TWO NEW INTEGRATED ZVT CELLS FOR INPUT STAGES OF DOUBLE-CONVERSION UPS'S

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***Abstract* – This paper proposes two new integrated ZVT auxiliary commutation cells to assist three converters (preregulator, battery charger and backup converter) that compose the input stage of several UPS's. The proposed cells are based on two distinct principles, where the zero voltage switchings of all semiconductors of the UPS input stages are achieved using only one resonant inductor with reduced volume. By integrating these cells it is possible to reduce the number of power devices and, therefore, the overall system cost. The description of these principles and their application to sixteen different UPS input stages are presented,. Experimental results based on a 1kW@100kHz prototype are presented to validate the operation principles of the proposed integrated ZVT auxiliary commutation cells.**

KEYWORDS

UPS, Soft Switching, ZVT, Battery Charger and preregulator.

I. INTRODUCTION

Uninterruptible power systems (UPS) have been spreading in all world due to increasing number of critical loads. In this way, the number of different UPS models increased significantly, requiring efforts of several research groups and government entities to standardize this crescent market. Among several standards, it is interesting to highlight the standard IEC 62040-3, which classifies UPS's in three types: passive-standby, line-interactive and double-conversion. Among these three groups, the double-conversion UPS's presents a superior performance that is usually indispensable for critical loads.

These UPS's are composed of a preregulator and a dc-ac inverter between utility grid and critical load. In addition, they must be able to recharge the battery bank when necessary, and, in the event of a utility power failure, to guarantee the power supply from batteries to the critical load. Therefore, double-conversion UPS's have at least four subsystems (power converters), as shown in Fig. 1: preregulator, battery charger, backup converter and an inverter. These four subsystems can be integrated, reducing the number of power devices that compose the overall system.

A special attention should be given to preregulator converter, because the standards relating to the harmonic content of the injected utility grid current are more severe (IEC 61000-3-2). Among several single-phase preregulator topologies, the boost converter has been more used for power factor correction [1], [2], by its simple structure, low cost and easy control.

In addition, UPS manufacturers and researchers have been accompanied the world trend to reduce volume, weight and size of electronic equipments. A simple manner to reduce significantly the volume of the magnetic elements present in UPS's, and improve the dynamic response of these UPS's, is to increase the switching frequency of the converters that compose each subsystem. However, auxiliary commutation cells should be included to avoid the reduction of the efficiency and the increasing of the EMI (Electromagnetic Interference) [3], [4]. As each UPS has many converters, several auxiliary commutation cells would be necessary [5], which would increase the cost and would make difficult their application in UPS's.

This paper proposes two new integrated ZVT (Zero Voltage Transition) auxiliary commutation cells (IACC) to assist three converters (preregulator, battery charger and backup converter) that compose the input stage of several UPS's. The proposed cells are based on two distinct principles, where the zero voltage switchings of all semiconductors of the UPS input stages are achieved using only one resonant inductor with reduced volume. By integrating these cells it is possible to reduce the number of power devices and, therefore, the overall system cost. The description of these principles and their application to sixteen different UPS input stages are presented, using the proposed integrated ZVT cells. Experimental results based on a 1kW@100kHz prototype are presented to validate the operation principles of the proposed IACC's.

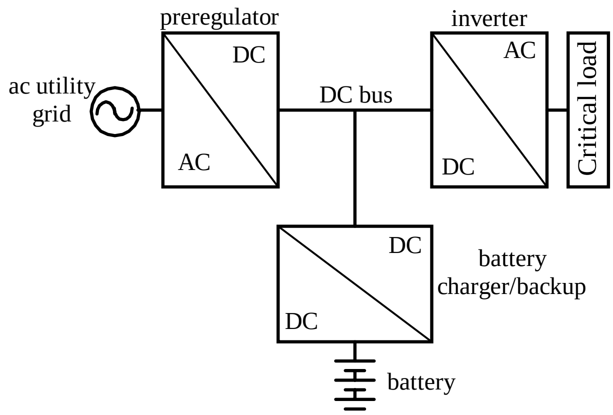


Fig. 1. Subsystems that compose a double-conversion UPS.

II. INPUT STAGE OF UPS'S

The input stage of an UPS is composed of three subsystems (preregulator, battery charger and backup converter) and it should present the following features:

- Power factor correction (PFC);
- Universal input (85 V_{RMS} – 265 V_{RMS});
- Flexibility in the choice of the battery bank voltage;
- Without low frequency current/voltage ripple in the battery bank charge process.

The preregulator converter should be able to correct the power factor for all input voltage range, where the boost converter operating in continuous conduction mode (CCM) has been more used for this application [1], [2]. In relation to the battery charger, it must be a step-down dc-dc converter (flexibility in the choice of the battery bank voltage level), where the output voltage has the same polarity of the input voltage of this converter. Therefore, there are several dc-dc converter topologies with these features, and the designer should define which converter is the best one for his application. With the inclusion of this converter for dc bus and battery bank interface it is possible to eliminate low frequency ripples (120 Hz) in the battery bank charge process. On the other hand, the backup converter must be a step-up dc-dc converter, which could be the own preregulator converter [6].

