# ZERO-CURRENT ZERO-VOLTAGE TRANSITION PWM CONVERTERS WITH MAGNETICALLY COUPLED AUXILIARY CIRCUIT

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*Abstract* – **This paper presents a novel methodology to synthesize Zero-Current Zero-Voltage Transition (ZCZVT) topologies. The proposed methodology is based on the Auxiliary Voltage Source (AVS) concept, which permits extend the proposed new circuits to an entire class of converters. As the AVS concept is derived directly from the Resonant Transition mechanism, the new class of ZCZVT converters resembles some of the well-known Zero-Voltage Transition (ZVT) converters, holding their main advantages such as simplicity, low reactive energy and high performance. Theoretical and experimental analyses are carried out throughout the paper taking the boost converter as the case study. Nevertheless, it can be extended to other PWM topologies, even the AC-DC and DC-AC converters. Experimental and comparative results have been obtained from three laboratory prototypes rated to 1 kW, 50 kHz, confirming the feasibility of the novel synthesis concept and also the reliability of the new ZCZVT converters in what refers to efficiency as well as to *di/dt* and *dv/dt* control.**

*Keywords* – **boost converter, soft-switching, ZCZVT.**

## I. INTRODUCTION

Recently developments of new semiconductors such as silicon carbide (SiC) [1] and Cool MOS [2] have become a promising solution to reduce significantly the switching losses associate to high frequency converters. These new semiconductors shrink the switching times to tens of nanoseconds, which permit to the converters operate at higher frequency without penalizing the overall system efficiency. Despite of the low switching and conduction losses, there still remain other issues that impair high frequency Pulse Width Modulation (PWM) converters. One such issue is related to the electromagnetic interference (EMI) [3] that exacerbates with the high *di/dt* and *dv/dt* produced by the new semiconductor devices. An alternative to minimize the high *dv/dt* and *di/dt* is the use of soft-switching techniques. In general, soft-switching techniques shape the voltage and/or the current through the semiconductors in such way that low *dv/dt* is provided for the Zero Voltage mode converters [4,5] and low *di/dt* is provided for the Zero Current mode converters [4].

Soft-switching techniques have been intensively explored for decades aiming to provide converters that could reduce the switching losses and EMI associated problems.

The ZVT is one of the most well succeeded and consolidated technique in the state-of-the-art of soft-switching converters [6-11]. It is capable to provide a wide load range under soft-switching conditions with low, or even no, additional stresses on main semiconductor devices and very low stresses on auxiliary devices. These characteristics are obtained due to the unique location of the auxiliary circuit that is indeed in parallel with the main power path. Additionally to the auxiliary circuit location, it is activated only during a small interval during the main switch(es) turn-on commutations. Therefore, the ZVT converters can work as close as possible to their PWM counterparts. Regrettably, ZVT technique can aid effectively just the turn-on process (truly-soft switching). For the turn-off process its benefits are dependent on the semiconductor technology [12-14]. Consequently, the ZVT technique will present a minor effectiveness with minority carrier devices semiconductor type due to their major turn-off losses. Based on the soft-transition concept, i.e., the parallel auxiliary circuit acts only during the switching intervals, which initiate with the ZVT technique, the Zero-Current Transition - ZCT technique [15], was soon developed. The ZCT technique intends to provide converters with quite reduced turn-off switching losses meanwhile turn-on losses were primarily disregarded [15] or partially reduced [16,17]. Historically, the ZCT technique assisting both turn-on and turn-off switching processes was presented as a forced commutation circuit for voltage source inverters in [18]. At that time the auxiliary circuit intends only to commutate the partially controlled SCR devices. This way, the ZCT technique is also semiconductor technology dependent, once majority carrier semiconductors presents major turn-on losses.

Following the soft-transition concept a semiconductor technology independent technique is presented with the Zero-Current and Zero-Voltage Transition - ZCZVT technique [19,20]. As its name suggests, the ZCZVT technique provides turn-on and turn-off commutations with truly-soft switching and further *di/dt* and *dv/dt* control. The ZCZVT technique resembles the ZCT technique and except by [15], in both techniques, the auxiliary circuit is activated

Artigo submetido em 15 de maio de 2008; primeira revisão em 26 de agosto de 2008; segunda revisão em 12 de novembro de 2008. Recomendado para publicação pelos Editores da Seção Especial, João Carlos dos Santos Fagundes e Felix Alberto Farret.

twice, during turn-on and turn-off switching. The auxiliary circuit of ZCTs and ZCZVTs provides a current impulse that commutates the PWM pole (main devices). This current impulse is achieved by means of a resonant-like circuit that is activated always a device goes on commutation independently of which device is on conduction (switch or diode). In spite of the resonant auxiliary circuit yield truly-soft switching conditions for all main device commutations, it produces reactive energy in excess, increasing semiconductors RMS rate and even the conduction losses [20]. Therefore, the ZCTs and ZCZVTs converters presented hitherto are not so effective in improving the converter efficiencies as their precursors ZVT's. For this reason there is a necessity to obtain an efficient solution to reduce the losses and EMI problems associated to the medium and high power application PWM converters. In order to give an alternative to current ZCTs and ZCZVTs state-of-the-art, this paper proposes a novel class of ZCZVT with low reactive energy and better performance. This novel class is obtained by means of a synthesis methodology based on the Resonant Transition mechanism requirements in spite of the simple integration of ZCT's and ZVT's auxiliary circuits.

