Quasi-ZVS Active Auxiliary Commutation Circuit for Two Switches Forward Converters

José Renes Pinheiro, José Eduardo Baggio, Luciano Shuch
UFSM/CT/DELC/NUPEDEE
CEP: 97015-900 – Santa Maria, RS – Brazil
jbaggio@sm.conex.com.br, renes@ctlab.ufsm.br

***Abstract* – This paper presents an active auxiliary circuit (AAC) which performs a quasi-ZVS commutation at main switches of forward converters with two switches. One small volume resonant inductor, one diode and one switch that commutates ZCS compose the AAC. It is not necessary the use of a third winding in the transformer neither auxiliary voltage sources to achieve soft switching. The use of an appropriate command, different than it is used conventionally in forward converters with two switches becomes possible the implementation of this converter. Complete analysis of the operation stages are presented, as well as design procedures for the correct operation of the converter. Experimental results are obtained based on a prototype operating at 250W and 48VDC on the output, proving the feasibility of this AAC applied to forward converters with two switches. Furthermore, a new concept of soft switching is introduced, where the main switches commutate Quasi- ZVS.**

I. INTRODUCTION

In the progress of the science, many efforts have being released, with the aim of obtaining better performance and volume reduction of power converters, since that these are present in most of the electronic apparels. The elevation of the commutation frequency allows volume reduction of the magnetic components and of the capacitors present in the circuits, resulting in a decrease of the converter volume. However, with the increase of the frequency, the commutation losses become quite expressive, decreasing the performance and consequently increasing the sinks volume. By the use of soft switching techniques, as ZVS and ZCS, the above-mentioned drawbacks are overcame.

When the forward converter is used, it is necessary to pay attention to the transformer core demagnetization. Commonly, the demagnetization is made with the use of a third winding in the transformer. Otherwise, in the forward converter with two switches, the demagnetization is obtained without the need of a third winding, limiting the maximum duty cycle in 50%.

In [1, 2] are presented non-dissipative snubber circuits where the main switches turn on under ZCS and turn off under ZVS condition. In [1], the resonant inductor is placed in series with the load, doing this inductor to conduct the load current. In [2], the snubber is placed in parallel with the load. These snubber are not appropriate when MOSFET switches are employed, since turn on capacitive losses occur.

In [3] an auxiliary voltage source is introduced from the third winding, which supplies energy to the LC resonant circuit through one auxiliary switch, assuring commutation under zero voltage at the main switches.

The third winding of the transformer is eliminated in [4], and an auxiliary voltage source is obtained the transformer trapped energy from the primary winding.

In [5] is presented a circuit that operates with two forward converters coupled magnetically through a transformer of three windings. The power transfer is controlled by the phase shift of the two converters. This circuit also presents the advantage of accomplishing soft commutation in the main switches.

In [6], an auxiliary resonant circuit with one switch and one resonant inductor applied to a full-bridge converter is presented. A similar circuit can be applied to forward converters with two switches, modifying the command signals of the main switches.

For the adequate operation of the auxiliary circuit, it is necessary that the switches operate as demonstrated in Fig. 1.

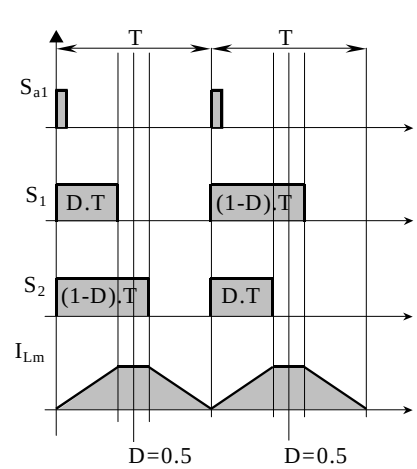

Fig. 1 – Command logic signals of the switches and transformer magnetization current.

It can be seen that the use of this command does not modify the power transfer relation of the two switches forward converter. It only introduces a delay time in the demagnetization process of the transformer.