III. PROPOSED INTEGRATED ZVT AUXILIARY COMMUTATION CELLS

The proposed IACC's can be applied to the input stage of several UPS's that present the features described in Section II, defining the boost converter as the preregulator converter. During the normal operation mode of double-conversion UPS's, the preregulator (boost) converter maintains the dc bus and, at the same time, the battery charger (step-down converter) operates to charge the battery bank. When the ac utility grid fails, the battery bank maintains the dc bus through the backup converter (step-up converter). Thus, the proposed IACC's should be able to achieve zero voltage switching in all main switches for the different operation modes. Two new IACC's are presented in the following subsections.

A. Cell I

The input current should be deviated for the auxiliary commutation cell to achieve the ZVT commutation of the preregulator (boost) main switch. With this, the resonant process is released, discharging the capacitor across the main switch. This energy deviated to the auxiliary commutation cell must be regenerated to the load [4] or to the input [7] at the end of the resonant process. Therefore, the principle for the integration of the preregulator and battery charger auxiliary commutation cells is to use the energy accumulated at the end of the commutation process of the preregulator converter, which it would be regenerated, to achieve the zero voltage switching of the battery charger main switch, as illustrated in Fig. 2(a). The integrated ZVT cell responsible

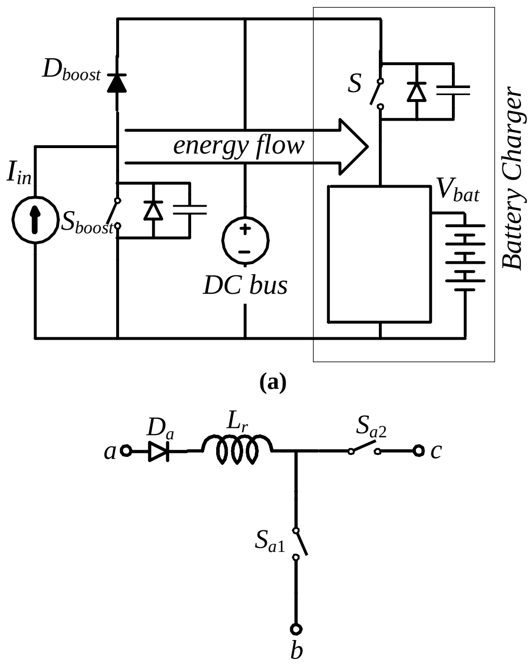


Fig. 2. Proposed IACC I: (a) Cell I principle; (b) Cell I.

for the commutation process described above is shown in Fig. 2(b), which is composed of two auxiliary switches (S_{a1} and S_{a2}), one auxiliary diode (D_a) and one resonant inductor (L_r).

This integrated ZVT cell is applied to UPS's input stages where the drain of the battery charger main switch is connected to the cathode of the boost diode and the commutation frequencies of the two converters are the same. The IACC I, presented in Fig. 2(b), is connected in the following way:

(i) Point "a" is connected to the drain of the preregulator main switch, if the switch is a MOSFET (collector if the switch is an IGBT);

(ii) Point "b" is connected to the ground of the preregulator converter;

(iii) Point "c" is connected to the source of the battery charger main switch, if this switch is a MOSFET (emitter if the switch is an IGBT).

B. Cell II

This principle is based on the fact that the commutations of the preregulator and battery charger main switches occur at the same time, as shown in Fig. 3(a), that is, only one inductor will resonate with two capacitors connected in parallel with the main switches (usually intrinsic capacitors) at the same time, discharging these capacitors. The cell responsible for this commutation process is presented in Fig. 3(b), which is composed of two auxiliary switches (S_{a1} and S_{a2}), three auxiliary diodes (D_{a1}, D_{a2} and D_{a3}) and one resonant inductor (L_r). This integrated ZVT cell is applied to UPS's input stages where the preregulator and battery charger main switches are connected to the same ground and the commutation frequencies of these converters are the same.

The IACC II, illustrated in Fig. 3(c), is connected in the following way:

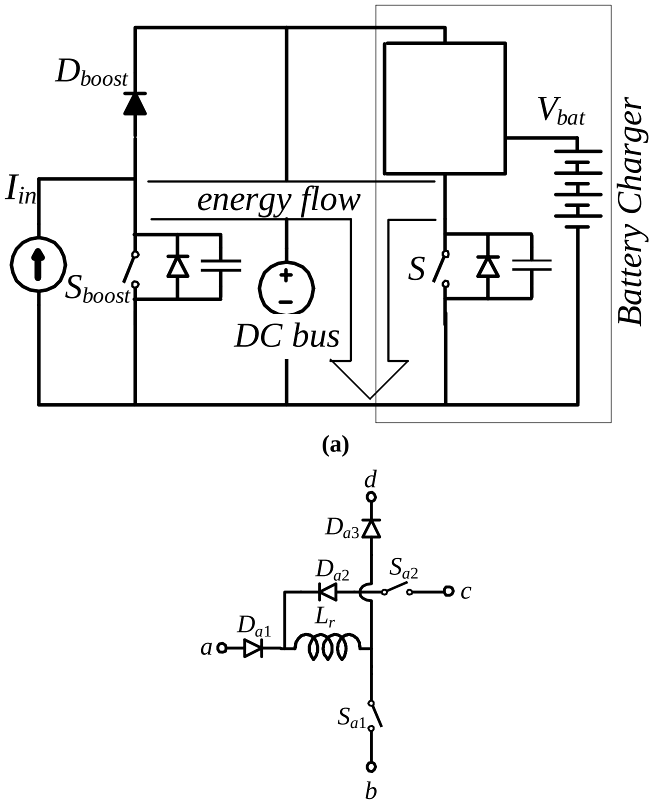


Fig. 3. Proposed IACC II: (a) Cell II principle; (b) Cell II.

(i) Point “a” is connected to the drain of the preregulator main switch, if this switch is a MOSFET (collector if this switch is an IGBT);

(ii) Point “b” is connected to the ground;

(iii) Point “c” is connected to the drain of the main switch battery charger, if this switch is a MOSFET (collector if this switch is an IGBT);

(iv) Point “d” is connected to the cathode of the boost diode, that is, connected to the positive terminal of the dc bus.

III. PROPOSED INPUT STAGES OF DOUBLE-CONVERSION UPS’S

This section presents several input stages of double-conversion UPS’s using the two IACC’s proposed in the previous section. It is important to point out that all main switches of these topologies operate under soft-commutation of ZVT type and the auxiliary switches operate with soft-commutation of ZVS (Zero-Voltage Switching) and/or ZCS (Zero-Current Switching) types. In addition, the proposed IACC’s employ only one resonant inductor with reduced volume (low average and rms current levels) and the power devices of these cells are not subjected to voltage stresses.

A. Topologies using the IACC I

In Fig. 4 is presented the input stage of a double-conversion UPS where the preregulator converter (boost) is also responsible by the backup mode and a buck converter is the battery charger. This topology is largely used by industry due to its low cost, but the preregulator design is more complex due to the fact that the input voltage of this converter can be the rectified utility grid voltage or the dc voltage supplied by the battery bank. As the drain of the battery charger main switch is connected to the cathode of the boost diode, the IACC I has been included as described in Section III and shown in Fig. 4(a). Moreover, three variations of the IACC I are presented in Fig. 4(b), (c) and (d). It is important to point out the topology illustrated in (c), which presents low number of power devices, the switch S_{a1} operates under soft-commutation of ZVS type making possible the use of a low cost MOSFET and, therefore, the diode D_{Sa1} and the switch S_{a1} are just one device (MOSFET). Fig. 5 illustrates the main theoretical waveforms that show the ZVT commutation of the main switches of the topologies presented in Fig. 4, where I_{in} is the maximum value of the input current and V_0 is the dc bus voltage level.

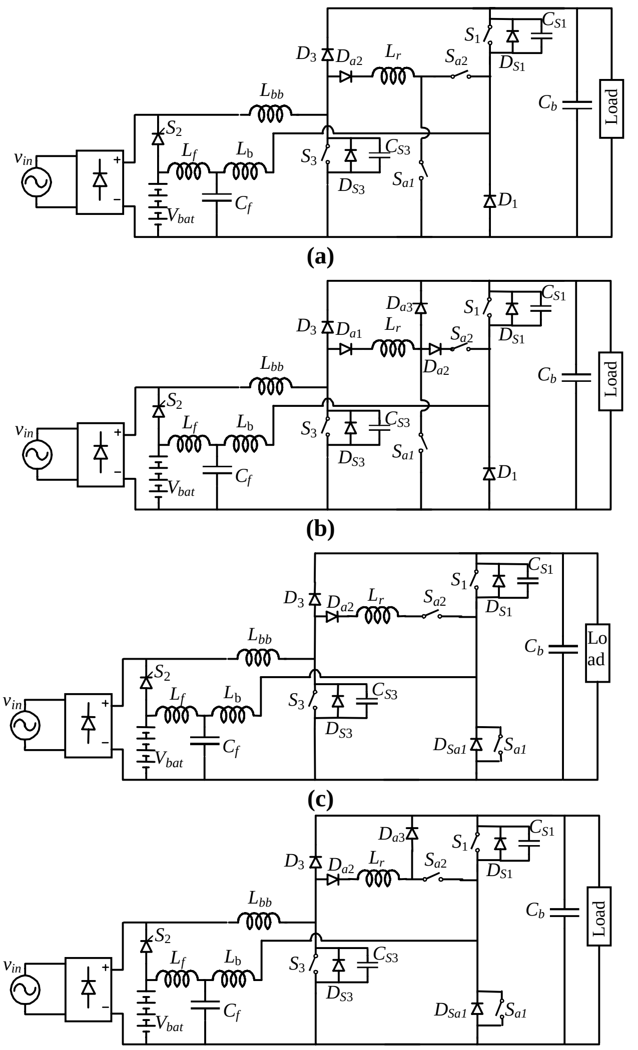


Fig. 4. Proposed topologies using the buck converter as battery charger: (a) Topology 1; (b) Topology 2; (c) Topology 3; (d) Topology 4.

