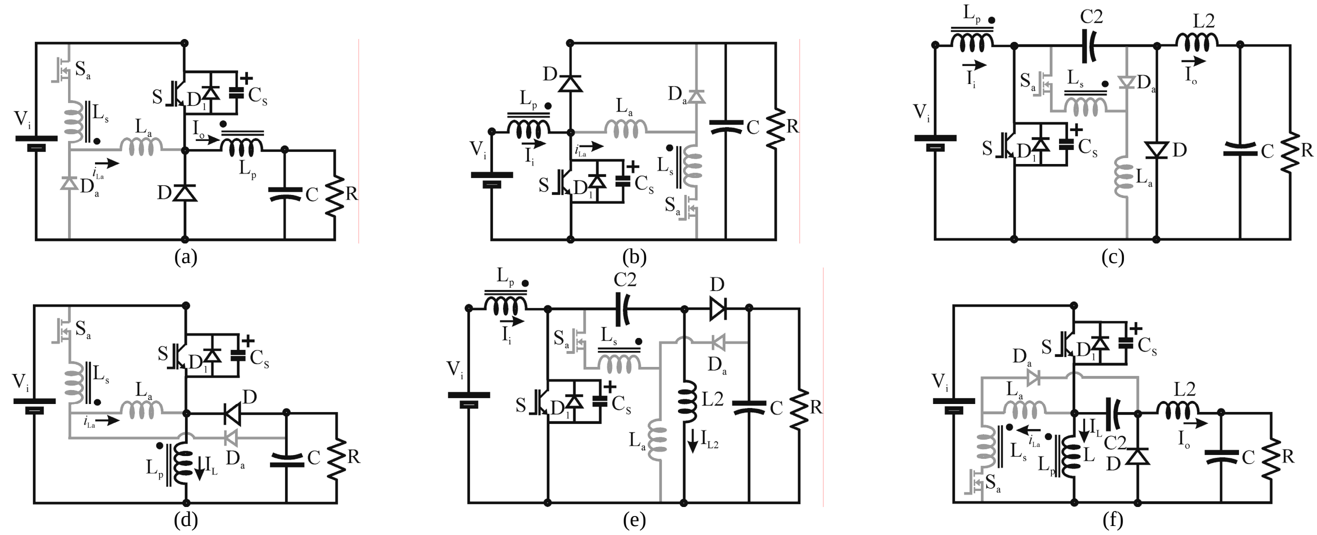


Fig. 9 – Alternative configuration for the New non-isolated single-ended ZCZVT PWM converters. (a) Buck; (b) Boost; (c) Cük; (d) Buck-boost; (e) SEPIC; (f) Zeta.

