NOVEL SYNTHESIS METHODOLOGY FOR RESONANT TRANSITION PWM CONVERTERS.

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Abstract – **In this paper a novel and unique methodology to analyze the Resonant Transition mechanism is presented. It is based on the Resonant Transition mechanism requirements, which permit to newcomers to perceive the Resonant Transition techniques as a whole instead of dissimilar soft-switching techniques. Furthermore, the knowledge of the Resonant Transition requirements makes possible the development of a novel synthesis methodology to generate Resonant Transition converters, in special the Zero-Current Transition (ZCT) and the Zero-Current-Zero-Voltage Transition (ZCZVT) topologies, which are suitable for medium and high power applications where minority carrier devices are predominant.**

Theoretical analysis is verified by means of experimental results obtained from laboratory prototypes rated at 1kW, 40kHz.

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

I. INTRODUCTION

For decades one of the biggest challenges in power electronics concerns to provide power converters that present high dynamic performance, high power density and low losses. Intending to achieve those characteristics, the soft-switching area gained quite interest in the 80’s and 90’s. Nonetheless, the increasing development in semiconductor materials and packaging, have offsetting the advantages claimed by soft-switching topologies. After a huge number of soft-switching topologies and countless researches, there still are many questions unanswered and, despite of the intense efforts, the soft-switching subject remains unconcluded by the academic perspective. One example of such situation is evident when Resonant Transition converters are applied for minority carrier device based topologies. In these cases, to the Zero-Voltage Transition (ZVT) [1-10] technique to be effective, it requires fast switching semiconductors that present low switching losses during turn-off. However, such fast semiconductors can be capable to work at high frequencies and power densities without any soft-switching approach, offsetting the gains obtained by the ZVT technique. An alternative for standard semiconductors is found with the Zero-Current Transition (ZCT) [11] or the Zero-Current-Zero-Voltage Transition (ZCZVT) [14-16] techniques.

In spite of had been proposed in 1993, few modifications were presented to improve the ZCT performance. Furthermore, additional reactive energy has been introduced by the ZCT converters aiming to minimize the diode reverse-recovery losses, leading to an increase on the converter conduction losses.

The ZCZVT technique is the newest and so far the less explored alternative among the Resonant Transition techniques. It allows zero-current and zero-voltage conditions during both turn-on and turn-off processes, greatly reducing the switching losses. Nevertheless, the ZCZVT converters presented hitherto are very similar to the ZCT converters and so retain it main characteristics and weakness as the huge reactive energy that offset the converter efficiency gain reducing the advantages of using soft-switching techniques.

In order to contribute in the development of the Resonant Transition converters, mainly for the Zero-Current Zero-Voltage Transition techniques, this paper presents a new methodology to analyze the Resonant Transition mechanism which provides a generic approach that allows perceiving the Resonant Transition as whole and getting benefits from this perspective. The generic approach makes possible the development of a novel synthesis methodology to generate new Resonant Transition converters. As the proposed synthesis methodology is based on the Resonant Transition mechanism requirements rather than the integration of ZCT and ZVT auxiliary circuits, some of the common drawbacks of ZCT and ZCZVT converters presented until now, as well as the high reactive energy, can be avoided.

II. RESONANT TRANSITION TECHNIQUE

Depending on the source and the load, the PWM converters can be separated in four main groups, the DC-DC, DC-AC, AC-DC and AC-AC converters. Besides their different characteristics, all PWM converters operate under the same basic principle, that is, the power control is realized by means of pulsating current and voltage waveforms that are produced by the switching action of, at least, an active and a passive switch. This way it can be said that all PWM converter descend from the same basic PWM cell, which can be represented, in its simplest form, by a diode, a switch and an inductor disposed as shown in [8].

A. The Switching Process

The conventional switching process is characterized by non-zero voltage and current waveforms that produces an amount of losses which are directly proportional to the switching frequency. To reduce this dependence some additional circuitry may be added to the PWM basic cell in order to shape the current and voltage waveforms during the switching intervals and lessen the overlapping between the waveforms.

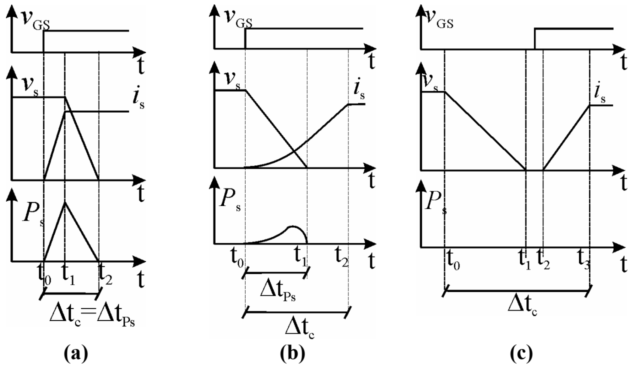


Fig. 1 – Theoretical voltage, current and losses during turn-on commutation process of a semicondutor. (a) Hard-switching; (b) Pseudo soft-switching; (c) Truly soft-switching.

By the semiconductor perspective there are basically three types of switching, the hard switching, the pseudo-soft switching and the truly-soft switching. In the hard switching the changing in the current state, during turn-on occurs at full bus voltage, in the same way as the voltage changes its state during turn-off state at full load current, Fig. 1(a). In the pseudo-soft switching the changing in the voltage (turn-on) and/or the current (turn-off) through the switch occurs with reduced di/dt (turn-on) or dv/dt (turn-off), Fig. 1(b). The limited di/dt (turn-on) or dv/dt (turn-off) reduces the waveforms overlapping and the losses, nevertheless, the overlapping still exists. Moreover, the switch gate drive efforts are very similar to those of hard switching operation. In the truly-soft switching the current through the PWM pole is handled in such way that the current is always negative before the ongoing device to be turned on and the outgoing device is turned-off, eliminating the voltage and current waveforms overlapping Fig. 1(c).