Another proposed input stage of a double-conversion UPS that uses the IACC I is presented in Fig. 6, where the zeta converter (non-isolated is depicted in Fig. 6(a) and isolated is shown in Fig. 6(b)) is used as battery charger.

An input stage composed of a preregulator converter and a bidirectional converter for dc bus and battery bank interface,

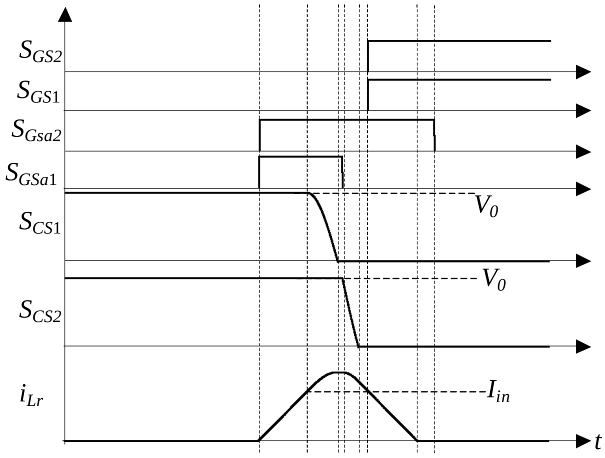


Fig. 5. Main theoretical waveforms of the commutation process of the circuits presented in Fig. 4.

using the IACC I, has been presented in [8]. It is not necessary to include the auxiliary switch S_{a1}, because one main switch of the bidirectional converter can be used as auxiliary switch. On the other hand, it is necessary to include a diode and a switch to achieve soft-commutation during the backup mode. Another variation of this circuit has been published in [9].

B. Topologies using the IACC II

This section presents input stages of double-conversion UPS's where the preregulator and battery charger main switches are connected in the same ground. In this way, the IACC II can be employed. Fig. 7 shows the proposed topologies, using the forward converter (Fig. 7(a)), the flyback converter (Fig. 7(b)), the SEPIC converter (Fig. 7(c)) or the isolated SEPIC converter (Fig. 7(d)) as the battery charger.

The main theoretical waveforms of the main switches soft-commutation process of the topologies presented in Fig. 7(c) and (d) are shown in Fig. 8, where D is the duty cycle. The voltage stress on the battery charger main switch is natural from these topologies (forward and flyback converters) and it

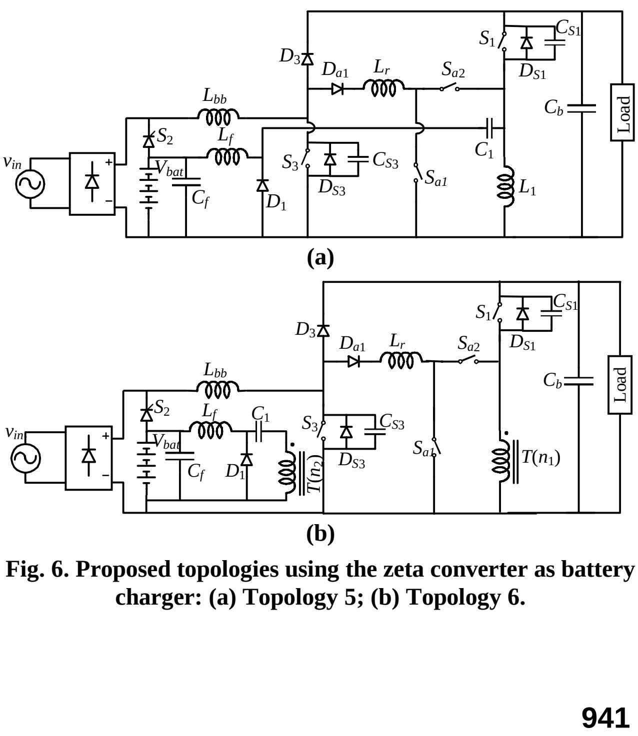


Fig. 6. Proposed topologies using the zeta converter as battery charger: (a) Topology 5; (b) Topology 6.

