# INTEGRATION OF iZVT AUXILIARY COMMUTATION CIRCUITS APPLIED TO UNINTERRUPTIBLE POWER SUPPLY

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***Abstract* – This paper proposes an iZVT circuit using the concept of integrated ZVT auxiliary commutation cell (iZVT) applied to a double-conversion uninterruptible power supply, operating with a Three-Level PWM inverter. This proposal has two objectives, which are: to reduce the number of additional components needed to obtain soft-switching and to minimize the circulating reactive energy by means of reusing the reactive energy of one commutation to assist another one, so that the efficiency improves without penalizing the cost. In this way, it is obtained ZVT commutation for all main switches and ZCS and ZVS for the auxiliary switches. To demonstrate the technique of integration of the auxiliary commutation circuits applied to a double-conversion UPS, simulation results of the system rated at 1kW – 100kHz are presented throughout the work.**

***Keywords* – Soft-switching, uninterruptible power supply (UPS), zero voltage transition (ZVT), integrated ZVT (iZVT) and integrated auxiliary commutation circuit (iACC).**

## I. INTRODUCTION

The widespread use of electronics equipments has caused an increase in the consumption of electric energy. To increase the electric energy generation, great investments are necessary and it causes large environmental impacts. Moreover, are needed studies related to the energy consumption quality improvement and its rational use, what is quite important. Consequently, these aspects are frequently subjects in the research community. The design of robust static converters with higher efficiency, high power factor, high power density, good dynamic response and as well as reduced emission of electromagnetic interference (EMI) [1], contributes allowing a better energy exploitation, justifying the improvement efforts. Another trend is to increase the power density, with the purpose of obtaining more compact converters, what is a necessary condition to minimize electric equipments.

With the increase of the switching frequency of the static converters it is obtained an improvement in their dynamic response and a reduction in the weight and volume of the magnetic elements and filters. On the other hand, the global efficiency of the converter is reduced, once the losses of commutation are proportional to the switching frequency and the power level involved. This means that, it does not compromise the global efficiency of the converter. The rise of the switching frequency must be followed by the reduction of the power of the converter or vice versa. However, if the commutation losses are diminished, without resulting in the conduction losses increase, the switching frequency can be raised, keeping the same power level.

Aiming to minimize the commutation losses of the semiconductor devices, commutation techniques have been developed to reduce the overlapping existing between current and voltage during the commutation. These techniques are: Passive techniques - snubbers [2], [3] and [4]; Active techniques - ZVS [5], ZCS [5], ZVT [6], ZCT [7], ZCZVT [8]. Among the soft-switching techniques, the ZVT is one of the most popular techniques. Its components are outside of the power flow and it processes only a small portion of the energy during a short period of time. Due to the turn-on of the main switch under zero voltage, its use becomes attractive together with majority carrier's device type as MOSFET's.

The use of circuits to aid the commutations for each converter that composes an uninterruptible power supply (UPS) [9], increases the number of components, the cost and the complexity of its design, what makes its use less attractive for the industry [10]. In this way, the cell proposed in [11] is applied to double-conversion UPS operating with Three-Levels PWM inverter. By using the iZVT it is possible to reduce the number of additional components, reducing the cost and increasing the efficiency of the system, which are the desired features of the power electronics industries.

In this way, the iACC (Integrated Auxiliary Commutation Circuit) considered reduces the number of additional components needed to accomplish commutations of the ZVT type for all of the main switches and commutation of the ZCS or ZVS type for the auxiliary switches, providing a system with high efficiency and low cost in comparison to the same system using ACC's independent for the same function.

## II. APPLICATION OF THE iACC TO DOUBLE-CONVERSION UPS

The integration concept of the auxiliary commutation circuits [11] is applied to a double-conversion UPS, illustrated in figure 1. This UPS is composed of one preregulator converter, (boost; $S_1, D_1$), acting as a regulator of the DC bus voltage, performing power factor correction (PFC) and also operating during the backup mode [12], hence, reducing the cost of the UPS; one battery charger (buck; $S_2, D_2$) to keep the charge of the battery bank; and one inverter (full-bridge; $S_3$, $S_4$, $S_5$ and $S_6$), to feed the load with high power quality. This UPS operates under different modes depending on the state of the utility grid and on the state of the battery bank. For each operation mode the commutation processes occur differently, depending on the load current direction, modifying the structure of the system for the different operation modes. Even so, the integration concept is applied with great effectiveness [11].