The soft-switching techniques make use of an auxiliary circuit that usually aids the turn-on or the turn-off commutation and the remaining commutation is aided by an snubber element that limits the dv/dt (turn-off snubber capacitor) or limits the di/dt (turn-on snubber inductor). Usually, when the auxiliary circuit aids the turn-on commutation of main switch, the converter is called 'ZVS', Fig. 2(b). On the other hand, when the auxiliary circuit aids the turn-off commutation, the converter is called 'ZCS', Fig. 2(a). When both, turn-on and turn-off commutations are aided only by snubber elements, the soft-switching is commonly called 'snubber', Fig. 2(c). On the contrary, when the auxiliary circuit is activating twice, aiding the turn-on and the turn-off, the converter may be called 'ZCZVS'. This situation occurs when a capacitive element slow down the dv/dt across the switches during the PWM pole switching process, nevertheless, when there is no limitation in the dv/dt, some authors call the converter 'ZC-QZVT', Fig. 2(d).

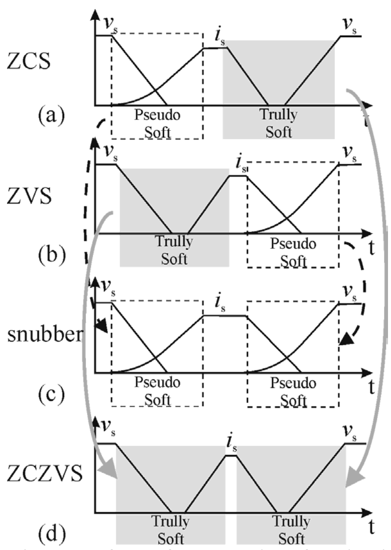


Fig. 2 – Theoretical waveforms for the main soft-switching techniques.

The 'Resonant Transition' converters (ZCT, ZVT and ZCZVT) differ from the 'Resonant Switching' converters (ZCS, ZVS and ZCZVS) by the auxiliary circuit perspective. In the Resonant Switching converters the commutation inductor is placed between the passive and active switch of the PWM pole. In the Resonant Transition converters, the commutation inductor, as well as the other auxiliary elements is indeed, in parallel with the PWM pole. This way, the auxiliary circuit of the Resonant Transition converters can be rated for just a fraction of the converter power, moreover, the additional conduction losses produced by the auxiliary elements can be smaller than those of the Resonant Switching converters whose commutation inductor must be rated for the whole converter power. Other advantage achieved by the Resonant Transition converters is the absence of voltage stresses on the PWM pole devices while in the Resonant Switching converters, at least one of the PWM pole devices suffer from additional voltage stresses.

B. The Resonant Transition Mechanism

The commutation mechanism of the 'Resonant Transition' converters consists in to provide an auxiliary path to divert the PWM pole current before the switching instant. To accomplish this task, there is a commutation inductor which is charged up from zero to the load current value. If the commutation technique allows the control of the dv/dt across the PWM pole switches, there is also a snubber capacitor C_s, across the switches terminals. Thus it will be a resonant interval that discharges C_s at the end of the inductor charge. The most important matter in the Resonant Transition techniques is to provide an adequate auxiliary voltage source to discharge the commutation inductor after the PWM pole switching be completed, Fig. 3.

For ZVT converters the auxiliary voltage source may appear in three basic forms, a Switched Auxiliary Voltage Source, a Constant Auxiliary Voltage Source, or a Resonant Auxiliary Voltage Source; as discussed in [10]. The intensive studies in the ZVT area ensured a set of alternatives to minimize some problems presented by the classical ZVT topology [1]. This variety of topologies make the ZVT a mature technique gaining attention, even in the industrial area, where some power supplies manufacture companies such make use of the ZVT technology [20-22].

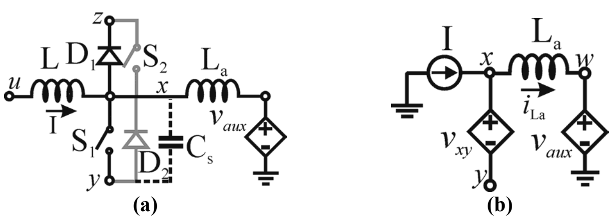


Fig. 3 – Basic Resonant Transition PWM Block. (a) With switch realization; (b) With dependent source simplification.

On the other hand, the ZCT technique [11,18-19], presented as the dual of ZVT technique in [11], gained less interest and few modifications had been proposed in the last years. For this reason the ZCT technique presented hitherto make use of just Resonant Auxiliary Voltage Source. Actually, the ZCT topological development is restrict to changes in the excitation source of a resonant circuit that is kept unchangeable in the ZCT auxiliary circuit structure.

As the ZCZVT technique is an attempt to generate a class of converters with both ZVT and ZCT auxiliary circuit assistence, researchers have been driven by the idea of integrating a ZVT auxiliary circuit with a ZCT auxiliary circuit, which leads to an auxiliary circuit based on a Resonant Auxiliary Voltage Source. In both cases, ZCT and ZCZVT topologies, the high reactive energy produced by the auxiliary circuit operation often off-set the energy saved in the commutation processes resulting in a reduced efficiency gain.