## II. SOFT-SWITCHING BASIC DEFINITIONS

The basic PWM cell or PWM basic building block is normally comprised by a filter inductor (L) and a couple of semiconductors (S-D) that operate in a complementary way [21]. The switching action provides the PWM modulation to control the power flow between source and load. Assuming that the filter inductor is large enough so that the current through it can be simplified to a constant current I; and the voltages applied across the devices are also constant, there will be two possible commutation processes, the turn-on process, where the current I is diverted from the diode D to the switch S; and, the turn-off process, where the current I is diverted from the switch S to the diode D. Due to the intrinsic characteristics (limitations) of the semiconductors in both commutation processes there will be a finite interval where voltage and current are imposed simultaneously on the device, producing losses. Furthermore, parasitic capacitances and inductances of the circuit produces current and voltage stresses that can increase the losses and semiconductors overrate. Aiming to alleviate the drawbacks aforementioned, soft-switching techniques make use of additional elements to shape the current and/or voltage waveforms on the semiconductor device. In a simple way the role of the additional elements is twofold: (i) to minimize the overlapping between current and voltage to reduce the switching losses; and, (ii) to limit the current ratio of change (*di/dt*) during the turn-on and/or the voltage ratio of change (*dv/dt*) during turn-off to avoid current and voltage stresses during commutation.

### *A. The Resonant Transition Mechanism*

According to Figure 1, the commutation mechanism for the Resonant Transition converters, Zero-Voltage (Figure 1.a) and Zero-Current (Figure 1.b), consists in providing conditions to charge and discharge the commutation inductor $L_a$ in order to deviate the current from the PWM pole to the auxiliary circuit. To accomplish such task, the commutation inductor $L_a$ is charged from zero to a value slightly higher than the load current. This way, the most important subject concerning the Resonant Transition technique is to provide an auxiliary voltage source to charge/discharge the commutation inductor $L_a$ every time the assisted device of the PWM pole goes into commutation. This auxiliary voltage source can come out in different ways and can be comprised by just one or a set of elements. Additionally, if the commutation technique allows the control of the *dv/dt* across the PWM pole, there will be additional resonant intervals that charge/discharges the snubber capacitor located across the PWM pole.

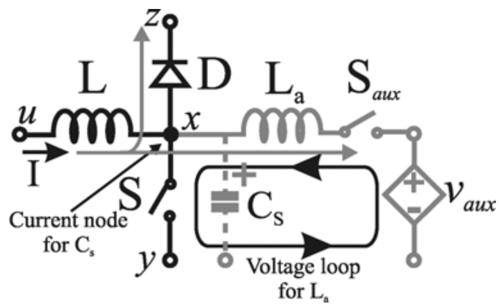


Fig. 1. Basic soft-transition circuit and its commutation inductor (La) voltage loop. The zero-voltage mode, ZVT (w. Cs ); The zero-current mode, ZCT (wo. Cs).

As ZVT technique was the first Resonant Transition technique presented in the literature [6], it presents more assorted types of auxiliary voltage sources (AVS) that can be gathered into only three broad groups or classes, as proposed in [11]. According to their characteristics, the groups can be named Switched Auxiliary Voltage Source (Switched or *Class A* AVS), Constant Auxiliary Voltage Source (Constant or *Class B* AVS) and Resonant Auxiliary Voltage Source (Resonant or *Class C* AVS).

Differently of ZVT converters AVS diversity, the ZCT technique [15] makes use of a *Class C* AVS. Its topological developments consist in the modification of the excitation source of a resonant circuit with the aid of a half- or full-controlled pole. The resonant circuit comprised by a simple LC is kept unchangeable in the ZCT auxiliary circuit structure [16,17], in other words, the ZCT is still based on a sinusoidal-like waveform to accomplish the AVS ($v_{aux}$) role. Therefore, the auxiliary voltage source presented in the ZCT converters family can be named Resonant Auxiliary Voltage Source (Resonant or *Class C* AVS) operates in a similar way of the AVS presented by the *Class C* ZVT converters.

As an attempt to generate a class of converters that could present the finest characteristics among ZVTs and ZCTs, which means that truly-soft transition for both turn-on and turn-off, the ZCZVT technique was proposed. To accomplish this task researchers have been driven by the idea of combining a ZVT auxiliary circuit with a ZCT auxiliary circuit [19]. Regrettably, the ZCZVT converters obtained from this methodology present high reactive energy produced by the auxiliary circuit that can off-set the energy saved in the commutation processes. For this reason, the ZCZVT technique presented hitherto is apparently justified only when the noisy ZCT converters cannot accomplish the EMI imposed by standard restriction or other specifications.

*B. The Resonant Transition Mechanism Requirements*

Considering that the voltage across the PWM pole can be simplified to a dependent voltage source $v_{xy}$ (Figure 1), to achieve the charge and discharge of the commutation inductor during turn-on and turn-off commutation, as depicted in the theoretical waveforms shown in Figure 2, the AVS must comply with the following restriction,

$$v_{aux} < v_{xy},\ \ for \quad (t_0 < t < t_1)$$
$$v_{aux} < v_{xy},\ \ for \quad (t_4 < t < t_5) \tag{1}$$

And

$$v_{aux} > v_{xy},\ \ for \quad (t_2 < t < t_3)$$
$$v_{aux} > v_{xy},\ \ for \quad (t_6 < t < t_7) \tag{2}$$

Where the instants $t_0$ to $t_7$ are defined in Figure 2, which also shows the waveforms of $v_{xy}$ and corresponding regions that can be assumed by the auxiliary voltage source, $v_{aux}$. In spite of that any waveform adequately shaped could comply with the regions defined in the shaded areas shown in Figure 2, from the theoretical perspective, it can be expected that there is two simple mathematical functions that could possibly attend for the restrictions (1) and (2), a continuous co-sinusoidal waveform and a discontinuous stepped waveform. These simple waveforms are represented in Figure 2.b.

