A NOVEL METHODOLOGY FOR OBTAINING INTEGRATED SOFT-SWITCHING STRUCTURES FOR MULTIPOLE SYSTEMS

J.L. Russi, J.R. Pinheiro, H.L. Hey
Federal University of Santa Maria – UFSM,
Power Electronics and Control Research Group - GEPOC
Santa Maria, Brazil
Email: jrussi@gmail.com, renes@ctlab.ufsm.br, heliohey@gmail.com

***Abstract* – This paper proposes a methodology to develop integrated auxiliary soft-switching cells for converters with multiple poles. The integrated cells obtained are a result of a combination of two cells from the same soft-switching (SS) technique or even of cells from different techniques, originating hybrid cells. The resulting cells present fewer components, are lighter and present smaller volume than the conventional ones. Experimental results are provided in order to demonstrate the concepts proposed in this paper.**

***Keywords* – Soft-switching, inverters, multi-pole systems.**

I. INTRODUCTION

The role of power electronics experts is to continue to mature technology as the industry evolves and converters' requirements become more demanding. Among the requirements are the search for converters more compact, lighter and which present better performance and control ability.

The application of high frequency operation on the converters and systems of converters helps to afford today's severe industry requirements. On the other hand, there are side-effects, such heating due to the efficiency degradation caused by the increase in the switching losses. As heating increases, the need of larger heatsinks increases as well, what can jeopardize the small volume and weight achieved by the high switching frequency.

The trade-off mentioned can be avoided basically by using modern technology semiconductor devices (not yet available worldwide) or by using soft-switching techniques [1]-[7], what increases the amount of components needed to implement the converters.

The choice in favor of soft-switching is made due to the improved power device utilization as a result of the reduction in the turn-on and turn-off energy loss. Besides, it is possible to realize low conducted EMI levels, as compared with their hard switching counterparts mainly due to the low *dv/dt*s presented by some techniques.

When the subject is multiple pole systems, most of the researches in the soft-switching field propose to apply cells originally developed for single pole converters [10],[11] instead of developing new ones for multiple pole systems. This occurs mainly due to the simplicity of single pole cells when compared to multipole ones. This approach results in soft-switching cells with a large amount of extra components.

Integrated soft-switching topologies have fewer components and this way, the resulting structure is more compact, cheaper and can be more reliable as a result of the smaller component count, making them more attractive. On the other hand, they may introduce synchronous switching requirements and more complex modulation techniques.

One characteristic present in most of the soft-switching cells is that they need the injection or the removal of current from some device of the main/auxiliary circuit. For instance, considering a boost converter with a ZVT or a turn-off snubber cell, it is needed to discharge the capacitor in parallel with the main switch by means of a branch which draws current from it. Thus, since several soft-switching techniques present the need of injecting or drawing current and these needs are complementary, the current can be drawn from a cell and this same current can be injected into another cell, *i.e.*, these two functions can be combined generating a new integrated soft-switching cell, minimizing the global energy necessary for the commutations when compared to individual cells.

In this paper it is developed a methodology to integrate the auxiliary cells of several soft-switching techniques for converters with multiple poles since thus far there are only works that aimed to integrate ZVT cells [8],[9].

By verifying all of the possibilities of interaction between several soft-switching techniques, the approach presented allows to generate new soft-switching integrated cells. These cells are a result of a combination of two cells from the same soft-switching technique or even of cells from different techniques, *i.e.*, hybrid cells. The integrated cells obtained present fewer components since some of these components are shared between the two cells, as well, it is expected better efficiency since there is only one energy transfer per switching cycle, instead of two as it occurs for individual cells. Besides, since several soft-switching techniques can be applied to a multipole system, it can be applied the technique which the features fit best to the semiconductor devices and to the current, voltage and frequency ratings of each pole of the system considered.

The literature available so far disregards the possibility of the integration of ZCT, ZCZVT, turn-on snubber, turn-on and turn-off snubber, etc converters. Besides, there is no work considering the integration of different soft-switching techniques. However, researches have succeeded on the matter of developing integrated ZVT power converter topologies [8],[9]. The main goal of this work is the integration of soft-switching cells with different operation features aiming to take full advantage of the characteristic benefits of each soft-switching technique, which is an approach that the literature still lacks and for this reason is investigated herein.