III. RESONANT TRANSITION MECHANISM

In this section the resonant transition mechanism is analyzed.

In order to achieve the charge and discharge of the commutation inductor (Fig. 3) during turn-on and turn-off commutation, the Auxiliary Voltage Source (AVS), Fig. 3(b), must attend the following restriction,

$$\begin{aligned} v_{aux} < v_{xy},\ for\ \ (t < t_1) \\ v_{aux} < v_{xy},\ for\ \ (t_4 < t < t_5) \end{aligned} \tag{1}$$

and

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

Where v_{aux} and v_{xy} are the dependent voltage sources shown in diagram of Fig. 3(b). Where v_{xy} is defined by the PWM pole operation and v_{aux} represents the all auxiliary circuit elements without the commutation inductor L_a, i. e., the AVS.

Examining the regions defined in the shaded areas of Fig. 4, that should be assumed by the auxiliary voltage source,

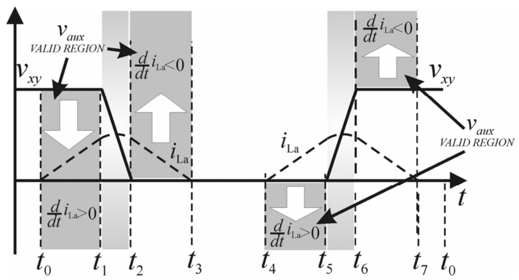


Fig. 4 – Region of valid values for the v_{aux} function, according to the waveforms of v_{xy}, i_{La}.

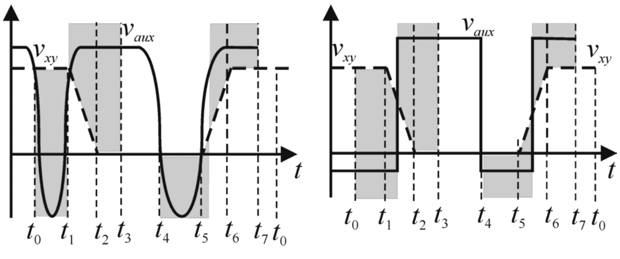


Fig. 5 – Two simple functions for v_{aux}. (a) A continuous time varying co-sinusoidal function; (b) A discontinuous function.

v_{aux}, it can be expected that there will be two simple functions that could attend for the restrictions (1) and (2) for both changes of v_{xy}: a *continuous time varying co-sinusoidal* function and a *discontinuous* function, which are represented in Fig. 5(a) and 5(b), respectively.

A. The Resonant Transition Turn-on (ZVT Technique)

In the ZVT technique there is the necessity to limit dv/dt rate across the switches that comprise the PWM pole, for this reason, in addition to the auxiliary circuit there is also a capacitance connected to the terminal '*x*', Fig. 3(a).

As mentioned before, the ZVT technique have been extensively explored and, in this technique both, *continuous time varying* (Resonant AVS, [10]) [2-4,6-9] and *discontinuous* (Switched AVS, [10]) [1,5] functions already had been used to implement the auxiliary voltage source. Additionally to this two approaches, a *constant* function also can be possible and have been used (Constant AVS, [10]) [2-4,6,9]. This constant time invariant function can only be used in the ZVT technique due to the PWM pole action (v_{xy}) that provide two different voltage levels that are used to charge and discharge the commutation inductor. The charge and discharge voltages of L_a are given by the difference between v_{xy} and v_{aux}, as shown in Fig. 6.

In a simplified form, the *continuous time varying* function is obtained by means of a resonant tank that provides a natural control of the auxiliary circuit current that increases in a resonant way to a value slightly higher than the load current, discharges the snubber capacitor C_s and right after decreases to zero, Fig. 6(a). Besides to the resonant tank the auxiliary circuit can also include a clamping voltage circuit that avoid voltage boosting across the resonant capacitor (C_r) and; a unipolar excitation source connected to the circuit by means of a simple current bi-directional switch, Fig. 7(a).

The *discontinuous* function is obtained by means of the

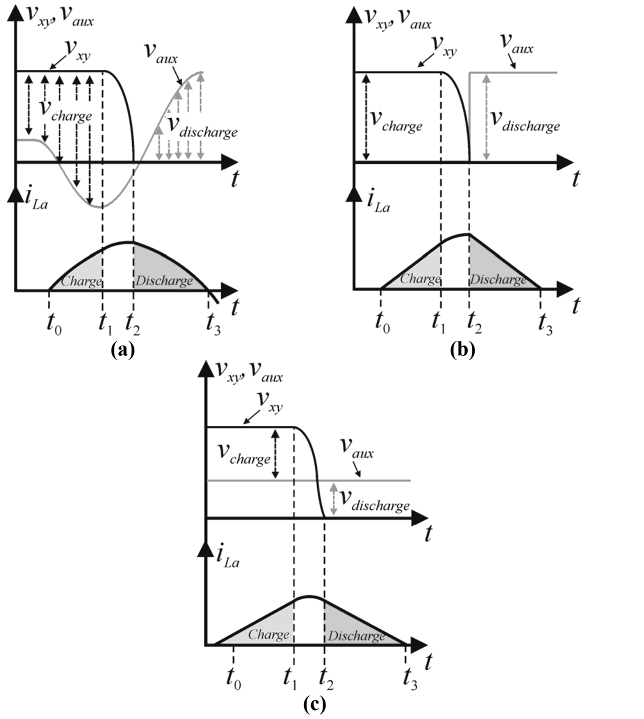


Fig. 6 - Waveforms of the controlled voltage source v_{xy}, v_{aux} and corresponding auxiliary circuit current I_a. (a) Resonant AVS (Class C); (b) Switched AVS (Class A); (c) Constant AVS (Class B).