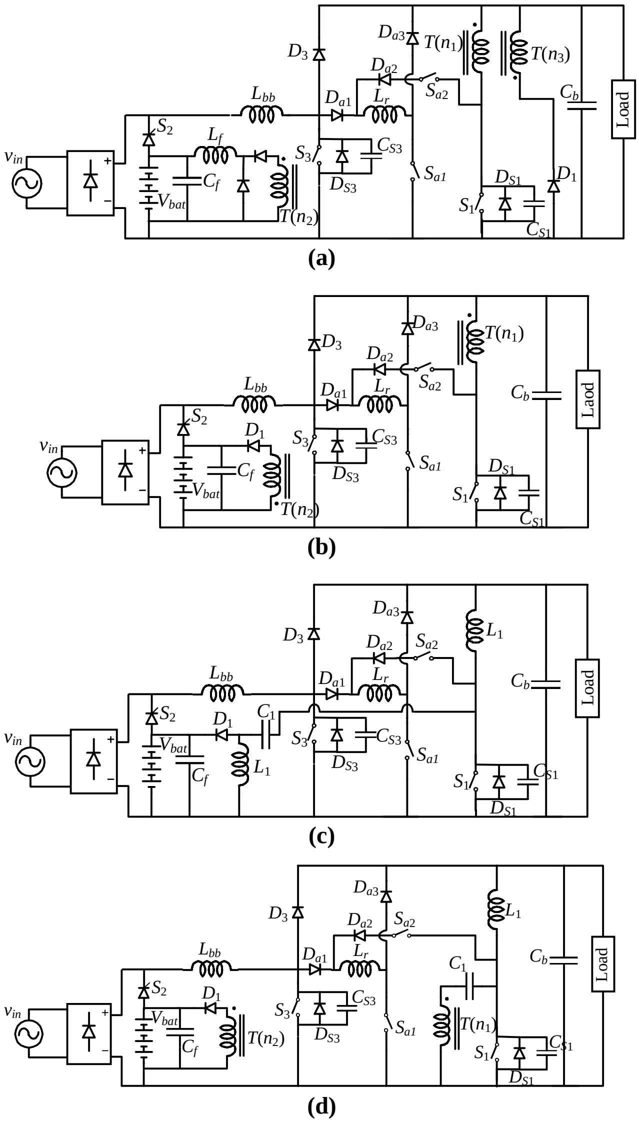


Fig. 7. Proposed topologies that using as battery charger the converter: (a) Forward (topology 7); (b) Flyback (topology 8); (c) Sepic (topology 9); (d) Isolated Sepic (topology 10).

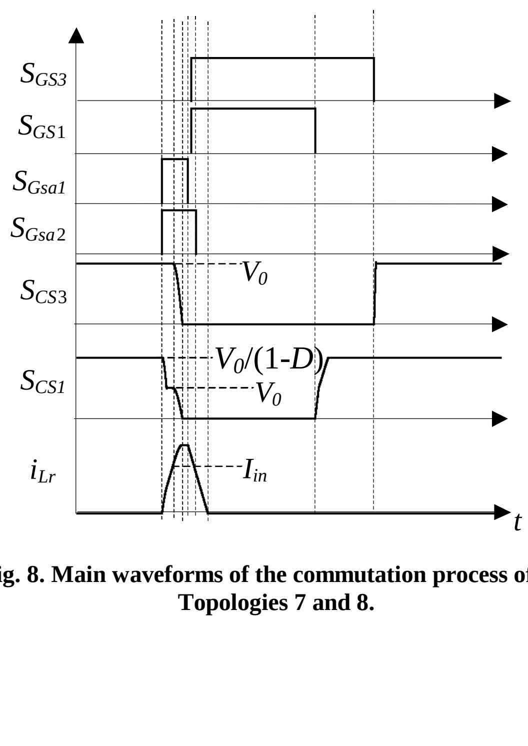


Fig. 8. Main waveforms of the commutation process of the Topologies 7 and 8.

not caused by the inclusion of the IACC.

C. Topologies using the IACC I and II

This subsection presents input stages of UPS's in which the battery charger topology employs more than one main switch. In these cases, it will be necessary to use variations of the two proposed IACC's.

Fig. 9 presents the proposed topologies, where the forward converter with two switches (Fig. 9(a)), the flyback converter with two switches (Fig. 9(b)), the push-pull converter (Fig. 9(c)) or the half-bridge converter (Fig. 9(d)) are used as battery chargers.

The main theoretical waveforms of the main switches soft-commutation process of the topologies presented in Fig. 9(a) and (b) are shown in Fig. 10. Finally, for the correct operation of the topologies proposed in Fig. 9(c) and (d) it is necessary that the commutation frequency of the preregulator converter is twice the battery charger commutation frequency.