Initially, the models for several soft-switching techniques are derived. These models represent the basic operation principles of each technique and present the elements needed to implement each technique. From the analyses of the obtained models, it is easy to verify every integration possibility in order to obtain integrated soft-switching cells. Then, the components redundant can be eliminated resulting in more compact structures.

The constraints that guarantee that each system of converters obtained operates adequately are commented and are a result from the analyses and the methodology presented herein.

The approach presented in this paper is useful for systems with multiple poles such as, inverters, UPSs, etc.

Section II presents models for the soft-switching techniques for a bidirectional single pole. In Section III the basic approach for obtaining integrated soft-switching systems is shown. Section IV presents the analysis of two-pole converters generated by the approach presented in Section III. Finally, Section V presents some experimental results.

II. TOPOLOGICAL MODELS FOR SOFT-SWITCHING TECHNIQUES

In this section are presented the models for the basic converters of the following SS techniques: (i) Turn-ON Snubber – TONS; (ii) Turn-OFF Snubber – TOFFS; (iii) Turn-ON AND Turn-OFF Snubber – TON&TOFFS; (iv) Zero Current Transition – ZCT; (v) Zero Voltage Transition – ZVT; and (vi) Zero Current and Zero Voltage Transition – ZCZVT.

By means of the analyses of these models it can be determined the fundamental elements for each SS technique and which ones are optional. These last ones are responsible for the topological variations within determined technique.

A. Turn-on Snubber

In order to turn on a switch with a finite *di/dt* it is needed an inductor placed in a series connection with this switch.

This series connection presents a difficulty related to the demagnetization of the inductor when the switch is turned off. Consequently, there must be a loop which contains this inductor and an element which presents the characteristics of a voltage source, responsible to demagnetize the inductor by applying a voltage on it with the adequate polarity. This way, this element is graphically represented by a controlled voltage source. Moreover, the auxiliary loop must present a way do disconnect the voltage source to allow that the voltage over the inductor can vary freely during its magnetization. The model obtained is shown in Fig. 1(a).

The different ways of implementing the voltage source E_a result in the topological variations of the turn-on snubbers.

The inductor L_{sa} must be demagnetized during the period that the switch S_{1a} is turned off. Then, there is a trade-off between the value of E_a and the period during which S_{1a} is in the OFF state, as shown below.

$$V_{Lsa} = L_{sa}\,\Delta I/\Delta t \tag{1}$$

$$E_a = L_{sa}\, I_t / T_{S1a\_Off\_Min} \tag{2}$$

B. Turn-off Snubber

In order to allow a semiconductor device to turn-off with a limited *dv/dt* it is necessary to have a capacitor in parallel with this device. The energy stored in this capacitor must be drained before the switch turn-on to reset the capacitor for the next operation cycle. As a result, some device which presents the characteristic of a current source must form a loop with the capacitor in order to provide its discharge.