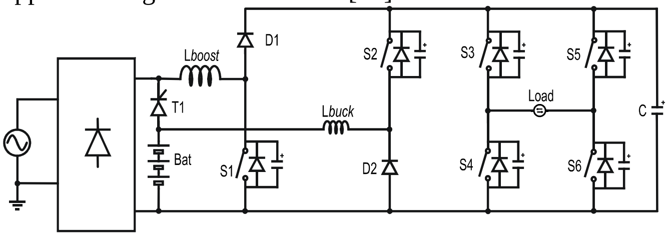



Fig. 1. Power stage of the double-conversion UPS.

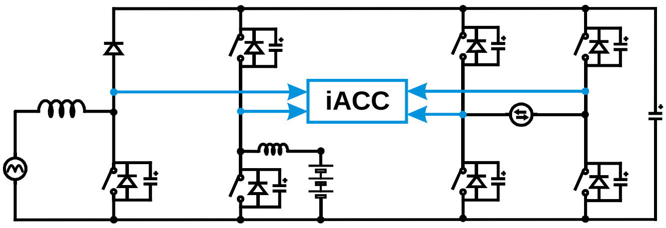



Fig.2. The principle of integration of auxiliary commutation circuits iZVT applied at UPS of double-conversion.

The iZVT principle applied to a double-conversion UPS is illustrated in figure 2, and the proposal of an iACC for this UPS is shown in figure 3. To allow the inverter operation with Three-Level modulation, there are two possible ways: to use an iACC with isolated voltage source or the use of two independent iACCs. The second option was used in this work due to its simplicity of implementation and because there is not any necessity of using an isolated voltage source. In figure 3 the comparison between a UPS using independent ACC's (figure 3(a)); and another one using the proposed iACC (figure 3(b)) is presented.

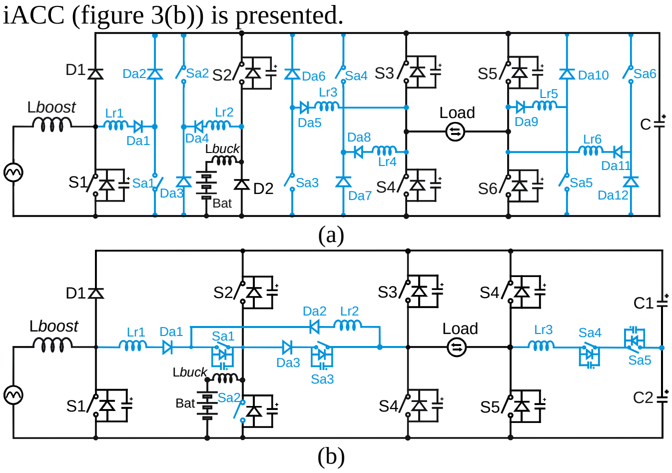



Fig. 3. Circuit simplified equivalent of the UPS: (a) Independent UPS using ZVT ACC (b) Proposed UPS using iACC.

The iACC is composed by three resonant inductors ($L_{r1}$, $L_{r2}$ and $L_{r3}$), three auxiliary diodes ($Da_1$, $Da_2$ and $Da_3$) and five auxiliary switches ($Sa_1$, $Sa_2$, $Sa_3$, $Sa_4$ and $Sa_5$). By using the proposed iACC, the main switches operate under soft-switching of the ZVT type, without current and voltage stresses, and the auxiliary switches commutate under zero-current, ZCS ($Sa_1$) and zero-voltage, ZVS ($Sa_2$, $Sa_3$, $Sa_4$ and $Sa_5$). The proposed iACC presents a large reduction in the number of auxiliary components when compared to the same UPS, using independent ACC circuit [6]. It presents just one auxiliary switch, three auxiliary diodes and three auxiliary inductors, resulting in the reduction of seven components. In the circuit proposed, the auxiliary switch $Sa_1$, operates under ZCS. Consequently, it is convenient to implement this switch with a minority carriers device type, since for these devices the commutation losses are related mainly to the turn-off process, given the fact that these devices present a residual current, called tail current [13, 14]. As a result, the component being used for this is an IGBT. For the other auxiliary switches the commutation is of the ZVS type, what makes more attractive the use of a majority carrier's switch such as a MOSFET. This device presents a parasite capacitance in parallel. In the ZVT technique, this capacitance is discharged before the switch to be turned on, preventing the main commutation losses for this type of device. These losses are known as turn-on capacitive losses. Since the auxiliary switch $Sa_2$ (commutation of ZVS type), presents an intrinsic diode (anti-parallel diode), this diode can be used as diode $D_2$, of the battery charger branch reducing even more the whole cost of the system.