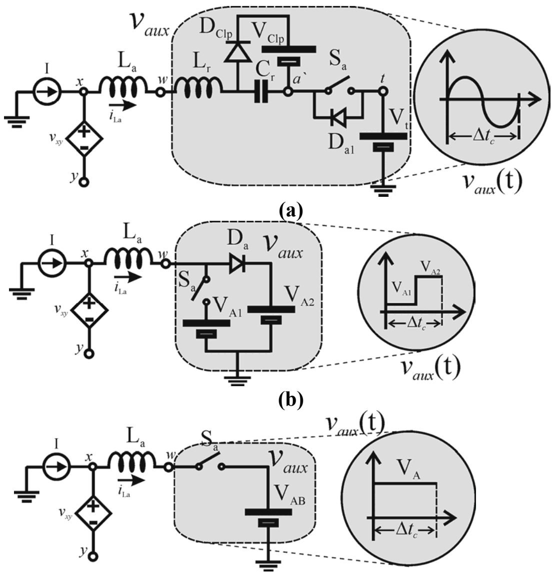


Fig. 7 – General diagram for ZVT PWM converters. (a) Resonant AVS (Class C); (b) Switched AVS (Class A); (c) Constant AVS (Class B).

switching process of an auxiliary pole (semi-controlled), that provides two distinct values to charge and discharge linearly the commutation inductor, Fig. 6(b), i. e., there is a semi-controlled pole that provides different voltages directly through the commutation inductor, Fig. 7(b).

The *constant time invariant* function make use of a constant voltage with a value between zero and the bus voltage (V_{zy}), which is connected to the circuit by means of a simple voltage bi-directional switch, Fig. 7(c). This way, the control of the two values applied to charge and discharge the commutation inductor is made by the switching action of the PWM pole, Fig. 6(c), i. e., by the voltage source v_{xy}.

B. The Resonant Transition Turn-off (ZCT Technique)

As mentioned before, the ZCT technique has been much less explored in the literature and the researches concerning this technique have made use of just the *continuous time varying* function. Differently from the ZVT technique that make use of voltage clamps, the ZCT technique explore different voltage sources applied across the resonant tank elements. The changes in the excitation source of the resonant tank are obtained with the action of a semi-controlled [11, 12] or full-controlled [13] auxiliary pole, Fig. 8.

C. The Resonant Transition Turn-on and Turn-off

The ZCZVT technique gathers the resonant transition processes of turn-on (ZVT) and turn-off (ZCT) into a single circuit. As the ZCT technique had explored the *continuous time varying* functions, the ZCZVT converters presented hitherto also incorporate it as a requirement to ensure the truly-soft turn-off commutation. The *continuous time varying* functions could present a simple current unidirectional switch or a full-controlled auxiliary pole.

IV. GENERALIZED CONCEPT

From the previous sections a generalized concept concerning the Resonant Transition technique can be

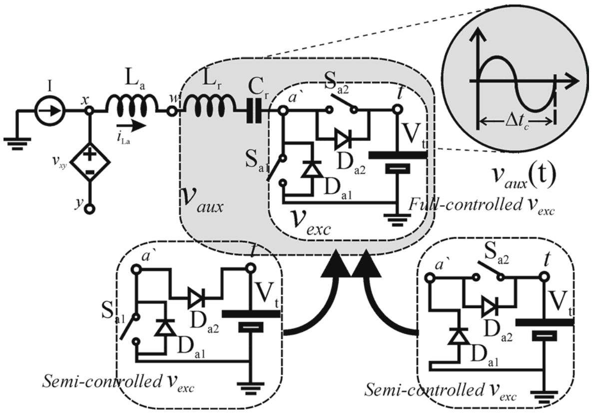


Fig. 8 - General diagram for Class C ZCT PWM converters with different excitation sources (Semi- and Full-controlled).

summarized in Table I. It shows that there are only two basic mathematical functions that can fully represent the resonant transition mechanism, a *continuous function* and a *discontinuous function*. These functions produce the three essential classes of Auxiliary Voltage Source (AVS), named Class A, that are characterized by a *pulsed waveform*; Class B, that is characterized by a *constant waveform*; and Class C, that is characterized by a *sinusoidal waveform*. Finally, the implementation of each AVS results in the well-known ZVT and ZCT converters.

Fig. 9(a) shows the generalized diagram of the circuit that produces a *continuous time varying sinusoidal waveform* based on a resonant tank. As the excitation source can appear in the semi- or full-controlled form, it is completely defined by a full-controlled pole. In the ZVT converters just one of the switches of the full-controlled auxiliary pole is turned on and kept on until the end of the auxiliary circuit operation.

Table I – Generalized Resonant Transition Concept and relationship.

Math functions	Class of AVS	Form of AVS	Family	
Discontinuous	A	Pulsed waveform	ZVT	ZCZVT
			ZCT	
	B	Constant waveform	ZVT	---
Continuous	C	Co-Sinusoidal waveform	ZVT	ZCZVT
			ZCT	

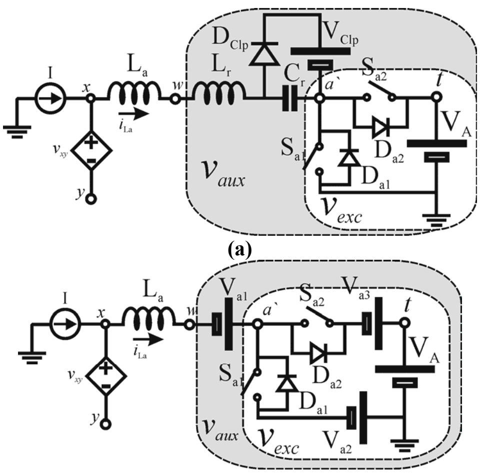


Fig. 9 – General diagram for Resonant Transition PWM converters. (a) Continuous waveform; (b) Discontinuous waveform.