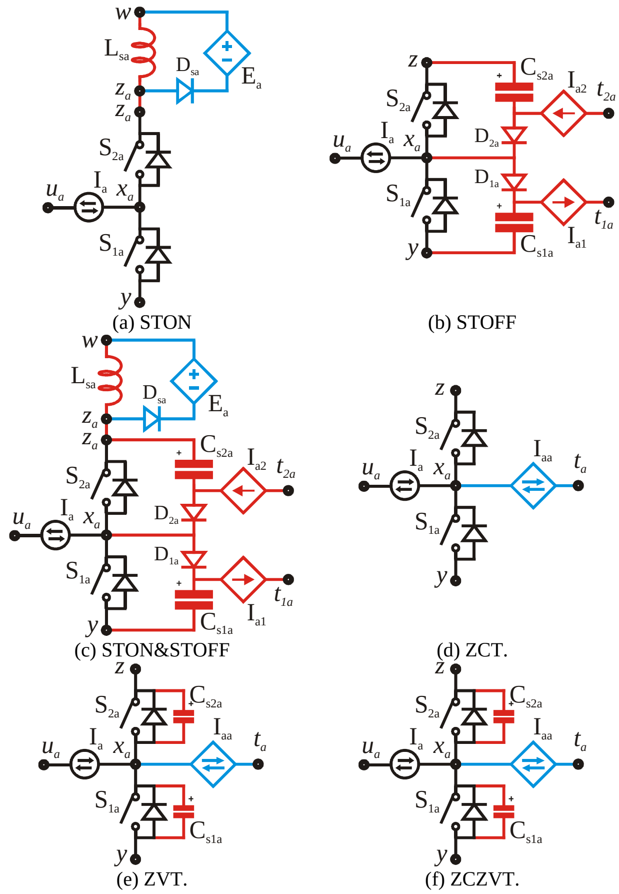


Fig. 1. Models for the soft-switching techniques.

Besides, there must be some device to avoid the dissipation of the energy stored in the capacitor on the switch junction when it turns-on.

The model for the turn-off snubber is shown in Fig. 1(b).

As commented, the capacitor $C_{s1(2)a}$ must be completely discharged. The current that must be removed from it is given by,

$$i_{Cs1(2)a}(t) = \frac{d}{dt}\left(q_{Cs1(2)a}\right) = C_{S1(2)a}\frac{d}{dt}\left(V_{Cs1(2)a}\right) \tag{3}$$

Integrating both sides of this equation and since $V_{Cs1a}=V_{zy}$, it can be obtained,

$$\int_0^{tf} i_{Cs1(2)a}(t)\,dt = C_{s1(2)a}V_{zy} \tag{4}$$

This equation shows that the amount of current to be removed from the capacitor is proportional to the DC-bus value and to the capacitor value. Moreover, it makes evident that the waveform of the current can be of an arbitrary shape.

C. Turn-off and Turn-On Snubber

To allow a semiconductor device to turn-off under a finite *dv/dt* and to turn-on with a controlled *di/dt* two elements are necessary: (i) a capacitor in parallel to it and (ii) an inductor in series with it, as discussed formerly.

A topology which presents both of these features can be obtained by the combination of the topologies that present these characteristics individually. Then, the resulting topology, Fig. 1(c), will present a capacitor connected in parallel with the switch plus a current source to discharge it and an inductor in series with the switch plus a voltage source to demagnetize this inductor.

The conditions to demagnetize the inductor are the same as those commented for the turn-on snubber. On the other hand, the energy stored in the capacitor $C_{s1(2)a}$ is greater than in the case of the turn-off snubber due to the absence of clamping of this capacitor, as defined by,

$$V_{Cs1(2)a\_Max} = V_{zy} + \sqrt{L_{sa}/C_{s1(2)a}}\, I_a . \tag{5}$$

Where $V_{Cs1(2)a\_Max}$ is the maximum voltage of $C_{s1(2)a}$.

Substituting (5) in (3) and integrating, it is obtained,

$$\int_0^{tf} i_{Cs1(2)a}(t)\,dt = C_{s1(2)a}\left(V_{zy} + \sqrt{L_{sa}/C_{s1(2)a}}\, I_a\right) \tag{6}$$

This expression shows that the amount of energy that must be removed from capacitor $C_{s1(2)a}$ is bigger than the energy that must be removed from the capacitors of the turn-off snubber.

D. Zero Current Transition

The ZCT converters must present an extra branch connected to terminal x_a, which is responsible for injecting and draining current from or into the pole, Fig. 1(d). The magnitude of the current must be enough to annul the current that flows through an active switch in order to provide its turn-off under ZCS.

The current through the auxiliary branch must increase and decrease in a slow fashion to provide a time interval long enough with null current through both active switches. After the turn-off under ZCS of a switch, the current through the auxiliary branch must decrease, becoming null.

The way of implementing the current source I_a generates the topological variations of the ZCT converters.

The only constraint to assure the correct operation of a ZCT converter is that the current (I_{aa}) through the branch connected to terminal x_a must be greater than the value of I_a, *i.e.*,

$$I_{aa} > I_a \tag{7}$$

E. Zero Voltage Transition

The ZVT converters present a capacitance in parallel with the switches that allow them to present a limited *dv/dt* rate during their turn-on and turn-off transitions.