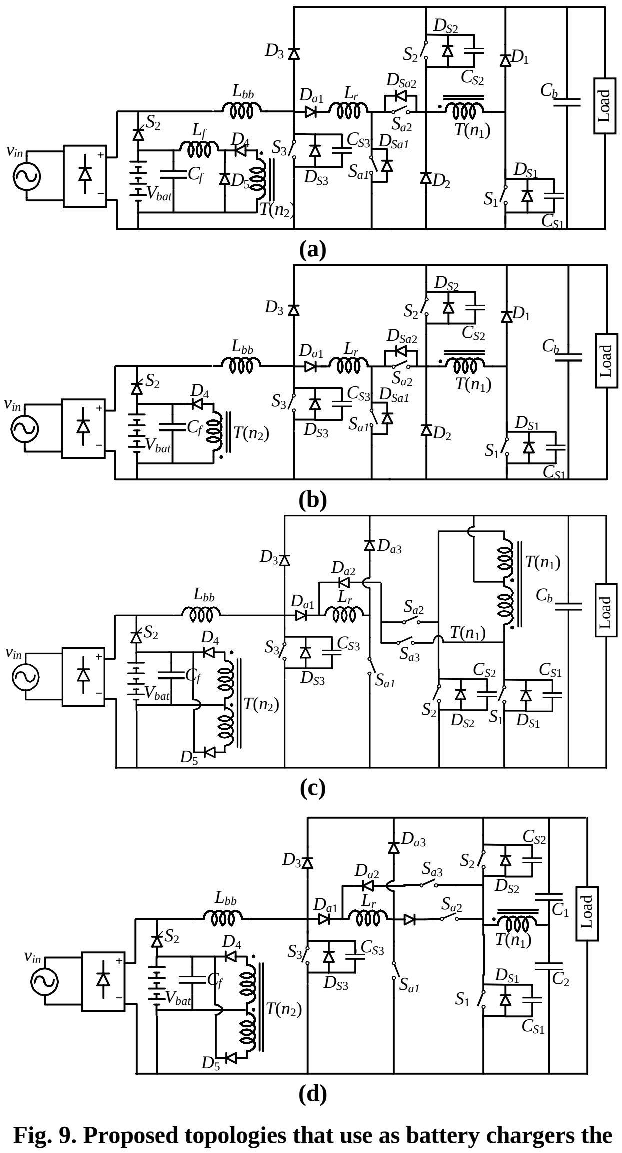


Fig. 9. Proposed topologies that use as battery chargers the converter: (a) Forward with two switches (topology 11); (b) Flyback with two switches (topology 12); (c) Push-pull (topology 13); (d) Half-bridge (topology 14).

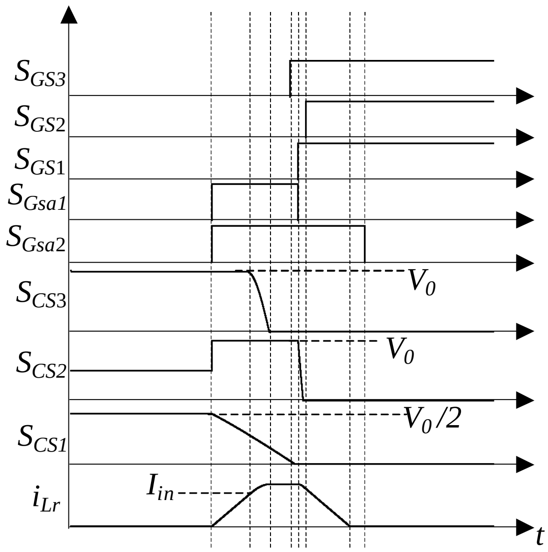


Fig. 10. . Main waveforms of the commutation process of the Topologies 11 and 12

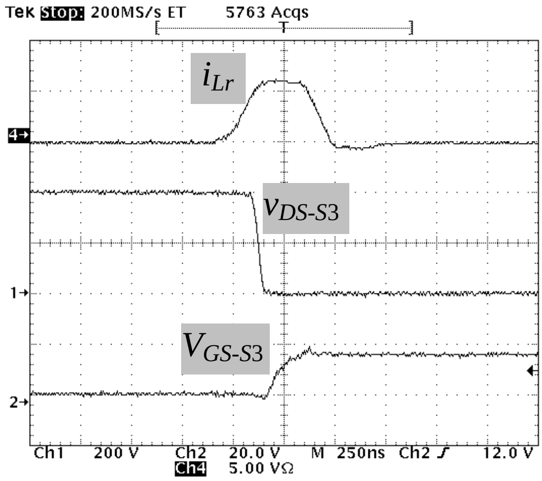
IV. Experimental Results

The topology 3 (Fig. 4(c)) has been chosen to be implemented among the proposed input stages, to demonstrate the soft-commutation process of all switches. This input stage has been widely used by the industry and the number of additional elements to achieve soft-commutation is small. The design procedure of this input stage is similar to that presented in [9]. The parameters of the experimental setup are shown in Table I.