In the same manner, Fig. 9(b) shows the generalized diagram of the circuit that produces a *discontinuous waveform* based on the switching action of a semi-controlled auxiliary pole. When a constant time invariant AVS is required, it can be derived from the diagram of Fig. 9(b) keeping one switch inactive meanwhile the other is turned on and kept on until the end of the auxiliary circuit operation.

V. NOVEL SYNTHESIS METHODOLOGY

According to Table I the ZCT Resonant Transition converters family make use of a Class C AVS. The Class C AVS is capable by itself to provide the charging and discharging polarity to inductor L_a, nevertheless it also uses a full-controlled excitation source that also can provide the charging and discharging polarity to L_a. Hence, the ZCT family presents a redundant auxiliary circuit. It results in an extra degree of freedom that is used for producing different converter switching strategies. Nonetheless the price paid for such redundancy is a higher reactive energy that increases conduction losses.

By Table I it is clear that there is an opportunity to explore the Class A AVS to provide ZCT and further ZCZVT converters, shaded cells.

The main advantages of using Class A AVS is two fold, the first one is avoid the reactive energy associated to the resonant process that characterize the Class C AVS; the second is to make the conduction losses of the auxiliary circuit to be proportional to the load current. This characteristic is very important, mainly when the load current varies in a wide load range, as in PFC converters and inverters. This feature will provide converters with less auxiliary circuit conductions losses and thus, more efficient.

According to Section 3, to make possible the Class A AVS ZCT and ZCZVT converters it is required that the voltage level applied to charge the commutation inductor L_a to reach negative values, as shown in Fig. 10. To accomplish this requirement at least one constant voltage source (V_{a1} or V_{a2}) must be non-zero and positive in the generalized circuit of Class A, as shown in Fig. 9(b). Considering that I>0 and thus, the semi-controlled auxiliary pole comprised by the switch S_{a1} and the diode D_{a2} of Fig. 9(b), there are six possible arranges (configurations) that are defined in Table II.

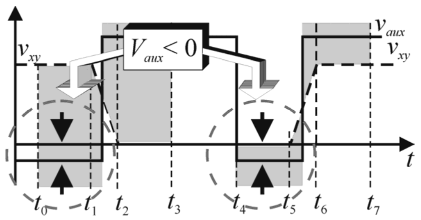


Fig. 10 –Class A AVS waveforms for ZCT and ZCZVT converters.

A. Definition of Auxiliary Voltage Source Restrictions

For the topologies derived in Table II, the restriction that ensure the operation of the circuits for a positive value of current I are derived below, where the semi-controlled pole is comprised by S_{a1} and D_{a2}.

1) First charge of L_a (main switch turn-on) - The condition to the current through commutation inductor (L_a) is given by,

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

Substituting i_{La} from the circuit shown in Fig. 9(b),

$$\frac{d}{dt}\left[\left(\left(V_{a1}+V_{a2}+v_{xy}\right)/L_a\right)t\right] > 0 \tag{4}$$

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} (Fig. 3(a)) before the main switch turn-on, expression (5) become

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

2) First discharge of L_a (main switch turn-on) - The condition to the current through commutation inductor (L_a) is given by,

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

Substituting i_{La} from the circuit shown in Fig. 9(b),

$$\frac{d}{dt}\left[\left(\left(-V_A+V_{a1}+V_{a3}+v_{xy}\right)/L_a\right)t+i_{La}(0)\right] < 0 \tag{8}$$

This way, the restriction can be expressed by,

$$V_{a1}+V_{a3} > V_A - v_{xy} \tag{9}$$

As v_{xy} is equal to zero after the main switch turn-on, expression (9) become

Table II – Configurations and restrictions for the auxiliary voltage sources.