These capacitances must be charged or discharged before the turn-on of a switch by means of an auxiliary branch that must behave as a current source and is connected to the terminal x_a of the topology, Fig. 1(e). Its current must not only be greater than the current of I_a, it also has to be enough to charge or discharge capacitors C_{s1a} and C_{s2a}.

Since these capacitors are actually in parallel, it is defined,

$$C_s = C_{s1a} + C_{s2a} \tag{8}$$

The amount of current that must flow is defined as,

$$i_{Cs}(t) - I_a = \frac{d}{dt}(q_{Cs}) = C_s \frac{d}{dt}(V_{Cs}) \tag{9}$$

Integrating both sides, and since V_{Cs}=V_{zy}, it is obtained,

$$\int_{t|_{iaa(t)=Ia}}^{tf} \left(i_{Cs}(t) - I_a\right) dt = \int_{t|_{iaa(t)=Ia}}^{tf} \left(i_{aa}(t) - I_a\right) dt = C_s V_{zy} . \tag{10}$$

Comparing equation (10) with (4) it can be seen that the current that must flow through the auxiliary branch of the ZVT converter is larger than the one of the turn-off snubber.

F. Zero Current and Zero Voltage Transition

The ZCZVT technique is the combination of the ZVT and ZCT techniques shown formerly. This way, the model of a ZCZVT converter is a result of the union of the models of these two techniques, Fig. 1(f). As a result, the model for the ZCZVT technique is the same of the ZVT one. However, for this case, the auxiliary branch (I_{aa}) must be activated twice: for the turn-on of the switches (ZVS transition) and for the turn-off of them (ZCS transition).

To guarantee the proper operation of a ZCZVT converter, the conditions defined in equations (7) and (10) must be assured.

III. INTEGRATION PRINCIPLE FOR MULTIPOLE SOFT-SWITCHING CONVERTERS

In this section, the opportunities for the integration of the auxiliary cells of the soft-switching techniques seen in the former section are investigated. The systems studied are comprised by bidirectional poles. Each switch presents an Auxiliary Commutation Cell, ACC, as depicted in Fig. 2.

The approach presented in this paper allows that two switches commutate in a soft way with only one energy transfer. This process always occurs from the negative DC-Bus to the positive one when one pole is operating as a boost (the current I_a enters into terminal x_a) and the other one operates as a buck converter (I_a leaves terminal x_a). Therefore, the current transfer can occur either through the ACC_{1a} and ACC_{2b} or through ACC_{1b} and ACC_{2a}.

The current transfer occurs through an auxiliary branch that is named hereafter Transfer Branch (TB). There may be up to two transfer branches for two bidirectional poles. They are connected to one of the terminals of the capacitors in parallel with the switches or to the terminal $x_{a(b)}$ of the pole.

It can be noticed that all the models but the turn-on snubber model (Fig. 1(a)) shown in Fig. 1 present a current source that drains current and other that injects current in the auxiliary cells. The techniques which present current sources can be combined among themselves originating systems such the one shown in Fig. 2. To make this possible, the source that drains current from the auxiliary cell of one pole must be combined with the one that injects current in the opposite auxiliary cell of the other pole.

When the converter is operating as a boost, the current must be drained from the positive terminal of capacitor $C_{s1a(b)}$ or from the terminal $x_{a(b)}$. On the other hand, when the converter operates as a buck, there must be current injected in

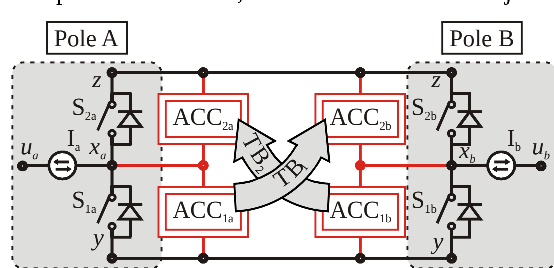


Fig. 2. System of converters.

the $x_{b(a)}$ terminal or in the negative terminal of capacitor $C_{s2b(a)}$. The current drained is actually the same current that must be injected and since the current is always drained (Fig. 2) from the converter operating as boost and injected in the converter that operates as a buck, it can only flow in the sense of the "boost" pole to the "buck" pole.