## III. A NOVEL SYNTHESIS METHODOLOGY

According to the previous Section, due to the linear charge and discharge of commutation inductor $L_a$, the

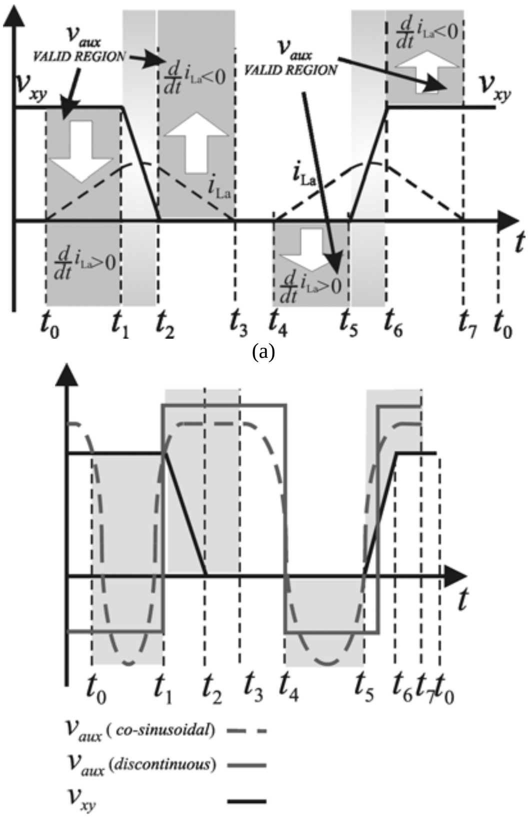



Fig. 2. Valid regions for the zero-current and zero-voltage auxiliary voltage source (AVS).

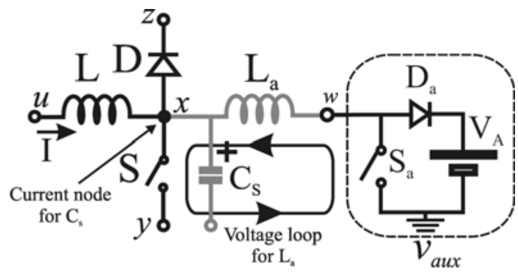



Fig. 3. Basic switched AVS circuit diagrams for Class A ZCZVT converters.

discontinuous waveform is the most suitable approach to produce waveforms with low reactive energy, once the resonance is restrained to the charge/discharge of Cs.

To make feasible the named *Class A* ZCZVT converters it is required that the voltage level applied to charge the commutation inductor $L_a$ must reach negative values, as shown in Figure 2.b. To accomplish this requirement at least one constant voltage source ($V_{a1}$ or $V_{a2}$), Figure 3, must be incorporated in the generalized circuit diagram of Class A derived from the ZVT converters, [11]. With the voltage sources $V_{a1}$ and $V_{a2}$ it can be obtained three different circuit configurations as described in Table I.

For the configurations derived in Table I, the restrictions that make them work under the ZCZVT operation are described below.

*1) Restriction 1* - For ***turn-on charge interval*** of inductor $L_a$ ($S_a$ turned on / $D_a$ turned off).

$$di_{La}(t)/dt > 0 \therefore v_{La}/L_a > 0 \tag{3}$$

Substituting $i_{La}$ from the circuit shown in Figure 3,

$$\left(V_{a1} + V_{a2} + v_{xy}\right)/L_a > 0 \tag{4}$$

This way, the restriction can be expressed by,

$$V_{a1} + V_{a2} > -v_{xy} \tag{5}$$

As $v_{xy}$ is equal to the voltage $V_{zy}$ (Figure 3) before the main switch turn-on, expression (5) becomes,

$$V_{a1} + V_{a2} > -V_{zy} \tag{6}$$

*2) Restriction 2* - For ***turn-on discharge interval*** of inductor $L_a$ ($S_a$ turned off / $D_a$ turned on).

$$di_{La}(t)/dt < 0 \therefore v_{La}/L_a < 0 \tag{7}$$

Substituting $i_{La}$ from the circuit,

$$\left(-V_A + V_{a1} + v_{xy}\right)/L_a < 0 \tag{8}$$

This way, the restriction can be expressed by,

$$V_{a1} < V_A - v_{xy} \tag{9}$$

As $v_{xy}$ is equal to zero after the main switch turn-on, expression

TABLE I – AUXILIARY CIRCUIT ZCZVT TOPOLOGIES.

| Topology | Constant Voltage Sources (in AVS) | |
|---|---|---|
| | $V_{a1}$ | $V_{a2}$ |
| 1 | > 0 | = 0 |
| 2 | = 0 | > 0 |
| 3 | > 0 | > 0 |

(7) becomes,

$$V_{a1} < V_A \quad (10)$$

*3) Restriction 1* - For ***turn-off charge interval*** of inductor $L_a$ ($S_a$ turned on / $D_a$ turned off). $v_{xy}$ is equal to zero before the main switch turn-off, thus, a similar development of expression (3) results in,

$$V_{a1} + V_{a2} > 0 \quad (11)$$

*4) Restriction 2* - For ***turn-on discharge interval*** of inductor $L_a$ ($S_a$ turned off / $D_a$ turned on). $v_{xy}$ is equal to $V_{zy}$ after the main switch turn-off, thus a similar development of expression (7) results in,

$$V_{a1} > 0 \quad (12)$$

From the restriction defined in (6), (10), (11) and (12) a set of auxiliary circuit can be synthesized, as shown in Figure 4.a -4.c, where the possible connections with the terminals of the PWM pole (Figure 3) are defined by the letters *y*, *z*, *u* and *x*.