## III. DESIGN PROCEDURE OF THE iACC

The switches choice is a function of the type of commutation that occurs. For the switch $Sa_1$ the commutation is of the ZCS type, being the switch an IGBT. In the other switches of the iACC, the commutations occur under ZVS, and the switches are MOSFET's, as commented previously.

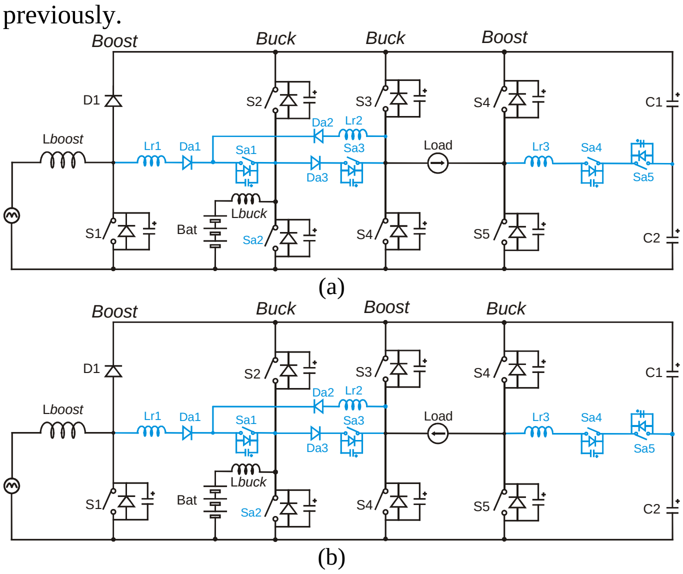



Fig. 4. Distinct commutation processes of the inverter legs: (a) Normal mode, left leg of the inverter operates as boost (b) Normal mode, left leg of the inverter operates as buck.

The values of the resonant inductors $L_{r1}$ and $L_{r2}$ are designed to minimize the effects of the reverse-recovery in the main diodes and as a function of the maximum $di/dt$ allowed by the semiconductors. This criterion is used for the design of most of the ACC components [15], as it follows.

Equation (1) is used to calculate the values of $Lr$:

$$Lr = \frac{V_L}{di/dt_{(max)}} \tag{1}$$

Finally, the value of the resonant capacitors ($C_{S1}$, $C_{S2}$, $C_{S3}$ and $C_{S4}$), located in anti-parallel with the main switches must be designed in order to guarantee soft-switching with the smallest reactive energy.

The design of the capacitors must be carried out for the critical case, that is, when the UPS system operates in normal mode and the output load current has the direction illustrated in Figure 4(b), because, in this mode, the energy involved in the commutation process of the main switch $S_1$ should be employed to commutate other two main switches, $S_2$ and $S_3$. Furthermore, this critical mode must consider that the current of the preregulator converter ($i_{pre}$) has its minimum value and the current of buck ($i_{bat}$) and full-bridge inverter ($i_o$) present their maximum values.

The necessary energy for the commutations of the second leg of the inverter comes from the capacitors $C_1$ and $C_2$, which do not have any influence in the determination of the resonant capacitors ($C_{S1}$, $C_{S2}$, $C_{S3}$ and $C_{S4}$), being the capacitors ($C_{S5}$ and $C_{S6}$) designed for the same values of $C_{S3}$ and $C_{S4}$, considering that all the auxiliary capacitors of the inverter have the same values.