When the current sources are integrated, there is the requirement of synchronous operation, *i.e.* some events are connected and have to occur at the same time, or after another event. For example, the turn-off of a switch occurs just after the turn-on of another one or some switch must be turned on when another switch is in the ON state, etc.

It apparently seems that since some events must occur synchronically, both counterparts would operate with the same frequency. Actually, the ZCZVT converters need the intervention of the current source I_{aa} during their turn-on and turn-off transitions. As a result, when another converter interacts with a ZCZVT converter, these converters have to operate at multiple frequencies, being the frequency of the ZCZVT twice lower.

The auxiliary branches are connected between the terminals x_a, x_b, C_{s1a+}, C_{s1b+}, C_{s2a-} and C_{s2b-}. The analysis of the voltages of these terminals is important to evaluate if the current can start or stop to flow from one terminal to another of the transfer branch spontaneously or not. It will begin to flow in a spontaneous way if the voltage between the two terminals of the TB is positive when the TB is activated and will stop spontaneously if at the end of the process this voltage becomes negative. When these conditions are not fulfilled, there is the need of inserting a voltage source or a component with the characteristic of a voltage source in the auxiliary branch, what makes the practical implementation of the transfer branch more difficult.

The voltages of the terminals where the transfer branch is connected are shown in TABLE I. In this table, the voltage of terminal *y* can be considered as the reference voltage. The analysis of these voltages is important since it is related to some of the requirements of the transfer branch.

The voltages of the terminals connected to the transfer branches in the end of the energy transfer process are shown in TABLE II. These voltages are related to the energy management of the energy that has flown through the transfer branch.

The research developed is based on a system composed by two bidirectional converters (Fig. 2) aiming a system as generic as possible; however, it is also useful for simpler systems such as a system composed by a boost and a buck converter, or a bidirectional converter and a buck or boost converter.

In the next section, the possibilities of integrated operation of the proposed models to the various techniques are analyzed. The model proposed for the turn-on snubber is the only one that does not present any current source and then, it cannot work together with any other of the techniques shown.

TABLE I
Voltage of the terminals connected to the transfer branch in the beginning of the transfer process.

	Positive Terminal	Negative Terminal
TONS	-	-
TOFFS	$V_{Cs1+}=V_{zy}$	$V_{Cs2b-}=0$
TONS& TOFFS	$V_{Cs1a+}=V_{zy}+\sqrt{\frac{L_{sa}}{C_{s1a}}}I_a$	$V_{Cs2b-}=-\sqrt{\frac{L_{Sb}}{C_{s2b}}}I_b$
ZCT	$V_{xa}=0$	$V_{xb}=V_{zy}$
ZVT	$V_{xa}=V_{Cs1a+}=V_{zy}$	$V_{xb}=V_{Cs2b-}=0$
ZCZVT	$V_{xa}=0$; $V_{xa}=V_{Cs1a+}=V_{zy}$	$V_{xb}=V_{zy}$; $V_{xb}=V_{Cs2b-}=0$

TABLE II
Voltage in the terminals connected to the transfer branch at the end of the transfer process.

	Positive Terminal	Negative Terminal
TONS	-	-
TOFFS	$V_{Cs1+}=0$	$V_{Cs2b-}=V_{ZY}$
TONS& TOFFS	$V_{Cs1a+}=0$	$V_{Cs2b-}=V_{ZY}$
ZCT	$V_{xa}=V_{zy}$	$V_{xb}=0$
ZVT	$V_{xa}=0$	$V_{xb}=V_{zy}$
ZCZVT	$V_{xa}=V_{zy}$; $V_{xa}=0$	$V_{xb}=0$; $V_{xb}=V_{zy}$

IV. NOVEL INTEGRATED SOFT-SWITCHING CELL FOR TWO TURN-OFF SNUBBER POLES

For the system of converters depicted in Fig. 3, it is possible to transfer energy from the negative DC-Bus to the positive one, flowing through capacitors C_{s1a} and C_{s2b} or C_{s1b} and C_{s2a}, discharging these capacitors.