II. THE AUXILIARY CIRCUIT FOR FORWARD CONVERTER WITH TWO SWITCHES

This paper presents a forward converter operating with soft commutation at the main switches (turn-on: Quasi-ZVS and turn-off: ZVS), and soft commutation of the ZCS type at the auxiliary circuit devices.

In Fig. 2 is presented the utilized topology circuit. It is composed by two main switches (S_1 e S_2), two main diodes (D_1 e D_2), one transformer (T_1, T_2), two rectifier diodes (D_3, D_4) and two capacitors (C_1 e C_2). The L_d inductor represents the leakage inductance of the transformer. The auxiliary circuit is formed by one resonant inductor L_r, one auxiliary switch S_{a1} and one diode D_{a1}.

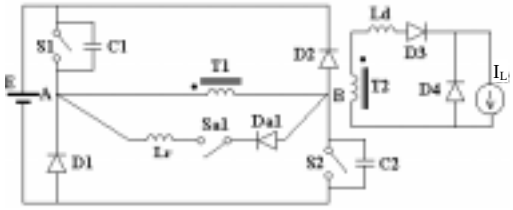

Fig. 2 – Utilized topology.

The nine operation stages are presented as follow:

Stage 1 (t_0-t_1): Initially it is considered that the L_d inductor current is equal to the load current. The switches S_1 and S_2 are conducting, and the voltage source E transfers energy to the load through S_1, T_1 e S_2 at the primary side, and through T_2, L_d and D_3 at the secondary side. The auxiliary switch S_{a1} is turned off. The magnetizing current i_M of the transformer increases linearly supplied by the voltage source E. The current through T_1 is the sum of the load current (I_L) and the magnetizing current i_M. This stage is depicted in Fig. 3.

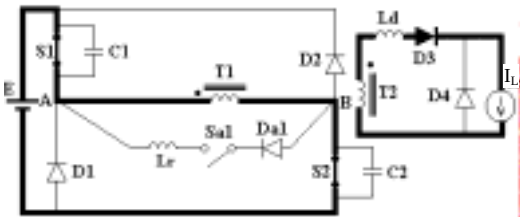

Fig. 3 – Stage 1.

Stage 2 (t_1-t_2): At instant t_1, only the S_2 switch is turned off, and the voltage on the C_2 capacitor increases in a linear form. It can be seen in fig. 4.

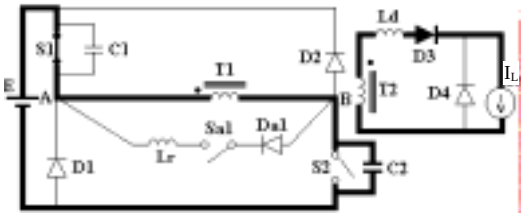

Fig. 4 – Stage 2.

Stage 3 (t_2-t_3): At instant t_2 the voltage on C_2 capacitor reaches voltage E, and the diode D_2 conducts. The transformer current freewheels through diode D_2 and the switch S_1. This stage can bee seen in fig. 5.

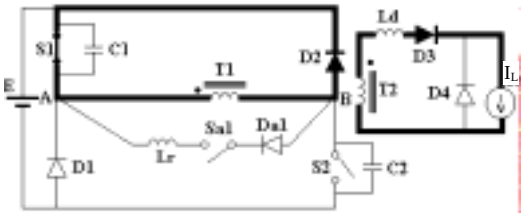

Fig. 5 – Stage 3.

Stage 4 (t_3-t_4): At instant t_3, the switch S_1 is turned off, and it starts the resonance process between the capacitor C_1 and leakage inductor L_d energies, where the current through leakage inductor L_d decreases and the voltage on C_1 increases. In this stage begins the load current transfer from the diode D_3 to diode D_4. It can be seen in fig. 6.

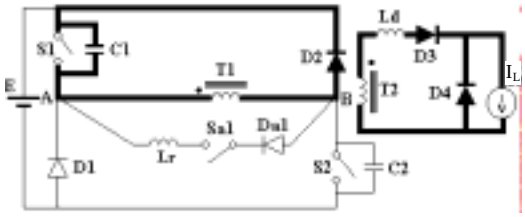

Fig. 6 – Stage 4.