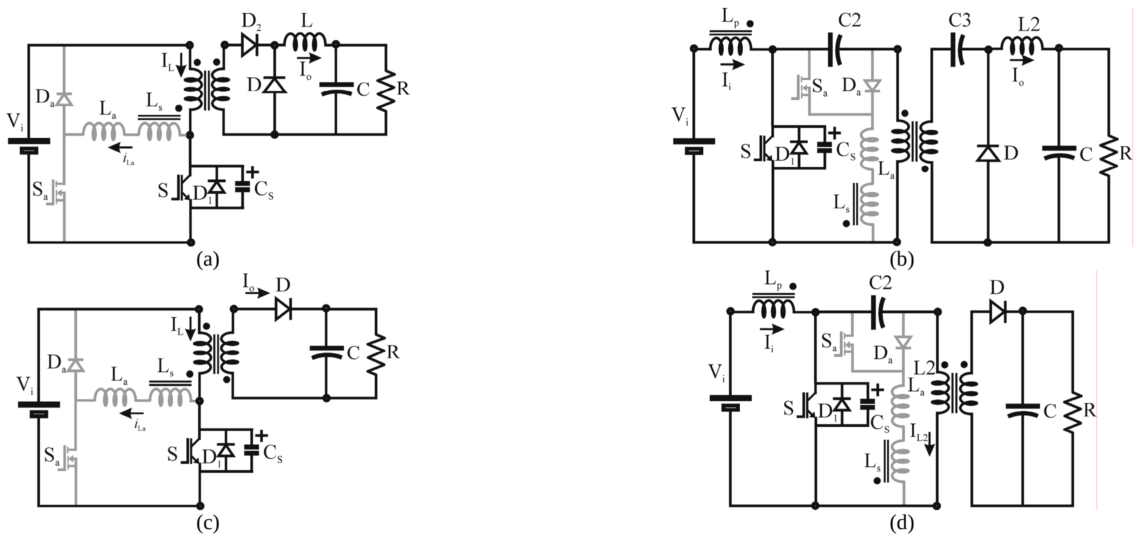


Fig. 10 – New isolated single-ended ZCZVT PWM converters. (a) Forward; (b) Cük isolado; (c) Flyback; (d) SEPIC isolado.

converter with secondary winding of magnetically coupled auxiliary source in series connections to inductor L_a are shown, respectively in Fig 12, 13 and 14.

The waveforms showed in Fig. 12(a) concerns the main switch turn-on. It can be seen that the turn-on takes place at zero voltage and zero current, simultaneously. Furthermore,

Table II – Prototypes experimental parameters.

Component	Prototype 1
V_i / V_0	150 V_{DC} / 400 V_{DC}
P_0 / f_s	1.0 kW / 50 kHz
L	1.46 mH (L_M)
C	470 uF
S	IRG4IBC30KD
S_a	IRFP460
D, D_a	MUR1560
Spike killer (SA 14x8x4.5)	(10 turns)
Coupled Inductor	EE-65/39
N (n_2/n_1)	0.3 (21/70)
L_a	9.24 µH (L_{k2})
C_S	1 nF

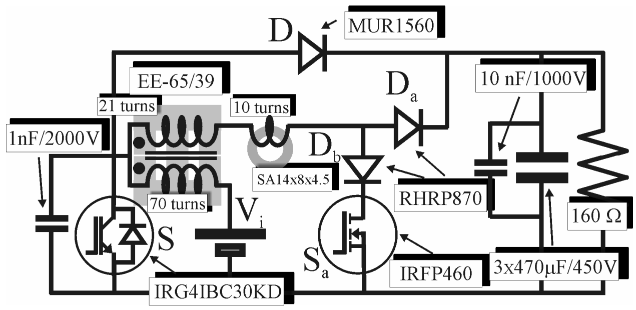
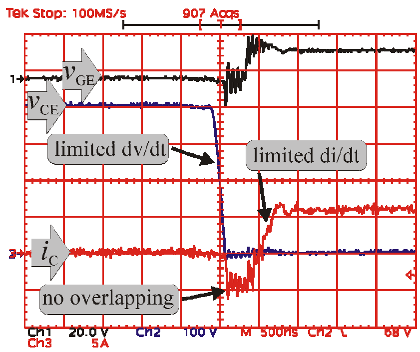


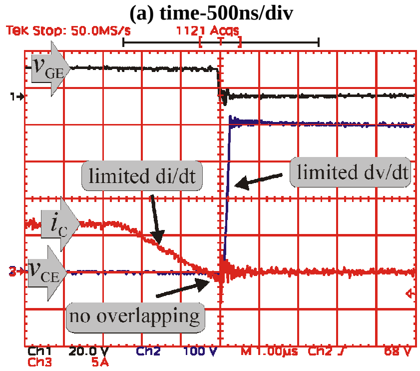
Fig. 11 – Laboratory prototype of the ZCZVT PWM boost converter

both voltage and current change with a controlled rate, ensuring better conditions to the semiconductor physical limitations (carrier lifetime). It also is expected that the di/dt and dv/dt controlled could also contribute to a better EMI performance.