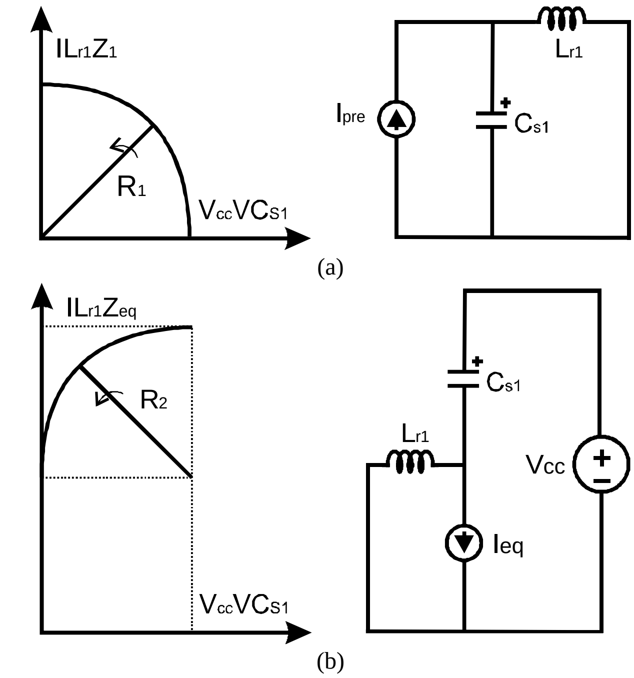



Fig. 5. Commutation Process: (a) State-plane and equivalent circuit for the commutation of $S_1$, (b) State-plane and equivalent circuit for the commutation of $S_2$ and $S_3$.

The state-plane and the equivalent circuit of the commutation process of the preregulator converter is shown in Figure 5(a), where $I_{p1}$, which is the peak current through the resonant inductor $L_{r1}$, will be utilized to assist the commutation of the other two main switches ($S_2$ and $S_3$), whose state-plane and equivalent circuit are illustrated in Figure 5(b). For this reason, to guarantee the soft-switching it must be guaranteed that the peak current of the two state-planes are equal. By this procedure, the value for $C_{S1}$ is obtained.

Equation (2), calculation of $C_{S1}$:

$$C_{S1} = \frac{C_{eq}\left(V_{DC} + Z_{eq} I_{eq}\right)^2}{V_{DC}} \tag{2}$$

where:

$$Z_{eq} = \sqrt{\frac{Lr_1}{C_{eq}}}, \tag{3}$$

$$Z_{L1} = \sqrt{\frac{Lr_1}{C_{S1}}}, \tag{4}$$

$$C_{eq} = C_{S2} + C_{S3} + C_{S4} \tag{5}$$

$$I_{eq} = I_{bat} + I_{inv} \tag{6}$$

$V_{DC}$= DC bus voltage.

Similarly, the values of the inductor $Lr_3$, $C_{S5}$ and $C_{S6}$, are obtained for iACC.

Thus, by means of equation (2) and using the intrinsic capacitors of the switches $S_2$, $S_3$, $S_4$, $S_5$ and $S_6$ (for volume reduction), the design of the iACC is concluded.

## IV. RESULTS OF SIMULATION

The considered system was simulated to verify the principle of operation of the applied iACC to the double-conversion UPS, operating with Three-Level PWM inverter, shown in Figure 6.

In Table 1, the main parameters of the design are presented. The results of the simulations will be presented individually to demonstrate the principle of operation for all modes of operation.

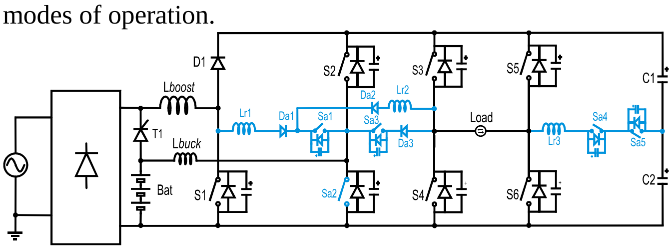
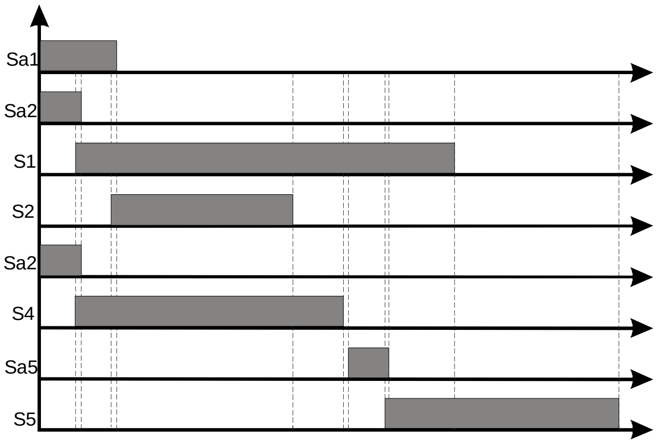



Fig. 6. Simplified circuit the simulated UPS.