As it can be seen, the auxiliary circuit shown in Figure 4.a resembles the auxiliary circuit of the ZVT boost converter proposed by Hua [5]. Therefore, it can be expected that it holds the Hua's ZVT auxiliary circuit merits and drawbacks. Likewise, as several modifications have been proposed to improve their features, the proposed ZCZVT also can incorporate the Hua's ZVT variations. As a common complaint concerns its hard-switching auxiliary switch turn-off, which is usually solved with the introduction of some sort of passive turn-off snubber, a set of novel ZCZVT circuits can be generated by means of the introduction of different turn-off snubber cells. In spite of it, some ZVT converters [9,10] with Snubber Assisted Auxiliary Switch hold a special characteristic that ensures an improvement not only to the auxiliary switch turn-off, but also for the main switch turn-off. It is achieved due to the unique location of the auxiliary snubber that is placed in such way that it can be shared for both switches [9,10]. Two variations of the Snubber Assisted Auxiliary Switch are applied to the ZCZVT auxiliary circuit of Figure 4.a with a single auxiliary source $V_{a1}$, as shown in Figure 4.b and 4.c. The "Snubber Assisted Auxiliary Switch" Figure 4.b, derived from [9], which consists of a bypass diode ($D_{Csa}$) and a snubber capacitor ($C_{sa}$); and a "Modified Snubber Assisted Auxiliary Switch" Figure 4(c), derived from [10] that split the snubber into two parts, a flying capacitor ($C_{sa}$) and a grounded capacitor ($C_{sa2}$).

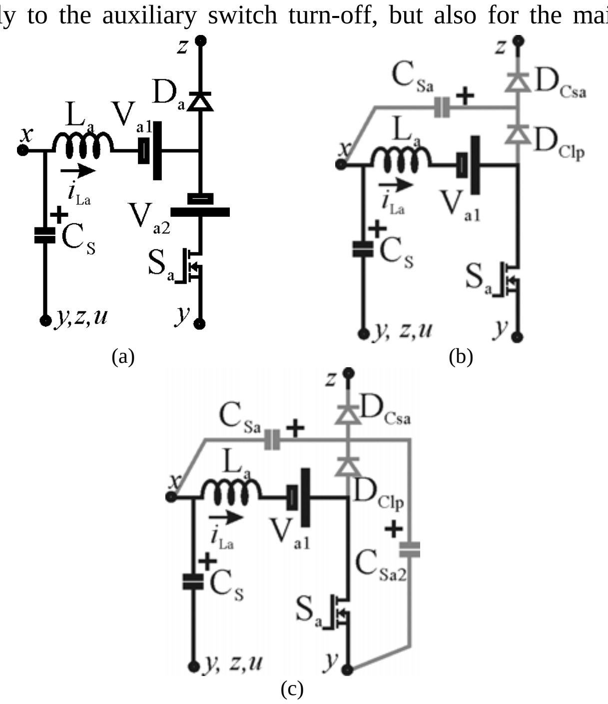



Fig. 4. *Class A* ZCZVT auxiliary circuits. Configurations for (a) the Simple ZCZVT; and for (b)-(c) the Snubber Assisted Auxiliary Switch ZCZVTs.

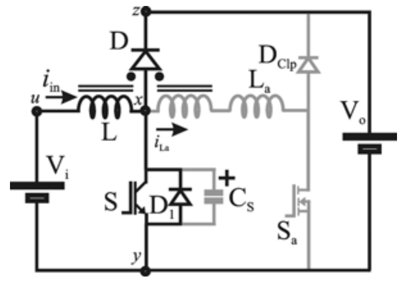


Fig. 6. Simple ZCZVT PWM boost converter.

## IV. SIMPLE ZCZVT PWM BOOST CONVERTER

This Section analyzes the operation of the simple ZCZVT PWM boost converter, with AVS shown in Figure 4.a.

### *A. Auxiliary Voltage Source Implementation*

The constant voltage source $V_{a1}$ present in ZCZVT auxiliary circuit, Figure 4.a, can be implemented by means of a large capacitance or by means of the magnetic coupling among two or more windings wrapped in the same core. The interesting feature of the magnetic coupling implementation is that it can result in small size converters. For this reason the magnetic coupling is chosen to implement the required constant auxiliary voltage source, where the secondary winding is disposed in the auxiliary circuit (forming the actual auxiliary voltage source) and the primary winding is the filter inductor itself.