Config.	Auxiliary Voltage Sources			$I>0$ and S_{a1}/D_{a2}		$I<0$ and S_{a2}/D_{a1}	
	V_{a1}	**V_{a2}**	**V_{a3}**	$v_{xy}=0$	$v_{xy}=V_{zy}$	$v_{xy}=0$	$v_{xy}=V_{zy}$
1	$\neq 0$	$=0$	$=0$	$V_{a1}>0$	$V_{a1}>-V_{zy}$	$-V_{a1}>0$	$-V_{a1}>-V_{zy}$
				$V_{a1}<V_A$	$V_{a1}<V_A-V_{zy}$	$-V_{a1}<V_A$	$-V_{a1}<V_A-V_{zy}$
2	$=0$	$\neq 0$	$=0$	$V_{a2}>0$	$V_{a2}>-V_{zy}$	$-V_{a2}>0$	$-V_{a2}>-V_{zy}$
				-------------	-------------	-------------	-------------
3	$\neq 0$	$\neq 0$	$=0$	$V_{a1}+V_{a2}>0$	$V_{a1}+V_{a2}>-V_{zy}$	$-(V_{a1}+V_{a2})>0$	$-(V_{a1}+V_{a2})>-V_{zy}$
				$V_{a1}<V_A$	$V_{a1}<V_A-V_{zy}$	$-V_{a1}<V_A$	$-V_{a1}<V_A-V_{zy}$
4	$\neq 0$	$=0$	$\neq 0$	$V_{a1}>0$	$V_{a1}>-V_{zy}$	$-V_{a1}>0$	$-V_{a1}>-V_{zy}$
				$V_{a1}+V_{a3}<V_A$	$V_{a1}+V_{a3}<V_A-V_{zy}$	$-(V_{a1}+V_{a3})<V_A$	$-(V_{a1}+V_{a3})<V_A-V_{zy}$
5	$=0$	$\neq 0$	$\neq 0$	$V_{a2}>0$	$V_{a2}>-V_{zy}$	$-V_{a2}>0$	$-V_{a2}>-V_{zy}$
				$V_{a3}<V_A$	$V_{a3}<V_A-V_{zy}$	$-V_{a3}<V_A$	$-V_{a3}<V_A-V_{zy}$
6	$\neq 0$	$\neq 0$	$\neq 0$	$V_{a1}+V_{a2}>0$	$V_{a1}+V_{a2}>-V_{zy}$	$-(V_{a1}+V_{a2})>0$	$-(V_{a1}+V_{a2})>-V_{zy}$
				$V_{a1}+V_{a3}<V_A$	$V_{a1}+V_{a3}<V_A-V_{zy}$	$-(V_{a1}+V_{a3})<V_A$	$-(V_{a1}+V_{a3})<V_A-V_{zy}$

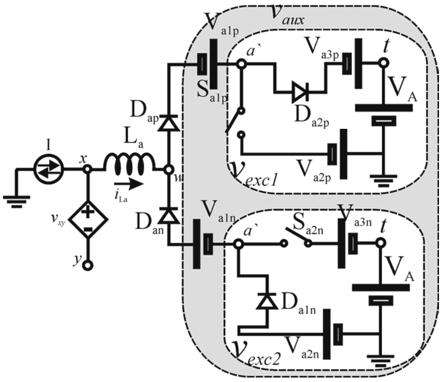


Fig. 11 –Bidirectional Class A AVS circuit diagram for ZCT and ZCZVT converters.

$$V_{a1}+V_{a3}>V_A \tag{10}$$

3) Second charge of L_a (main switch turn-off) - The condition to the current through commutation inductor (L_a) is given by expression (3). As v_{xy} is equal to zero before the main switch turn-off, the similar development of expression (3) will result in the condition below,

$$V_{a1}+V_{a2}>0 \tag{11}$$

4) Second discharge of L_a (main switch turn-off) - The condition to the current through commutation inductor (L_a) is given by expression (7). As v_{xy} is equal to V_{zy} after the main switch turn-off, the similar development of expression (7) will result in the condition below,

$$V_{a1}+V_{a3}>V_A-v_{zy}=0 \tag{12}$$

The expression (6), (10), (11) and (12) represent the general restrictions that ensure the operation of the Class A AVS, applying those restriction to each configuration one can obtain the restrictions shown in Table II for I>0 (S_{a1} and D_{a2}). Making a similar analysis the restrictions for I<0 (S_{a2} and D_{a1}) can be obtained as found in Table II. As it was expected, the restrictions for I<0 (S_{a2} and D_{a1}) present opposite polarity for all auxiliary voltage sources, this way a bidirectional Class A AVS requires two separate excitation sources, one for the positive current I and other for negative values of I, as shown in Fig. 11.

B. The Auxiliary Voltage Source Implementation

The utilization of magnetic elements to perform the auxiliary voltage sources (V_{a1}, V_{a2} and V_{a3}) is an easy way to accomplish them for a number of reasons, such as simplicity, ruggedness and compactness. The magnetic realization of V_{a1}, V_{a2} and V_{a3} consist on the use of a single magnetic core with a primary winding forming a closed loop with a voltage source and one or more secondary winding(s) that play(s) the role of each auxiliary voltage source. The location of the primary winding produces a variety of topologies by exchanging the primary winding among the terminals of the diagram of Fig. 3. If the primary winding is connected between terminal '*x*' and '*u*', the voltage at each secondary winding will change according to the main PWM pole commutations, Fig. 12(a) for I>0 and Fig. 12(b) for I<0. It means that will be a polarity inversion that could be used in order to simplify the bidirectional Class A AVS shown in Fig. 11. The polarity inversion makes possible the use of a

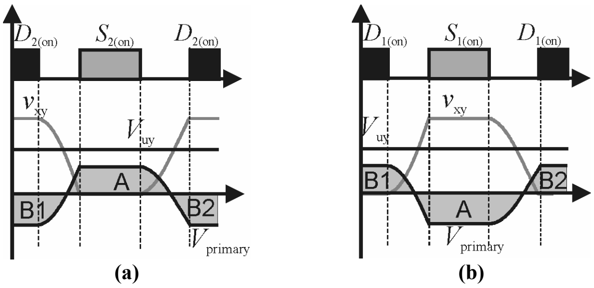


Fig. 12 –Waveforms for the primary winding and v_{xy}. (a) I>0; (b) I<0.

Class A AVS as shown in Fig. 9(b), with just a full-controlled pole.

VI. CLASS A ZCT INVERTERS

By means of the novel synthesis methodology presented in Section VI, a new class of ZCT inverters can be disclosed. These ZCT inverters are implemented with a Class A AVS, which make them unique. Furthermore, it allows a set of advantages presented only for ZVT inverters hitherto, such as variable timing control for the auxiliary switches and simple design methodology.