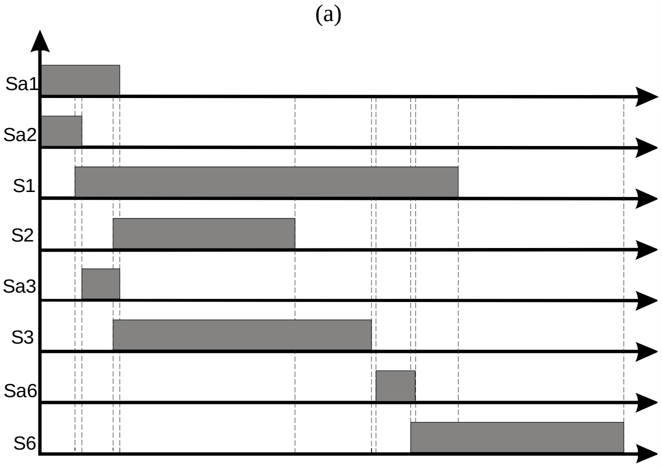
**TABLE I**
**Specifications of the UPS**

| | |
|---|---|
| Nominal Power ($Po$) | 1000 W |
| Output Voltage ($Vo$) | 220 rms |
| Input Voltage ($Vin$) | 220 Vrms ± 10% |
| Battery Bank Voltage ($Vbat$) | 96 V |
| Switching Frequency ($fs$) | 100 kHz |
| Current Charge of the Battery Bank ($Ibat$) | 1,4 A |
| Resonant Inductor ($Lr1$, $Lr2$ and $Lr3$) | 5 µH |
| Capacitor $C_{S1}$ | 4 nF |
| Capacitor $C_{S2}$ | 480 pF |
| Capacitors $C_{S3}$, $C_{S4}$, $C_{S5}$ and $C_{S6}$ | 680 pF |
| Capacitors $C_{DC1}$ and $C_{DC2}$ | 250 µF |
| Boost inductor ($Lboost$) | 550 µH |
| Buck inductor ($Lbuck$) | 5,5 mH |

To assure the correct operation of the UPS with iACC the command logic of the switches must take into account the synchronism necessary for the correct operation of the auxiliary circuit. The command logic is presented in figure 7, where the commutations of all the converters are synchronized with the commutations of the left leg of the inverter (which is integrated). The switching logic depends on the sense of the current through this leg. In figure 7(a) the command logic corresponds to the load current with the sense illustrated in Figure 4(a), while in figure 7(b) the command logic presented is for the current sense illustrated in Figure 4(b). The command logic will not be presented for the backup modes because they are similar to the ones presented for the normal modes. In the backup mode, the battery charger is disabled; therefore switch $S_2$ is not turned on during this mode.




(a)

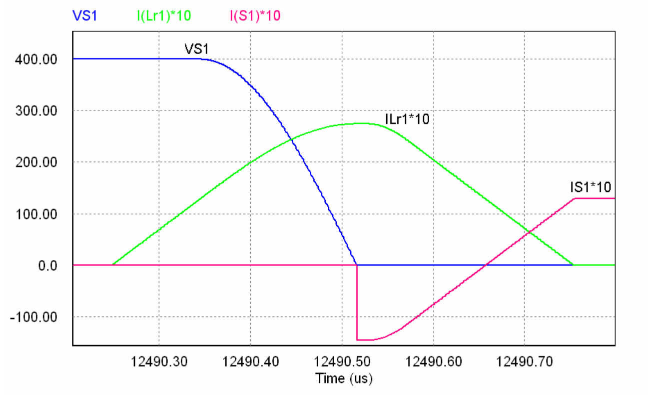



(b)

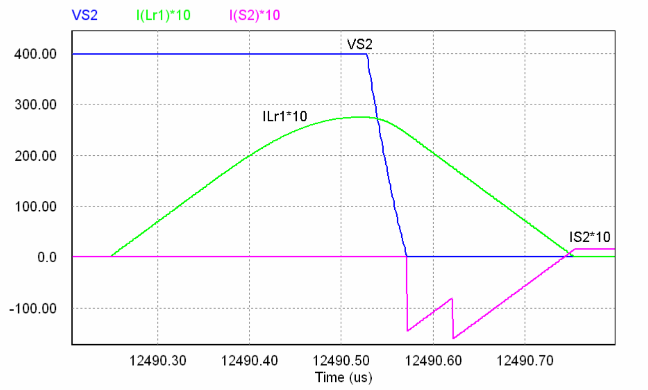
Fig. 7. Command logic. (a) Normal mode: the load current has the sense illustrated in Figure 4(a), (b) Normal mode - the load current has the sense illustrated in Figure 4(b).