Stage 5(t_4-t_5): At instant t_4, the voltage across the capacitor C_1 reaches voltage E and the diode D_1 conducts. Between the points A and B is applied a voltage equal to –E, and the magnetizing current i_M begins to decrease linearly. In the secondary side, the L_d inductor current decreases linearly. This stage is depicted in Fig. 7.

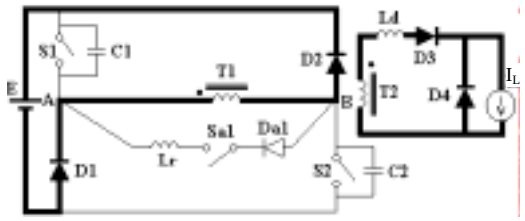

Fig. 7 – Stage 5.

Stage 6 (t_5-t_6): At t_5, the L_d inductor current reaches zero, blocking diode D_3. The full load current flows through diode D_4. This stage is depicted in Fig. 8.

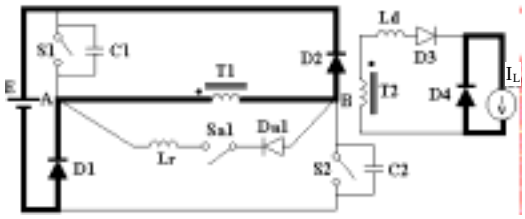

Fig. 8 – Stage 6.

Stage 7 (t_6-t_7): At t_6, the magnetizing current i_M reaches zero. The ZVS command of the switches S_1 and S_2 are enabled. Since the voltages across the capacitors C_1 and C_2 are equal to E, the switches S_1 and S_2 do not turn on. S_{a1} auxiliary switch turns on (ZCS due to the presence of the Lr inductor), and it starts the resonance process between the energy in the C_1 and C_2 capacitors and L_r inductor. This stage is depicted in Fig. 9

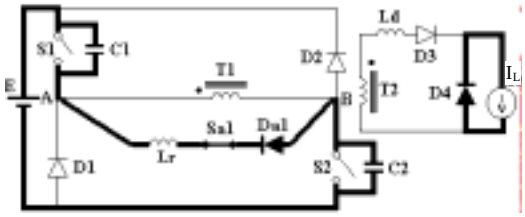

Fig. 9 – Stage 7.

Stage 8 (t_7-t_8): At t_7, the voltage on the C_1 and C_2 capacitors are equal to E/2. From this instant, a positive voltage is applied between the points A and B, allowing the D_3 diode conducts. Unlike of the previous stage, the resonance process occurs between the C_1 and C_2 capacitors and the L_r and L_d inductors energies. This stage can be seen in Fig. 10.

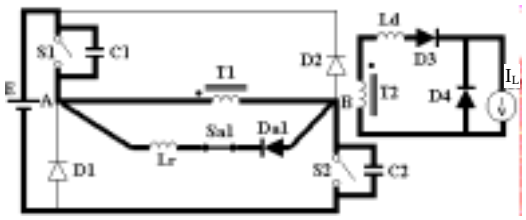

Fig. 10 – Stage 8.

Stage 9 (t_8-t_9): At t_8, the voltage on the C_1 and C_2 capacitors reaches a voltage near to zero Volts. Therefore, the S_1 and S_2 switches turn on, applying the voltage source E across T_1 primary winding terminals. The L_d inductor current increases linearly, transferring the load current from diode D_4 to diode D_3. At instant t_9 the L_d inductor current reaches the load current value I_L. This stage is depicted in Fig. 11.

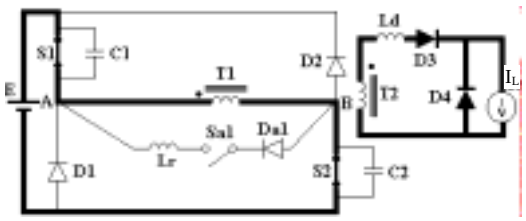

Fig. 11 – Stage 9.

In Fig. 12 are presented the main theoretical waveforms of the forward converter with two switches.