### *B. Principle of Operation*

In steady-state operation, the Simple ZCZVT boost converter, depicted in Figure 5, presents twelve circuit

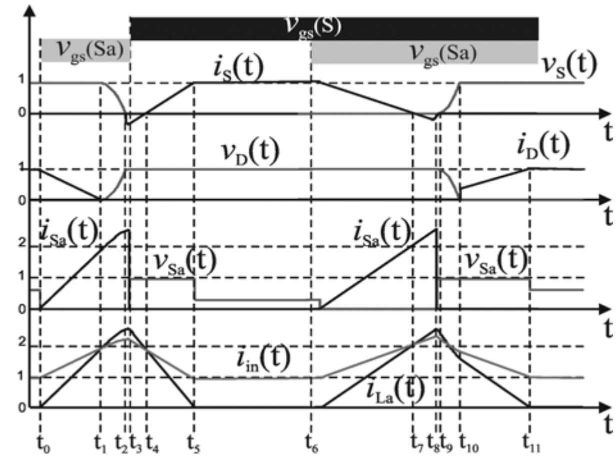


Fig. 5. Theoretical waveforms for the Simple ZCZVT boost converters.

modes, as can be seen by the main theoretical waveforms given in Figure 6. All the current waveforms are normalized by the average input current ($I$) as well as the voltage waveforms by the output voltage ($V_o$). Thus the vertical scales are refered by the units in p.u..

The circuit modes are described as follows.

***Turn-on Process:***

***Mode 1. ($t_0$,$t_1$):*** In this mode the auxiliary inductor is charged linearly.

***Mode 2. ($t_1$,$t_2$):*** At $t_1$, main diode D turns off, thus the current through $L_a$ resonates with the voltage $v_{Cs}$, discharging the capacitance $C_s$ in a resonant way.

***Mode 3. ($t_2$,$t_3$):*** At $t_2$, $v_{Cs}$ reaches zero and the body diode of main switch conducts. The current $i_{La}$ increases linearly due to the existence of the voltage $Nv_{Lm}$ across $L_a$.

***Mode 4. ($t_3$,$t_4$):*** This mode starts when the auxiliary switch $S_a$ turns off and main switch turns on. Current through $L_a$ decreases linearly.

***Mode 5. ($t_4$,$t_5$):*** At $t_4$, main switch body diode turns off and current $i_{in}$ deviates to main switch S linearly until $i_{La}$ reaches zero.

***Mode 6. ($t_5$,$t_6$):*** In this mode the auxiliary circuit is off and the converter operates as its PWM counterpart, governed by the PWM modulation.

***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.

***Mode 8. ($t_7$,$t_8$):*** At $t_7$ the current through main switch reaches zero and its body diode turns on.

***Mode 9. ($t_8$,$t_9$):*** In this mode the current decreases linearly through main switch body diode until it reaches zero.

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

***Mode 11a. ($t_{10a}$,$t_{11}$):*** At $t_{10a}$ main diode starts conducting and $i_{La}$ decreases linearly due to the voltage $Nv_{Lm}$ applied across $L_a$.

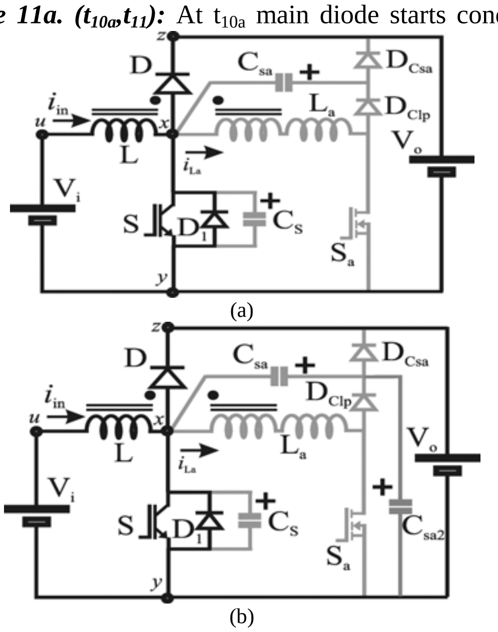



Fig. 7. Snubber Assisted ZCZVT PWM boost converters. (a) Snubber Assisted; (b) Modified Snubber Assisted.

***Mode 11b. ($t_{10b}$,$t_{11}$):*** At $t_{10b}$ $i_{La}$ reaches zero and capacitor $C_s$ is charged by current $i_{in}$.

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

As it can be seen by Figure 6 the resonant processes are restricted to the charge and discharge intervals of capacitor $C_s$. The linear charge and discharge of inductor $L_a$ ensures low reactive energy and thus, it is expected low conduction losses on the auxiliary circuit elements.

## V. SNUBBER ASSISTED ZCZVT PWM BOOST CONVERTER

This Section analyses the operation of the snubber assisted ZCZVT PWM boost converter, whose diagram is shown in Figure 7.a. The current waveforms are normalized by the average input current ($I$) as well as the voltage waveforms by the output voltage ($V_o$).

In steady state operation of the Snubber Assisted ZCZVT boost converter presents twelve circuit modes and the main theoretical waveforms are given in Figure 8. The circuit modes are similar to those of the Simple ZCZVT boost converter, despite of the following modes.

***Mode 4. ($t_3$,$t_4$):*** This mode starts when the auxiliary switch $S_a$ turns off and main switch turns on. Current through $L_a$ resonates charging the snubber capacitor $C_{Sa}$ until it reaches the voltage $V_0$.