In Figure 8 it is presented the commutation process for the system operating in the normal mode and when the load current has the sense illustrated in Figure 4(a). As mentioned, the iACC must be designed for the critical case in order to assure soft-switching for all switches. Figure 8 shows the ZVT commutation process of the main switches $S_1$, $S_2$ and $S_3$, for the normal mode in the critical situation, that is, when the system operates with the current sense given for figure 4(a), with a commutation of the boost type and two commutations of the buck type; Figure 8(a) illustrates the commutation of the main switch $S_1$ (boost), 8(b) the commutation of the $S_2$ switch (buck); 8(c) the commutation of the $S_3$ switch (buck).

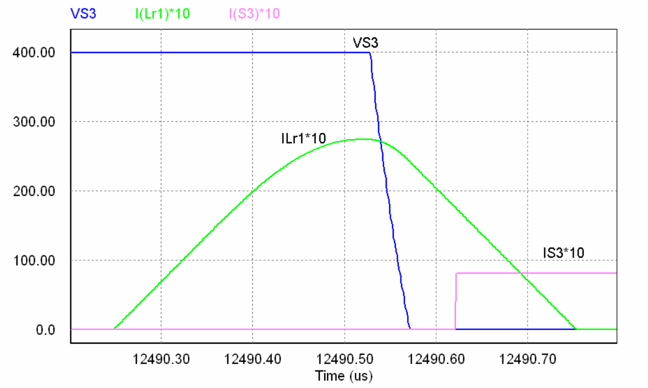
In Figure 9 are presented the results of the commutation process for the normal mode, this time, the sense of the load current is shown in Figure 4(b). In this operation mode two commutations of the boost type assist a commutation of the




(a)




(b)



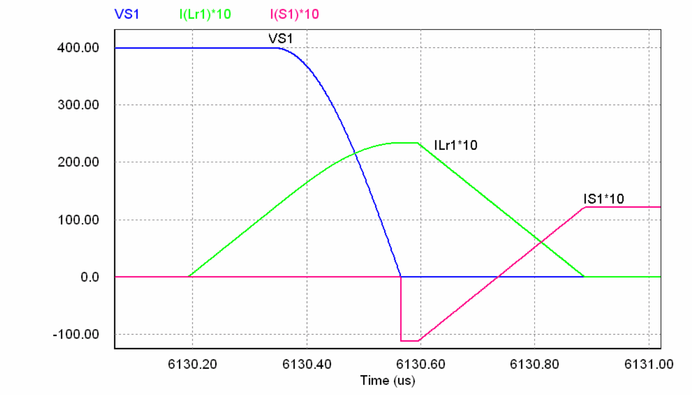

(c)

Fig. 8. Simulation results. Turn-on of: (a) Switch $S_1$, (b) Switch $S_2$, (c) Switch $S_3$.

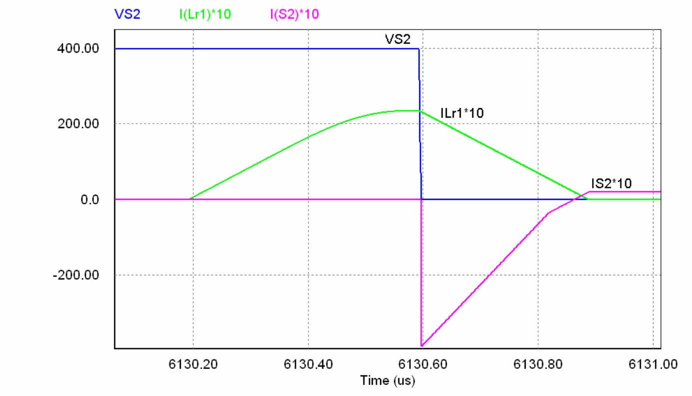
buck type. In Figure 9(a) it is shown the commutation of the main switch $S_1$ (boost), 9(b) the commutation of the switch $S_2$ (buck); 9(c) the commutation of the switch $S_4$ (boost), which occurs under ZVT. The commutations of the switches $S_5$ and $S_6$ are shown in Figure 10. These commutations occur in the same way independent of the operation mode and of the current sense.

The switches $S_5$ and $S_6$ present independent ACC for the accomplishment of the soft-switching. These commutations are shown in figures 10(a) and 10(b), respectively.