When I_a enters into terminal x_a, Fig. 3, as switch S_{1a} turns off, C_{s1a} is charged to the bus voltage V_{zy}. As S_{1a} turns on, C_{s1a} can be discharged. Similarly, if I_b leaves terminal x_b and S_{2b} turns off, C_{s2b} is charged to V_{zy}. As S_{2b} turns on, C_{s2b} can be discharged. Since the energy transfer occurs at the same time, the turn-on of the switches S_{1a} and S_{2b} must occur at the same time and then the discharge of C_{s1a} and C_{s2b} occurs simultaneously. For the same reason, both poles must operate at the same frequency.

The voltage applied on the transfer branch at the beginning of the energy transfer process is defined as,

$$V_{Cs1a+}-V_{Cs2b-}=V_{zy}. \quad (11)$$

It means that the current can start to flow naturally from C_{s1a} to C_{s2b} passing through the transfer branch.

At the end of the process, this voltage is defined as,

$$V_{Cs1a+}-V_{Cs2b-}=-V_{zy}. \quad (12)$$

Since the voltage applied on the transfer branch becomes negative, the current transfer can stop in a spontaneous way.

The least amount of current that must flow through the transfer branch to discharge C_{s1a} and C_{s2b} is defined in (13).

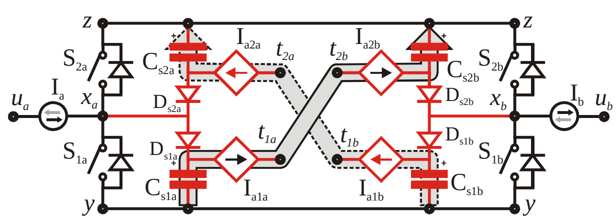


Fig. 3. Interconnection between the auxiliary cells of two turn-off snubbers.

$$\begin{cases} \int_0^{tf} i_{Cs1a(b)}(t)\,dt > C_{s1a(b)} V_{zy} \\ \int_0^{tf} i_{Cs2a(b)}(t)\,dt > C_{s2a(b)} V_{zy} \end{cases} \tag{13}$$

The turn-on of switches S_{1a}, S_{2b} must be simultaneous as illustrated by means of Fig. 4.

To be able to transfer current through capacitors C_{s1a} and C_{s2b} it is needed a branch that connects these two components creating a path where the current can flow through.

The sub circuit utilized to evaluate the necessary conditions and the possibilities of circuits able to execute such task is composed by capacitors C_{s1a} and C_{s2b}, the DC-Bus and the transfer branch itself, Fig. 5(a).

This circuit can be simplified by substituting capacitors C_{s1a} and C_{s2b} by its equivalent C_s, Fig. 5(b).

$$C_s = C_{s1a} C_{s2b} / \left(C_{s1a} + C_{s2b} \right) \tag{14}$$

One example of transfer branch is depicted in Fig. 5(c) and is composed by a unidirectional switch and an inductor.

At the beginning of the transfer process

$$V_{Cs1a\_Max} = V_{Cs2b\_Max} = V_{zy}\text{, i.e.,} \tag{15}$$

$$V_{Cs}(0) = 2V_{zy}. \tag{16}$$

After the current transfer process,

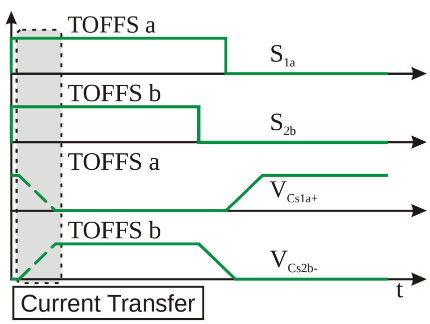


Fig. 4. Synchronicity needs for S_{1a}, S_{2b} and the transfer branch.