***Mode 10. ($t_9$,$t_{10}$):*** In this mode $i_{La}$ resonates with the voltage across both capacitors, i.e, with a parallel equivalent capacitor given by,

$$C_{eq} = C_S C_{Sa} \big/ \left( C_S + C_{Sa} \right) \tag{13}$$

This mode lasts until the current $i_{La}$ reaches zero ($t_{10}$).

***Mode 11. ($t_{10}$,$t_{11}$):*** At $t_{10}$ $i_{La}$ reaches zero and capacitors $C_s$ and $C_{Sa}$ are charged by current I.

## VI. MODIFIED SNUBBER ASSISTED ZCZVT PWM

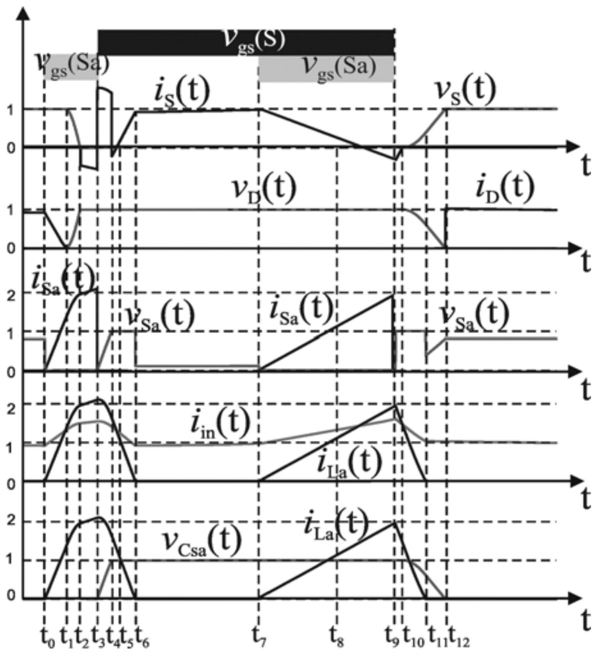



Fig. 8. Theoretical waveforms for the Snubber Assisted ZCZVT boost converter.

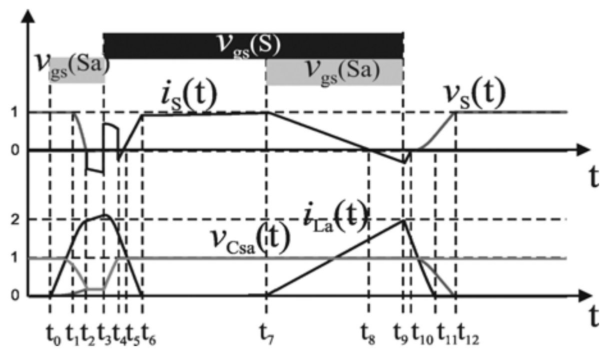



Fig. 9. Theoretical waveforms for the Modified Snubber Assisted ZCZVT boost converter.

BOOST CONVERTER

The diagram of the modified snubber assisted ZCZVT PWM boost converter is shown in Figure 7.b, where all the current waveforms are normalized by the average input current ($I$) as well as the voltage waveforms by the output voltage ($V_o$).

In steady state operation, the Modified Snubber Assisted ZCZVT boost converter presents twelve circuit modes. Actually, the modified snubber works very similarly to the snubber assisted auxiliary switch, its main differences are related to the following modes:

***Mode 2. ($t_1$,$t_2$) and Mode 10. ($t_9$,$t_{10}$):*** In these modes the current through $L_a$ resonates with the voltage across the equivalent capacitance ($C_{eq2}$) formed by capacitors $C_S$, $C_{Sa1}$ and $C_{Sa2}$. The equivalent capacitance is given by,

$$C_{eq2} = C_S + \left( C_{Sa} C_{Sa2} / \left( C_{Sa} + C_{Sa2} \right) \right) \tag{14}$$

***Mode 4. ($t_3$,$t_4$):*** In this mode the current through $L_a$ resonates with the voltage across the equivalent capacitance ($C_{eq3}$) formed by capacitors $C_{Sa1}$ and $C_{Sa2}$. The equivalent capacitance is given by,

$$C_{eq3} = C_{Sa} + C_{Sa2} \tag{15}$$

The main theoretical waveforms for the modified snubber assisted auxiliary switch ZCZVT boost converter are very similar of those of the snubber assisted auxiliary switch (Figure 8). The major differences are in the current $i_S$ and voltage $v_{Csa}$ waveforms, as can be seen in Figure 9.

## VII. COMPARATIVE AND EXPERIMENTAL RESULTS

In order to verify the theoretical analysis presented in the previous Sections, three laboratory prototypes have been implemented, a simple ZCZVT boost converter, a snubber assisted ZCZVT boost converter and a modified snubber assisted ZCZVT boost converter. The diagrams of the laboratory prototypes are shown in Figure 10 and their specifications as well as semiconductors and auxiliary circuit elements are shown in Table II.