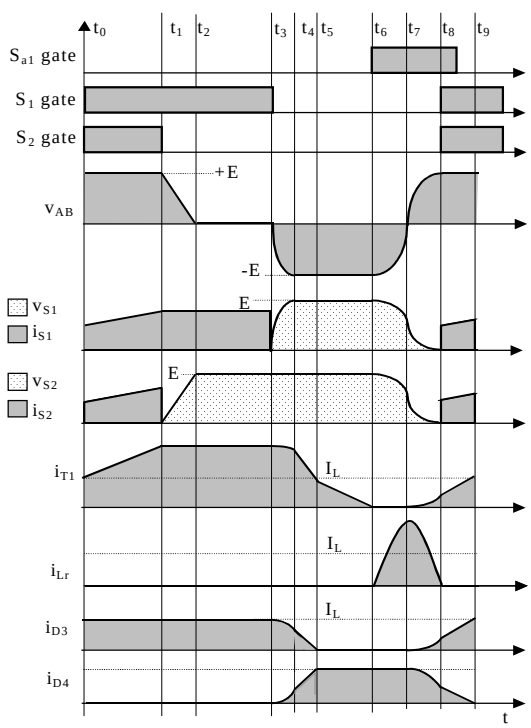

Fig. 12 – Main theoretical waveforms.

Special attention must be taken with the transformer magnetizing current. In stages 2 and 4, the commutations occur from the switches to the diodes, and the load current magnitude takes important hole. Whether the converter operating at no-load or even with low values of load current, the commutation time increases resulting in the increasing of the effective duty cycle. A compensation in the duty cycle must be performed for that the magnetizing current does not have a DC value.

III. Design Procedures

The switches of the majority carrier type such as MOSFETs are indicated to be used as main switches, since their commutations are ZVS (or quasi-ZVS). On the other hand, the commutation at the auxiliary switch S_{a1} is ZCS, and the use of switch of the minority carrier type is indicated.

A special care must be take to design the L_r resonant inductor. In stage 8, when the resonance between C_1 and C_2 capacitors and L_r and L_d inductors happens, the voltage across the capacitors must reach a value near to zero. This is the feature of the quasi-ZVS.

At instant that the voltage between the points A and B reaches zero Volts (v_{AB}=0), the load current flows through diode D_4, and the Ld inductor energy starts to resonate, as it can be seen in the equivalent circuit illustrated in Fig. 13. As the inductance L_r is very much smaller than the magnetizing inductance, the last one will be neglected in this analysis.

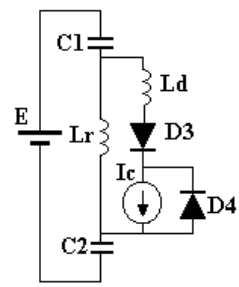

Fig. 13 – Stage 8 equivalent resonant circuit.

In this circuit, the C_1 and C_2 capacitors resonate with equivalent inductor to the paralleling of L_r and L_d inductors. In this resonance, a value near to zero Volts is stipulated (V_{QZVS}), in which the main switches must turn on. So, the value of the resonant inductor can be calculated by the equation [1].

$$L_r \leq \frac{L_d.\left(E^2 - \left(E - V_{QZVS}\right)^2\right)}{\left(E - V_{QZVS}\right)^2} \qquad [1]$$

IV. Project Example

Following is presented a design example of the proposed converter.

Input voltage: $E = 200V$
Output Power: $Po = 250W$
Output Voltage: $Vo = 48V$
Switching frequency: $f = 100\ kHz$
Duty cycle: $D = 0.45$
Transformer ratio: n= 1.8 : 1
$L_d = 18\mu H$
$V_{QZVS} = 20V$
$Lr \leq 4.22\mu H$

The value of 4.22μH is the maximum value of the L_r inductance, for that the commutations at main switches occur with 20 Volts, considering that the auxiliary circuit quality factor is high.

V. EXPERIMENTAL RESULTS

To implement the proposed topology, the project example parameters have been used. Table I presents a list of the devices and components available in the laboratory, which have been utilized in the prototype set-up.