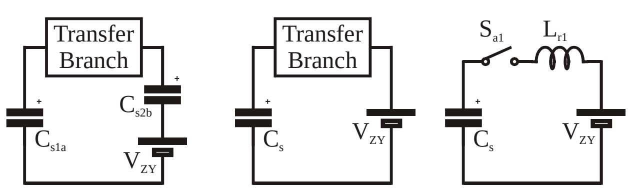
$$V_{Cs1a}(t_f) = V_{Cs2b}(t_f) = V_{Cs}(t_f) = 0. \tag{17}$$

This means that both capacitors must present the same *dv/dt* rate. As a result, since the same current flows through these capacitors, both of them must have the same capacitance value.

The state-plane for the equivalent circuit (Fig. 5(c)) is shown in **Fig. 6**. It can be seen that the center of resonance is V_{zy}, *i.e.*, there is no need of inserting a voltage source in the transfer branch. In this figure, I_s is the current through the transfer branch and Z_s is the characteristic impedance, defined as,

$$Z_S = \sqrt{L_{r1}/C_S}\,. \tag{18}$$

There is no restriction concerning the ratio between the values of the current sources I_a and I_b.



(a) (b) (c)

Fig. 5. Transfer loop.

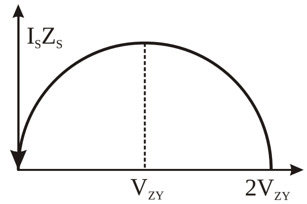


Fig. 6. State-plane.

The resulting system is shown in Fig. 7.

V. EXPERIMENTAL RESULTS

In order to demonstrate de feasibility of the concepts proposed in this paper, it was assembled a prototype for the converter shown in Section IV. The topology implemented is shown if Fig. 8 and the parameters used in TABLE III.

The oscilograms shown in this paper were obtained for the converter operating at nominal values, TABLE III.

The waveforms that show the capacitors C_{s1a} and C_{s2b} being discharged are shown respectively in Fig. 9(a) and (b). It must be noticed that the discharge process of capacitors C_{s1a} and C_{s2b} occurs simultaneously, thanks to the transfer branch implemented, which allows the current (i_{Lr1}, Fig. 9) to flow between the DC-Buses, discharging both capacitors. Such fact proves the effectiveness of the proposed TB that by means of only one current transfer, restores the adequate conditions to allow that capacitors C_{s1a} and C_{s2b} operate as turn-off snubbers for the switches S_{1a} and S_{2b}, respectively.

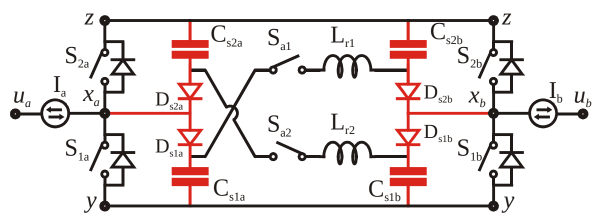


Fig. 7. Resulting system.

During the turn-off process of switch S_{1a}, the capacitor

TABLE III
Experimental parameters.

Parameter	Value
V_{Bus}	360 V
I_{Load_Max}	7.9 A
V_{Load_Max}	127 V
P_{Load}	1000 W
L_f	2.3 mH
C_f	4 µF
S_1, S_2, S_3 and S_4	IRG4PC40UD
S_{a1} and S_{a2}	IRG4BC30UD
D_{s1a}, D_{s2a}, D_{s1b} and D_{s2b}	RHRP870
D_{a1} and D_{a2}	RHRP870
L_{r1} and L_{r2}	6 µF
C_{s1a}, C_{s1b}, C_{s2a} and C_{s2b}	1.5 nF + 1.0 nF
f_s	40 kHz

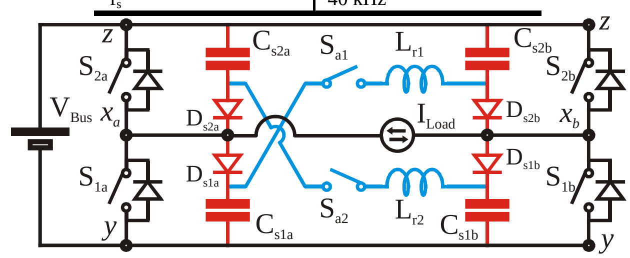


Fig. 8. Power stage of the topology implemented.