In a similar way, Fig. 12(b) shows the waveforms for the main switch turn-off, where it can be seen that it occurs

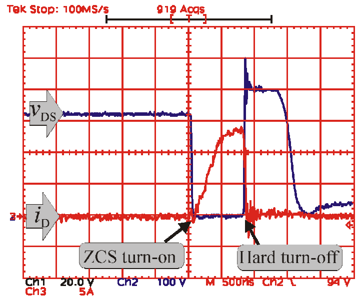


(a) time-500ns/div

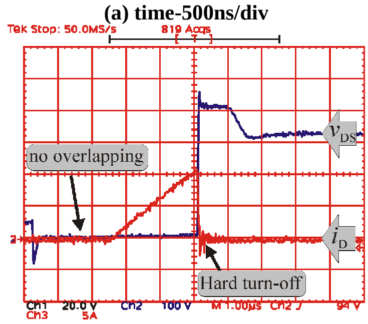


(b) time-1us/div

Fig. 12 – Experimental results for the New ZCZVT boost converter. (a) Main switch turn-on waveforms; (b) Main switch turn-off waveforms.
Scales: v_{GE}-20V/div; v_{CE}-100V/div ; i_C-5A/div ;



(a) time-500ns/div



(b) time-1us/div

Fig. 13 – Experimental results for Auxiliary switch. (a) Main switch turn-on process; (b) Main switch turn-off process.
Scales: v_{DS}-100V/div; i_C-5A/div

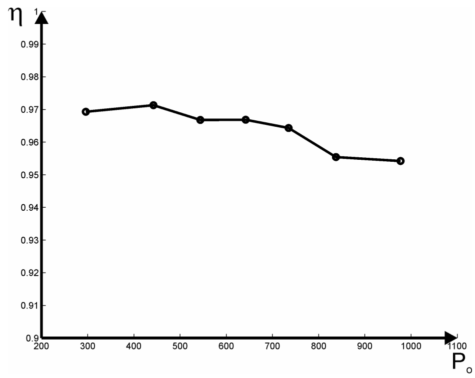


Fig. 14 – Efficiency curve.

under conditions alike, i. e., at zero voltage and zero current, simultaneously. Moreover, the controlled and constant di/dt applied to the main switch current during the turn-off provides better turn-off conditions to IGBT and other minority carrier device.

Fig. 13(a) shows the waveforms on the auxiliary switch during the main switch turn-on process. It can be observed that current through the auxiliary switch resembles the current of a conventional ZVT auxiliary switch, i. e., little reactive energy is presented. Additionally, its conduction losses will be proportional to the load current, ensuring low losses at low load conditions. The waveforms on the auxiliary switch during main switch turn-off process are shown in Fig. 13(b). The same explained for Fig. 13(a) is valid for Fig. 13(b). Thus, the low reactive energy is assured for both turn-on and turn-off, as well as the limited voltage and current rate of change and the proportional current stress to the load current.

The efficiency curve for the prototype is shown in Fig. 14. It can be seen that the converter achieve high efficiencies throughout the load range (95.5% to 97.1%). Nonetheless, it can be seen that at low load conditions, the low reactive energy and the low current stresses (actually proportional to the load), ensures a remarkable efficiency performance compared to other resonant based ZVT, ZCT and ZCZVT converters that presented low efficiency gains at low load conditions.

V. CONCLUSION

This paper presented and analyses a new class of Zero-Current Zero-Voltage Transition (ZCZVT) PWM Converters. The noteworthy characteristic of these new converters concerns the non-resonant auxiliary circuit that permits the current flow control between main and auxiliary circuits with low reactive energy. This feature makes these ZCZVT converters unique once other topologies present a significant amount of reactive energy.

Additionally, the auxiliary circuit current efforts are proportional to the load current which ensures that at light load conditions the losses will be lessen differently of any other ZCZVT where the losses are commonly proportional to the high load conditions, resulting in high losses at light load. Moreover, these characteristic are achieve maintaining the the advantages of the ZCZVT technique such as, zero-current and zero-voltage switching for the main pole semiconductors with controlled dv/dt and di/dt, good suitability for for both, majority and minority carrier devices, etc..

To verify the feasibility and confirm the theoretical analyses of the proposed the new ZCZVT converters, a new ZCZVT boost converter has been implemented in laboratory. The laboratory prototype is rated at 1.0 kW, 50 kHz and the experimental substantiate the analyses carried out throughout the paper.

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