TABLE I

DEVICES AND COMPONENTS

Components	Specifications
S_1, S_2	MOSFETs IRFP450
S_{a1}	IGBT G3N60C3D
D_1, D_2	RHRP870
D_3, D_4	MUR1515
D_{a1}	HFA25PB60
Transformer	EE-65/26, 45:29 tuns
Lr	EE-30/14 - 5 turns = 3.7uH
C_1,C_2	2.2nF

To implement the switches command signals it has been used an Erasable Programmable Logic Device - EPLD (EPM7128LC84-7/ALTERA) operating at frequency of 33.33MHz. With this ASIC it is possible to make the demagnetizing period adequate to reset the magnetizing flux, using programmable digital logic. The use of EPLD allows obtaining a compact logic circuitry as well as a simple and flexible command circuit layout. Furthermore, during the prototype development stage, the employing of this programmable device becomes adequate, once each modification in the command logic is made quickly by software, keeping the same hardware.

Fig. 14 presents the gate pulse of the S_{a1} switch, and collector-emitter current through Sa1, demonstrating the ZCS commutation at this switch.

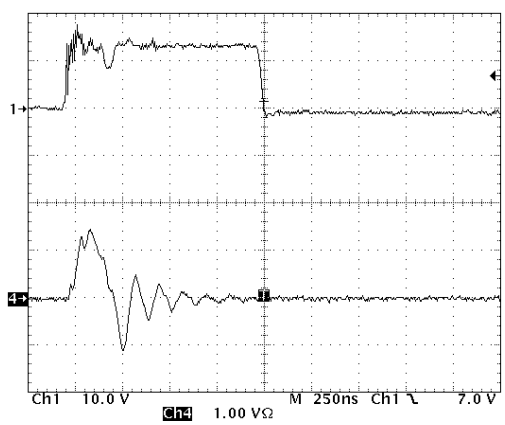

Fig. 14 – S_{a1} switch Gate (top) and collector-emitter current through S_{a1} (bottom).

The Quasi-ZVS commutation at the S_1 main switch can be seen in Fig. 15. In this figure, it can be seen that the gate signal is applied when the voltage across the switch is near to zero, after the resonance between the resonant capacitors and the resonant inductor energies. In the same picture, is shown the T_1 transformer current, demonstrating that the current increases only after the voltage reaches 100 Volts (half of the input source voltage). At this instant, the voltage between A and B becomes positive.

The resonance between the C_1 capacitor and the L_r inductor energies is shown in Fig. 16. Fig. 17 shows the same waveforms, but a zoom of the quasi-ZVS commutation is focused. It can be seen in this figure, that the switching voltage reaches a value about the desired quasi-ZVS voltage.

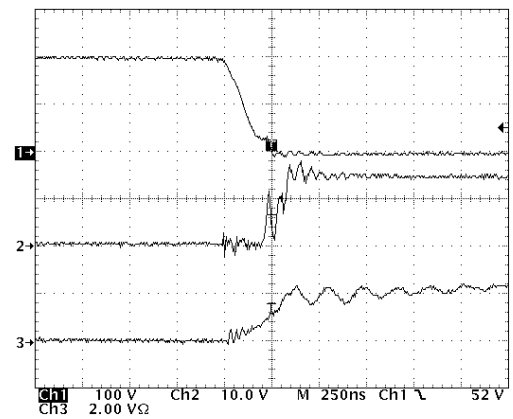

Fig. 15 – S_1 switch drain-source voltage (top), gate-source voltage on S_1 switch (center) and current through the transformer primary side (bottom).

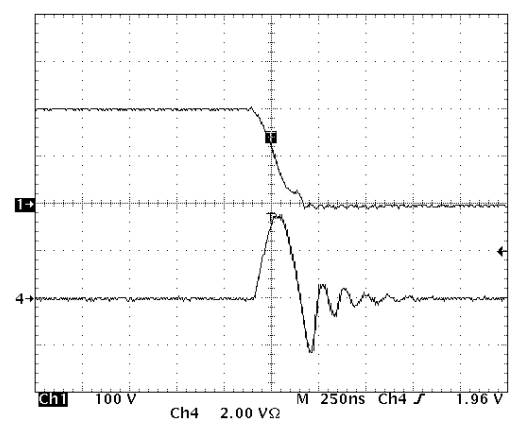

Fig. 16 – S_1 switch drain-source voltage (top) and resonant inductor current (bottom).