The diagrams for one inverter leg of the two novel ZCT Class A inverters are depicted in Fig. 13 (without capacitors C_{sp},C_{sn}). The main theoretical waveforms for the novel ZCT inverters are shown in Fig. 14. It can be seen that the charge (t_0,t_1 and t_5,t_6) and discharge (t_2,t_4 and t_7,t_9) of commutation inductor are both linear processes. It also can be seen that PWM pole devices not present stresses as in their PWM hard-switched counterpart.

In order to verify the theoretical analysis, one ZCT Class A inverter has been implemented. The diagram of the

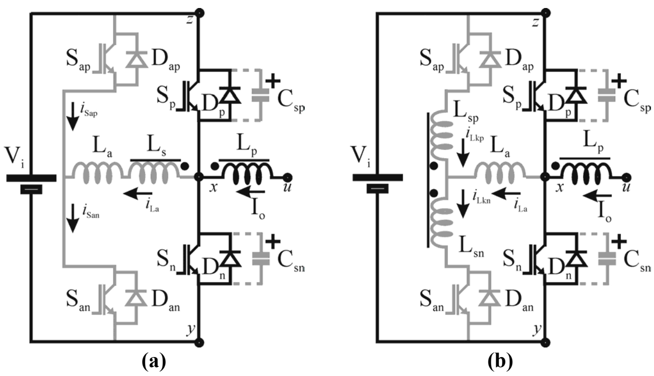


Fig. 13 – Novel ZCT (ZCZVT) inverter with Class A AVS. (a) With single secondary winding; (b) With splited secondary winding.

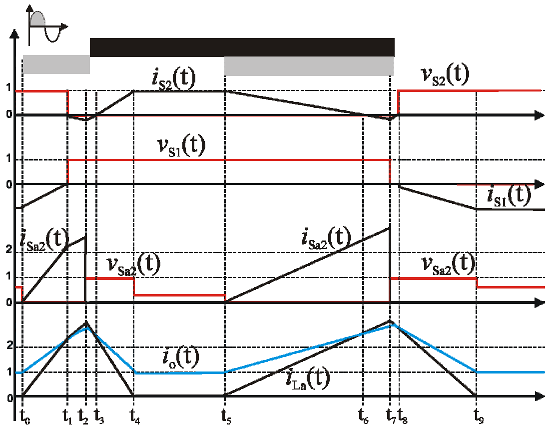


Fig. 14 – Theoretical waveforms for the Novel ZCT Class A inverters.

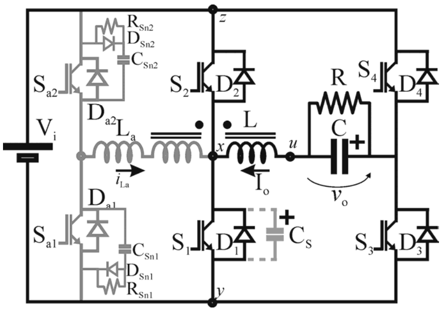


Fig. 15 – Diagram of the Novel single-phase H-bridge ZCT (ZCZVT) Class A inverter.

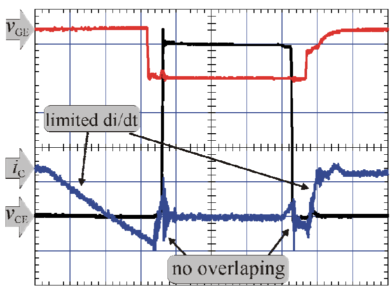
Table III – ZCT and ZCZVT prototypes experimental parameters.

Parameter	ZCT	ZCZVT
V_i / V_0	250 V_{CC} / 127 $V_{(RMS)}$	
P_0 / f_s	1,0 kW / 40 kHz	
L / C (filter)	0,93 mH (L_M) / 2 x 20 uF	
S_1, S_2, S_3, S_4	SK45GB063	
S_{a1}, S_{a2}	SK45GB063	
N (n_2/n_1)	0,42 (18 turns/45 turns)	
L_M *(magnetizing)*	0,938 mH	
L_{k1} , L_{k2} *(leakages)*	24,9 µH / 4,7 µH	
L_a *(aux. inductor)*	4,7 µH (L_{k2})	
C_S *(aux. capacitor)*	------	4,7 nF
$R_{Sn1,2}$ / $C_{Sn1,2}$ / $D_{Sn1,2}$	100 Ω / 4,3 nF / UF5406	
Spike killer	SA 14x8x4.5 (8 turns)	

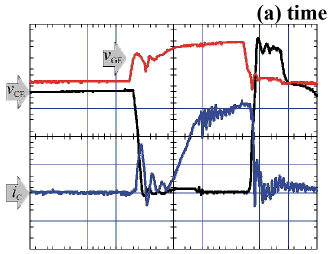
laboratory prototype implemented is shown in Fig. 15 (without capacitor C_{s1}). The parameters of the implemented prototype are shown in Table III.

Fig. 16(a) shows the main switch S_1 waveforms. It can be seen that it actually commutates at zero-current during both turn-on and turn-off process, furthermore, there is no overlapping between voltage and current waveforms ensuring the trully-soft switching process discussed in Section II. Besides no overlapping, switch S_1 and respective diode D_2 turn on and off at a limited current rate of change (di/dt) be in agreement with the physical restriction of the semiconductors, reducing their losses and efforts.