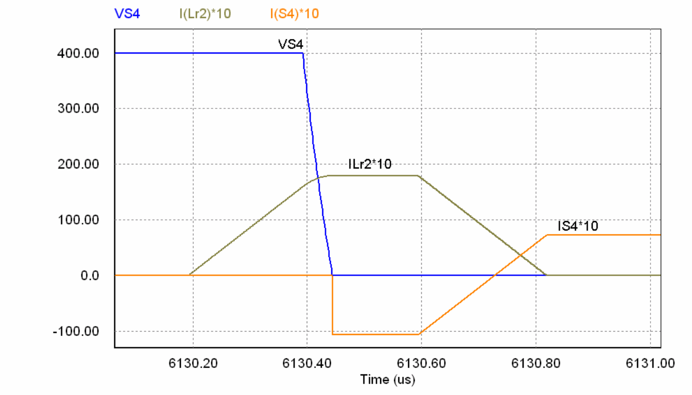
Figure 11 presents the simulation results for the auxiliary switches. In figure 11(a) the voltage and current for the switch $Sa_1$ are shown and its commutation is of the ZCS type. In Figure 11(b) the voltage and current for the switch $Sa_2$ are shown, and its commutation is of the ZVS type,




(a)

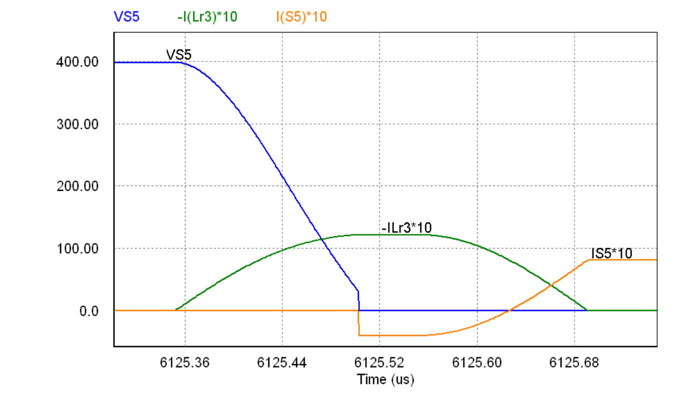



(b)

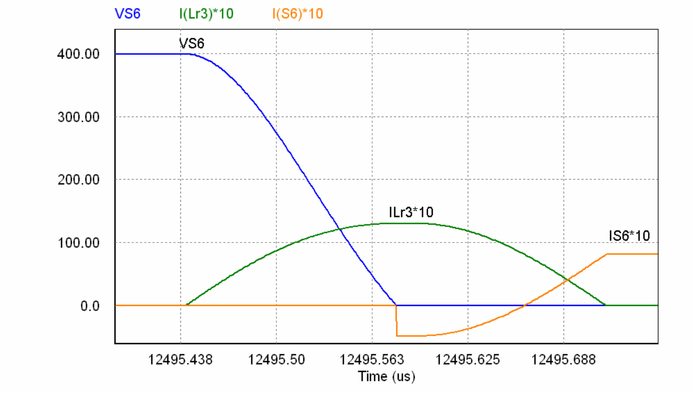



(c)

Fig. 9. Simulation results. Turn-on of: (a) Switch $S_1$; (b) Switch $S_2$; (c) Switch $S_4$.

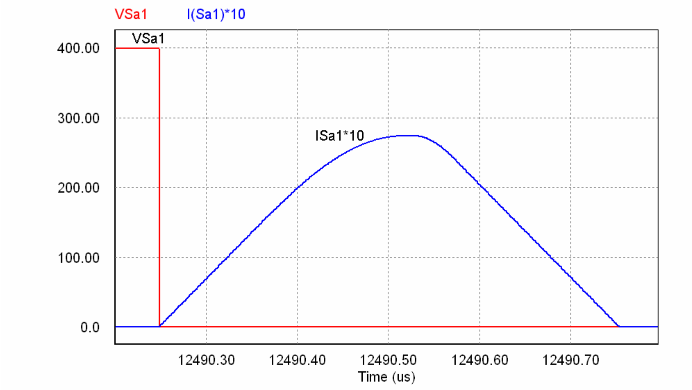



(a)

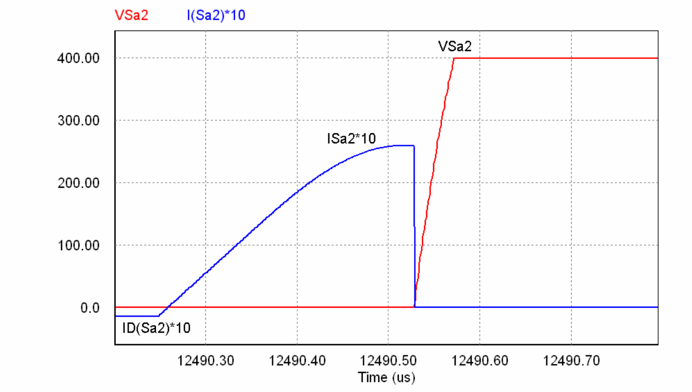



(b)

Fig. 10. Simulation results. Turn-on of (a) Switch $S_5$; (b) Switch $S_6$.