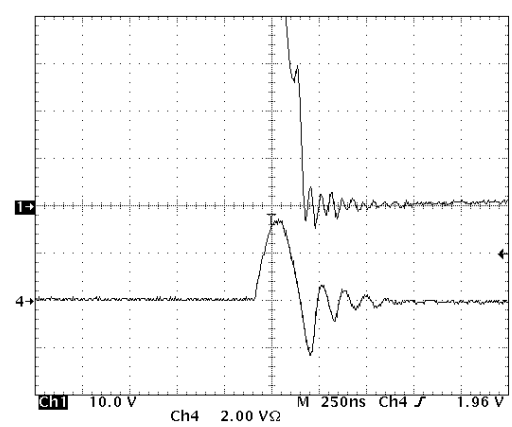

Fig. 17 – S_1 switch drain-source voltage (top) and resonant inductor current (bottom).

One of the advantages of this auxiliary commutation circuit is that it presents low rms current value. It can be

seen in Fig. 18, where are presented the transformer and the resonant currents.

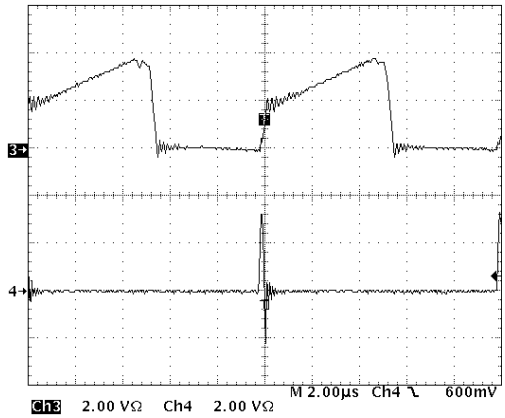

Fig. 18 – Current through the T_1 transformer (top) and through the resonant inductor (bottom).

In Fig. 19 are presented the voltage and the current through the transformer operating at full load.

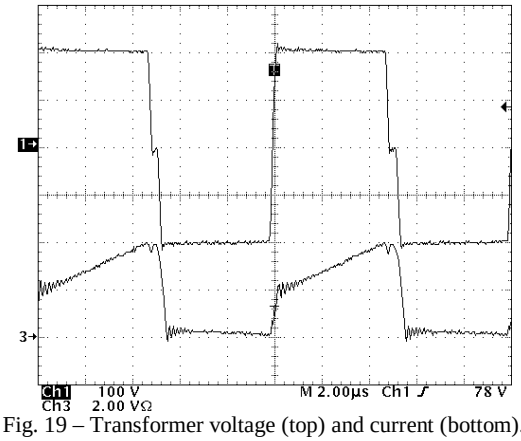

Fig. 19 – Transformer voltage (top) and current (bottom).

VI. CONCLUSIONS

In this paper is presented and studied an auxiliary commutation circuit and a proposed switch logic command applied to forward converters with two switches. Furthermore, it introduced a new concept of soft switching, where it is allowed the main switches commutate Quasi-ZVS.

The additional circuit presents few elements and a low rms current value through their devices. These features result in a auxiliary circuit of small volume and low cost.

In the auxiliary circuit, the semiconductor devices commutate under zero current, characterizing a circuit with low commutation losses.

L_d inductor can be realized by leakage inductance of the transformer, therefore there is not necessary the inclusion of an additional inductor.

At full load the effective duty cycle is near to 50%, as can be seen in Fig. 19, where the best profit of the switch is achieved. Due to this fact and once the converter operates with low commutation losses, high performance is obtained. The implemented breadboard prototype achieved efficiency around 91% at full load.

VII. REFERENCES

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