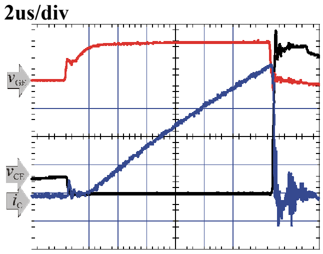
Fig. 16(b) shows the auxiliary switch S_{a1} waveforms during the turn-on process of S_1. In spite of a short current spike due to the discharge of its turn-off RCD snubber, the current through S_{a1} presents a linear like form, ensuring low reactive energy. Similarly, Fig. 16(c) shows the auxiliary switch S_{a1} waveforms during the turn-off process of S_1. It can be seen that the current rises up linearly until the switch turns off. The discharge of the turn-off RCD snubber during this process is almost meaningless, once right after S_1 had assumed the load current, almost whole energy stored in the auxiliary turn-off snubber to be regenerated to the load through S_1.



(a) time - 2us/div



(b) time - 500ns/div



(c) time - 1us/div

Fig. 16 – Experimental results for the Novel ZCT inverter. (a) Main switch waveforms; (b,c) Auxiliary switch waveforms. Scales: v_{GE} – 10V/div; i_C – 5A/div ; v_{CE} – 50V/div.

VII. CLASS A ZCZVT INVERTERS

A new class of ZCZVT inverters can be derived simply including a capacitor across each main switch, Fig. 13(with capacitors C_{sp},C_{sn}). These capacitors will limit the dv/dt across the main switches. As for the ZCT, the Class A AVS allows to the ZCZVT a set of advantages such as variable timing control for the auxiliary switches and simple design methodology. The main theoretical waveforms for the novel ZCZVT inverters are shown in Fig 17.

In order to verify the theoretical analysis, one ZCZVT Class A inverter has been implemented. The diagram of the laboratory prototype implemented is shown in Fig. 15 (with capacitor C_s). The parameters of the implemented prototype are shown in Table III.

Fig. 18 shows the main switch S_1 waveforms. It can be seen that as in the ZCT case, S_1 commutates at zero-current during both turn-on and turn-off process and no overlapping between voltage and current waveforms is presented ensuring a trully-soft switching process. In addition to the limited current rate of change (di/dt) during switch commutations, the limited voltage rate of change (dv/dt) also

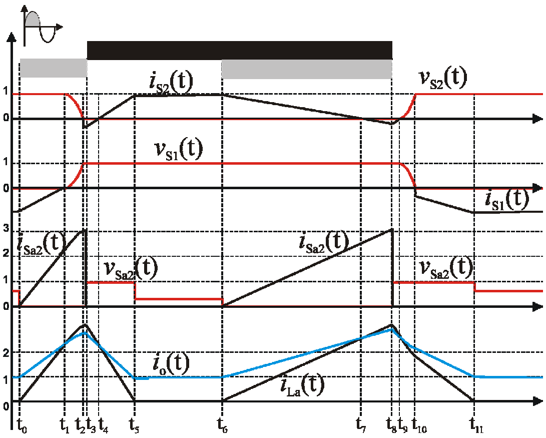


Fig. 17 – Theoretical waveforms for the Novel ZCZVT inverters.

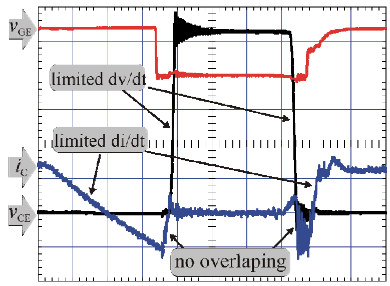


Fig. 18 – Experimental results for the Novel ZCZVT inverter. Scales: v_{GE} – 10V/div; i_C – 5A/div ; v_{CE} – 50V/div; time – 2us/div.

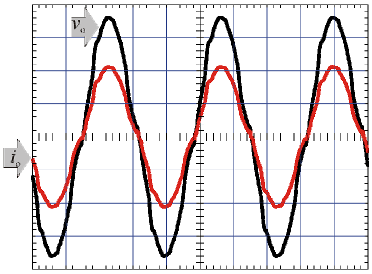


Fig. 19 – Load waveforms for the Novel ZCZVT inverter. Scales: i_o – 5A/div; v_o – 50V/div; time - 5ms/div.

allows a reduction on the semiconductor losses and efforts, and further may enhance the converter EMI performance.

Fig. 19 shows the load voltage and current waveforms obtained from the open loop inverter prototype, supplying a 1 kW resistive load at 127 V_{RMS}.

VIII. SUMMARY

This paper presented a simple, novel and unique methodology to analyze the Resonant Transition technique mechanism. It presents a qualitative analysis which is carried out based on the auxiliary voltage source (AVS) concept. Employing this concept to the resonant transition turn-on (ZVT technique) and turn-off (ZCT technique) the requirements of the resonant transition mechanism (zero-voltage and zero-current) are identified, allowing an easy way to perceive their main characteristics and limitations. The qualitative analysis split the Resonant Transition converters into two main classes of converters in function of AVS: (i) the *continuous time varying* AVS and (ii) the *discontinuous* AVS resonant transition converters. As demonstrated in the paper, the resonant transition analysis can be used as a synthesis methodology of novel converters. Furthermore, the qualitative analysis reveals that there is an opportunity to generate two entire classes of converters, the *Class A ZCT* and the *Class A ZCZVT* converters. The Class A (*discontinuous* AVS) permit to the ZCT and ZCZVT converters hold features only presented by ZVT converters before, such as variable timing control, low reactive energy, simple control, etc..

The novel Class A ZCT and Class A ZCZVT inverters are presented and verified experimentally by means of laboratory prototypes rated at 1kW, 40 kHz. The experimental results shown the feasibility and reliability of these two novel classes of converters that potentialize both ZCT and ZCZVT techniques.

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