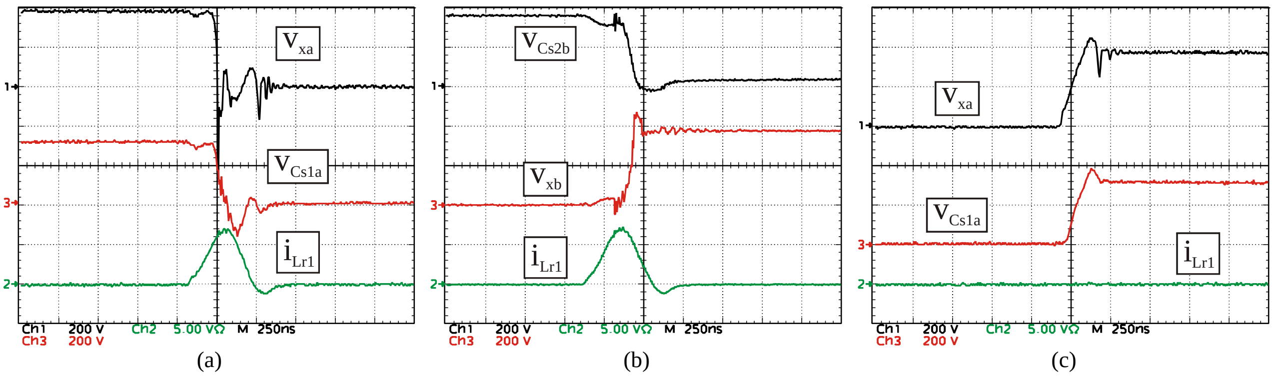


Fig. 9. Experimental waveforms. (a) S_{1a} turn-on; (b) S_{2b} turn-on; and (c) S_{1a} turn-off.

C_{s1a} charges in a slow fashion, until it reaches the bus voltage, Fig. 9(c), showing the effectiveness of the turn-off snubber. Because D_{s1a} is conducting, the voltage over the switch is the same voltage of capacitor C_{s1a}.

The waveforms for the opposite sense of current through the load will not be shown since they are redundant.

The experimental measurement of the efficiency of the proposed topology was made, Fig. 10. For comparison purposes it is also shown the efficiency curves of a RCD turn-off snubber (implemented for each main switch of the system and operating just like the proposed topology). In this figure, it is shown the efficiency as a function of the load value, *i.e.*, the output power was varied from 20% to its nominal value.

The results collected make evident that the proposed topology outperforms the RCD snubber by over two percent for the entire extent of the efficiency evaluation carried out.

VI. CONCLUSION

This paper presents the proposal of the integration of the soft-switching cells pertaining to several soft-switching techniques. This approach is based on the models presented for the converters which represent the soft-switching techniques.

The concept proposed is so far unpublished and from it can be derived dozens of new soft-switching cells, which may present improved characteristics compared to the ones known currently.

The conditions to start and to stop the current transfer were derived as well as the needs of certain events that must occur synchronically.

The experimental results show the effectiveness of the concepts proposed herein. The topology proposed behaved as theoretically predicted and the experimental evaluation highlights the benefits of the implemented topology in the matter of its efficiency.

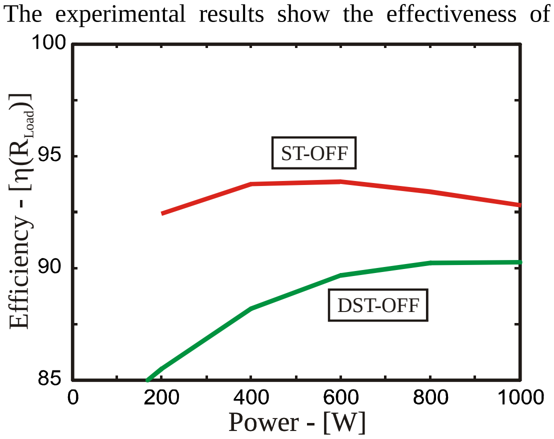


Fig. 10. Efficiency evaluation.

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