In Figure 11 it can be seen the experimental waveforms for the simple ZCZVT boost converter prototype. The main switch turn-on and turn-off process can be seen in Figure 11.a and 11.b, respectively. The commutation processes are characterized by totally controlled *dv/dt* and *di/dt* transitions. Additionally no overlapping between the voltage and current waveforms are presented. Figure 11.c shows the waveforms

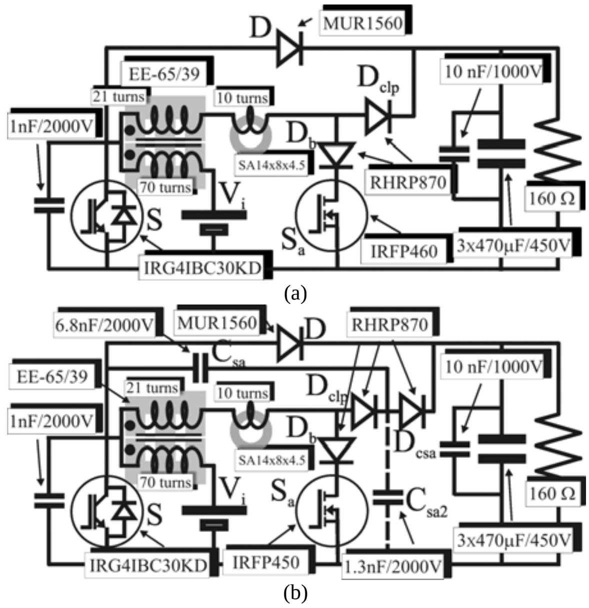



Fig. 10. Laboratory Prototypes. (a) Simple ZCZVT boost converter; (b) Snubber Assisted ZCZVT boost converter (wo. Csa2); Modified Snubber Assisted ZCZVT boost converter (w. Csa2).

**TABLE II -EXPERIMENTAL PROTOTYPES PARAMETERS**

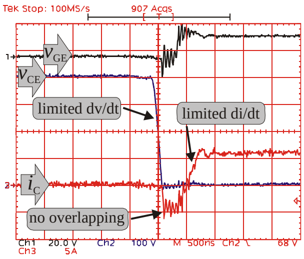
| Component | Parameter |
|---|---|
| $V_i$ / $V_0$ | 150 $V_{DC}$ / 400 $V_{DC}$ |
| $P_0$ / $f_s$ | 1.0 kW / 100 kHz |
| *L (input filter)* | 1.46 mH ($L_M$) |
| *C (output filter)* | 3 x 470 uF |
| $S$ / $S_a$ | IRG4IBC30KD / IRFP460 |
| $D$ / ($D_{Clp}$, $D_a$, $D_b$) | MUR1560 / RHRP870 |
| $N$ ($n_2$/$n_1$) | 0.3 (21 turns/70 turns) |
| $L_{k1}$ / $L_{k2}$ *(leakage inductances)* | 86.8 µH / 9.24 µH |
| $L_a$ / $C_S$ | 9.24 µH ($L_{k2}$) / 1 n F |
| $C_{sa}$ / $C_{sa2}$ | 6.8 nF* / 1.3 nF** |

* Only for snubber assisted auxiliary switch ZCZVT boost prototype.
** Only for modified snubber assisted auxiliary prototype.

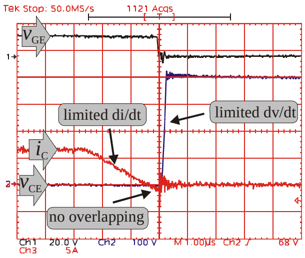
for the auxiliary switch during the main switch turn-on process. It can be observed that the waveforms are very similar to the Hua's ZVT converter [5]. The auxiliary waveforms for the main switch turn-off process are depicted in Figure 11.d.

The linear fashion of the current waveform through auxiliary switch Sa ensures low reactive energy, compared to other ZCZVT topologies [19,20]. The waveforms shown in Figure 11.c and 11.d reveal that auxiliary switch turn-off process take place under hard-switching conditions.

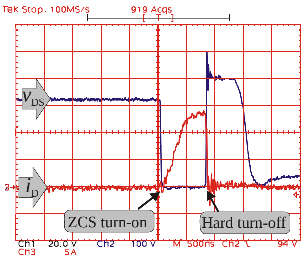
In Figure 12 it can be seen the experimental waveforms for the snubber assisted auxiliary switch ZCZVT boost converter prototype. The main switch turn-on and turn-off process can be seen in Figure 12.a and 12.b, respectively. The turn-on waveforms reveal that the current through the switch suffers from a current spike, which prevents the turn-on *di/dt* control through the switch. Nevertheless, the turn-off waveform shows a lower *dv/dt* accomplished by the flying capacitor $C_{Sa}$ that plays the role of a snubber capacitor for the main switch turn-off.



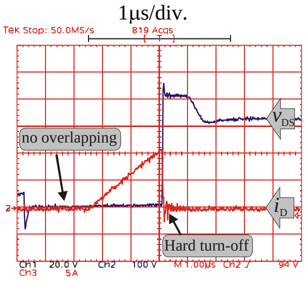

(a) Scales: $v_{GE}$: 20V/div, $v_{CE}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.




(b) 9Scales: $v_{GE}$: 20V/div, $v_{CE}$: 100V/div, $i_C$: 5A/div, Time: 1µs/div.



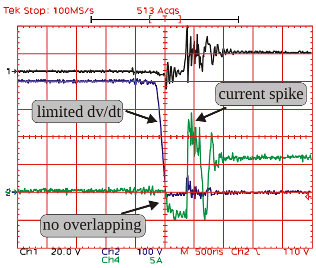

(c) Scales: $v_{DS}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.



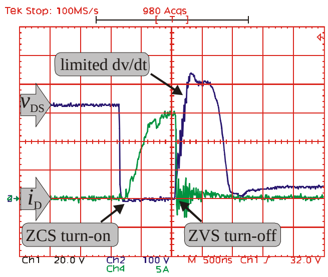

(d) Scales: $v_{DS}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.