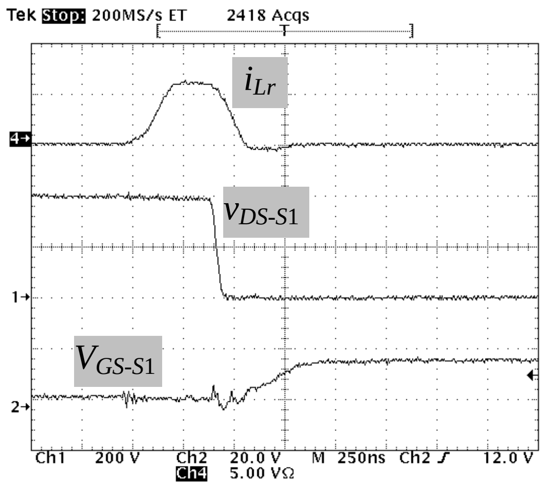
TABLE I
PARAMETERS OF THE EXPERIMENTAL SETUP.

Input Voltage	V_{in} = 84V_{rms}-265V_{rms} V
Output voltage	V_0 = 400V
Battery bank voltage	V_{bat} = 120V
Output power	P_0 = 1kW
Switching Frequency	f_s = 100kHz
Buck inductor	L_b = 5mH
Boost capacitor	C_b =500μF
Boost inductor	L_{bb} = 375μH
Resonant inductor	L_r = 9μH
Capacitor C_{S3}	C_{S3} =1.5nF
Switches S_1, S_3, S_{a2}	MOSFET IRFP450
Switch S_{a1}	IGBT G4BC20W
Diodes D_2, D_{a2}	MUR 1560

Figs. 11 and 12 show experimental results of the soft-commutation process when the converter is operating in the normal mode. Fig. 11(a) presents the voltage waveform across the main switch S_3, its respective command signal and the resonant inductor current. On the other hand, Fig. 11(b) illustrates the voltage across the switch S_1, its command signal and the current through the resonant inductor. Therefore, from Fig. 11 it is possible to verify the ZVT commutation of the main switches in the normal mode.



(a)

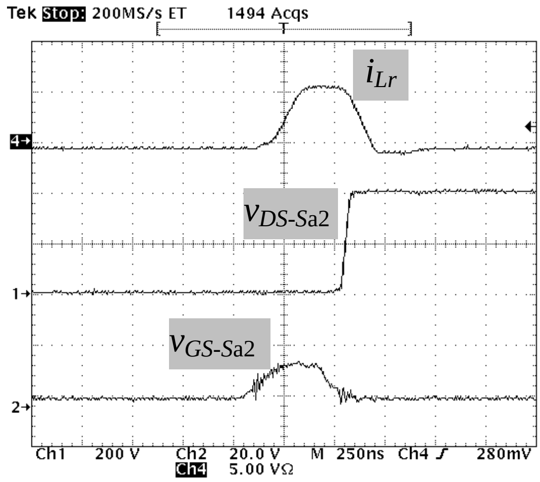


(b)

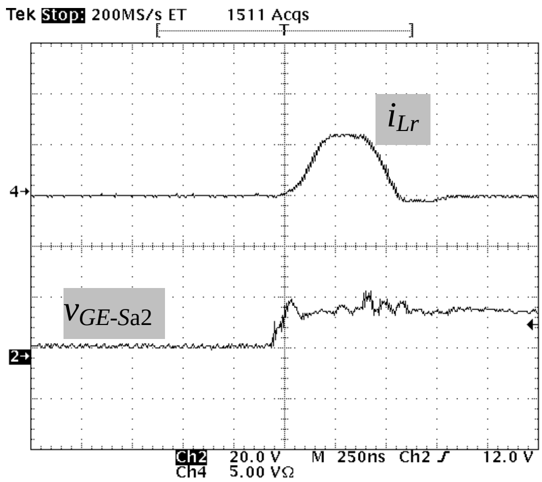
Fig. 11. Soft-commutation (ZVT) of the main switches in the normal mode: (a) Switch S_3; (b) Switch S1.

Fig. 12 shows experimental results obtained to verify the soft-commutation of auxiliary switches S_{a1} and S_{a2} in the normal mode. Fig. 12(a) presents the voltage waveform across the switch S_{a2} and its command signal, illustrating the ZCZVS turn-on and ZVS turn-off. Fig. 12(b) shows the command signal of the switch Sa_1 and the current through this switch, demonstrating its ZCS commutation.

Figs. 13 and 14 show experimental results obtained to verify the soft commutation of the switches in the backup mode. Fig. 13 presents the voltage waveform across the switch S_3, its respective command signal and the current through the resonant inductor L_r. From these waveforms, it is possible to verify the ZVT commutation of main switch S_3. On the other hand, Fig. 14 depicts the voltage waveform across the auxiliary switch S_{a2}, its command signal and the current through the inductor L_r. These waveforms show the ZCS turn-on and ZVS turn-off of the auxiliary switch S_{a2}. The waveforms related to the soft-commutation process of the auxiliary switch S_{a1} in this mode are not presented, because the waveforms are very similar to that obtained in the normal mode (Fig. 12(b)).



(a)



(b)

Fig. 12. Soft-commutation of the auxiliary switches in the normal mode: (a) Switch S_{a2}; (b) Switch S_{a1}.