(a)

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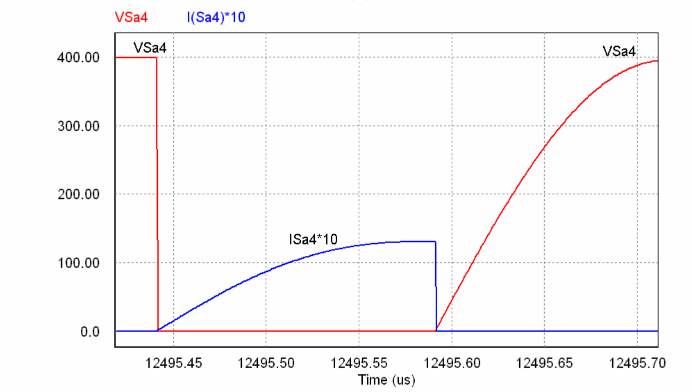


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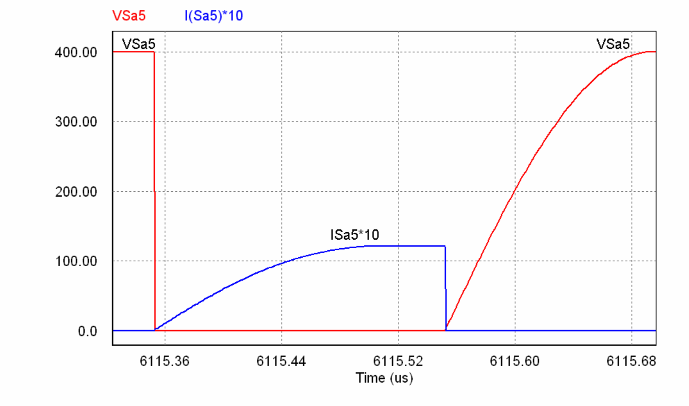


(d)

Fig. 11. Simulation results. Auxiliary switches (a) Switch $Sa_1$, (b) Switch $Sa_2$, (c) Switch $Sa_4$, (d) Switch $Sa_5$.

assured by the conduction of diode $D_{buck}$. In figures 11(c) and 11(d) are shown the voltage and current waveforms for the switches $Sa_4$ and $Sa_5$, and the commutation is of the ZVS type. The switches *Sa4* and *Sa5* are part of the ACC of the right leg of the inverter. Furthermore, the voltage across *Sa3* is approximately zero, because $VS2 \cong VS3$ on this commutation process.

The results for the backup mode will not be presented because they are similar to the ones presented for the normal mode. In the backup mode, the battery charger is disabled, operating only as an auxiliary circuit for the other converters and the preregulator converter operates as a DC-DC converter, using the battery bank as the input voltage source.

## V. CONCLUSION

By using the iZVT topology, a significant reduction in the number of additional elements necessary to obtain soft-switching is achieved. In this way, the efficiency can be increased keeping the reduced volume.

The iZVT was applied in a double-conversion UPS in order to demonstrate the integration principle, the ZVT circuit presented in [6] was chosen since it is the one with less additional elements, to has an easier design and it is spread both in the academicals world and in the industry.

The iACC is composed by only three resonant inductors, five auxiliary diodes and five auxiliary switches, for the accomplishment of soft-switching of the ZVT type for the main switches, without current or voltage stresses; besides, it accomplishes soft-switching of the ZCS type or ZVS type for the auxiliary switches. For a UPS operating with a Three-Level PWM inverter it is obtained a reduction of the volume of the filters, if compared to the same UPS operating with a Two-Level PWM inverter.

It is obtained a significant reduction in the number of additional elements when compared to the same system using independent ZVT circuits [6]. Another advantage regards to the commutations of the auxiliary switches, which are: ZCS or ZVS, reducing the commutation losses in these switches. Finally, the intrinsic anti-parallel diode of main switch $S_{a2}$ (MOSFET) can be used as the main diode ($D_2$) of the battery charger, reducing even more the costs of the system as a whole. The operation of the double-conversion UPS with the iACC considered was detailed, as well as its command logic for the operation in the normal mode operating with a Three-Level PWM inverter.

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