Fig. 11. Experimental results for the Simple ZCZVT PWM boost converter prototype.

In Figure 13 it can be seen the experimental waveforms for the modified snubber assisted auxiliary switch ZCZVT boost converter prototype. The main switch turn-on waveforms, shown in Figure 13.a, reveals that the current spike in the modified converter is slightly smaller than that of the snubber assisted, Figure 12.a. The price paid for it is the loss of the ZVS turn-off for auxiliary switch during main switch turn-on process, Figure 13.b.

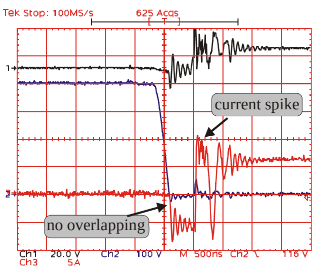



(a) Scales: $v_{GE}$: 20V/div, $v_{CE}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.

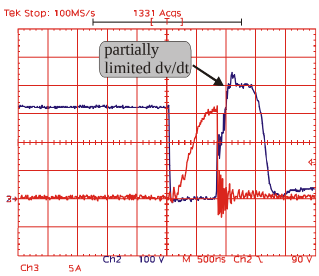



(b) Scales: $v_{DS}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.

Fig. 12. Experimental results for the Snubber Assisted Auxiliary Switch ZCZVT PWM boost converter prototype.




(a) Scales: $v_{GE}$: 20V/div, $v_{CE}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.




(b) Scales: $v_{DS}$: 100V/div, $i_C$: 5A/div, Time: 500ns/div.

Fig. 13. Experimental results for the Modified Snubber Assisted Auxiliary Switch ZCZVT PWM boost converter prototype.

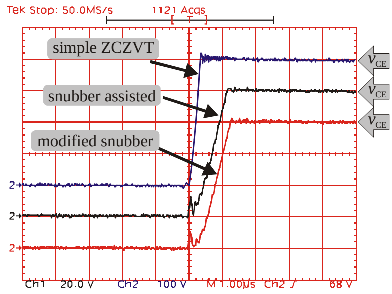



Fig. 14. Comparison among the main switch *dv/dt* during its turn-off transition. Scales: Ch: 100V/div, Time: 1µs/div.

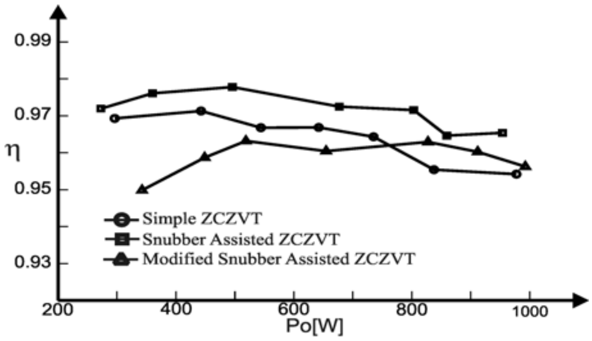



Fig. 15. Experimental efficiency curves.

Figure 14 shows the main switch turn-off *dv/dt* for the three prototypes. It can be seen that both, the snubber assisted and the modified snubber assisted can reduce significantly the *dv/dt*.

To evaluate the effects of snubbing the auxiliary switch and the inherent reduction of main switch *dv/dt* on the converter efficiencies, the laboratory prototypes were evaluated under different load currents. The resultant efficiency curves are shown in Figure 15. It can be seen that from 75% to full-load, both snubber assisted topologies presented better efficiency than the simple converter. Due to the higher auxiliary circuit current ($i_{La}$ and $i_{Sa}$) the modified snubber assisted auxiliary switch ZCZVT presented lower efficiency from low load conditions (< 75%). On the other hand, the snubber assisted auxiliary switch ZCZVT presented higher efficiency in the entire load range, keeping a good compromise between efficiency and *dv/dt* control.

## VIII. CONCLUSIONS

This paper presented a simple and practical methodology to synthesize ZCZVT converters. It is based on the auxiliary voltage source (AVS) concept which permits to synthesize a whole new class of converters. As the AVS concept was developed for the ZVT converters, the novel ZCZVT converters can easily be identified with their ZVT counterparts. This resemblance is not limited to the circuit diagrams, but also to the converters characteristics. This way, the novel ZCZVT class of converters held the merits of their ZVT counterparts as simplicity and auxiliary circuit low reactive energy. This feature is specially accomplished due to the elimination of the resonant tank, whose sinusoidal-like current expose the semiconductors to unnecessary conduction losses.

Theoretical analysis is verified by means of experimental results obtained from laboratory prototypes rated at 1 kW, 50 kHz. The results confirmed the novel synthesis concept and also shown that the three prototypes analyzed present very good performances. In spite of it, from 75% to full-load, both snubber assisted topologies (the Snubber Assisted Auxiliary Switch ZCZVT and the Modified Snubber Assisted Auxiliary Switch ZCZVT) presented better efficiency than the simple ZCZVT boost converter. The higher auxiliary circuit current ($i_{La}$ and $i_{Sa}$) presented by the Modified Snubber Assisted Auxiliary Switch ZCZVT lowers its efficiency at low load conditions (< 75%). On the other hand, the Snubber Assisted Auxiliary Switch ZCZVT presented higher efficiency in the entire load range, which makes it a strong candidate to applications where there are load variations.

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