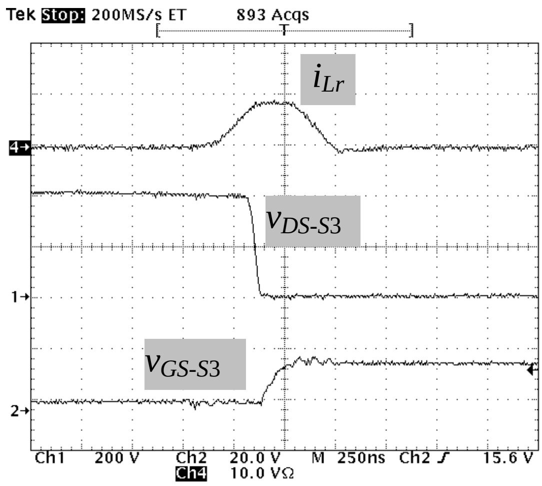


Fig. 13. Soft-commutation (ZVT) of the main switch S_3 in the backup mode.

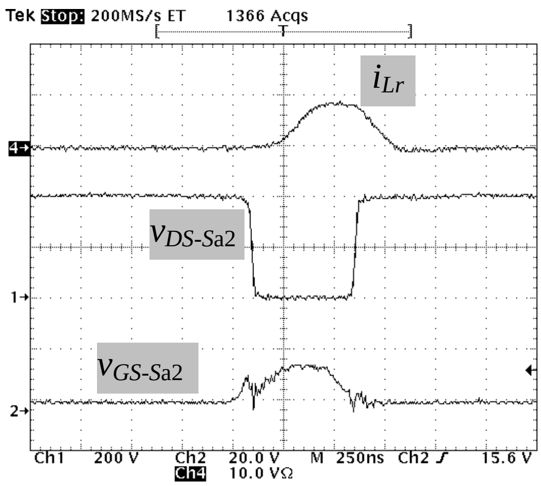


Fig. 14. Soft-commutation of the auxiliary switch S_{a2} in the backup mode: ZCS turn-on and ZVS turn-off.

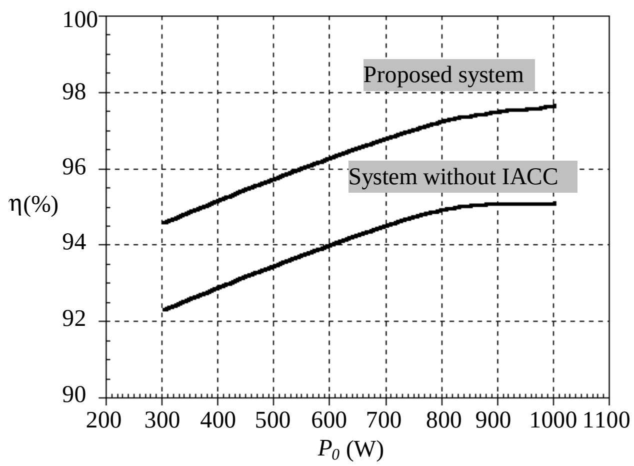


Fig. 15. Efficiency comparison in the backup mode.

The efficiency of the proposed system during the backup mode is presented in Fig. 15, where the maximum efficiency is 97.7% (full-load and V_{bat}=120V). This value is around 2.3% greater than the efficiency of the converter without the IACC, consequently, the autonomy of the battery bank is increased.

V. CONCLUSIONS

Two new integrated ZVT auxiliary commutation cells have been proposed, which present only one resonant inductor with reduce volume to achieve soft-commutation of ZVT type in the main switches in all operation modes and the auxiliary switches operate under soft-commutation of ZVS and/or ZCS types, without voltage stresses. Consequently, the overall system presents high efficiency, increasing the autonomy of the battery bank. By integrating these cells it is possible to reduce the number of power devices and, therefore, the system cost. A methodology to define which IACC has been introduced and how include it in the main circuit has been presented. In addition, sixteen input stages of double-conversion UPS's have been generated using the proposed IACC's. Experimental results based on a 1kW@100kHz prototype are presented to validate the operation principles of the proposed IACC's.

REFERENCES

[1] García, O., Cobos, J.A., Prieto, R., Alou, P., Uceda, J., "Power Factor Correction: A Survey" in *IEEE Power Electronics Specialists Conference*, pp.8-13, 2001.

[2] Liu, J., Chen, W., Zhang, J., Xu, D., Lee, F.C., "Evaluation of Power Losses in Different CCM Mode Single-Phase Boost PFC Converter via a Simulation Tool", in *IEEE Industry Applications Conference*, pp. 2455-2459, 2001.

[3] Smith, K. M., Smedley, K.M., "A Comparison of Voltage-Mode Soft-Switching Methods", in *IEEE Trans. on Power Electronics*, Vol. 12, n.2, pp. 376-386, 1997.

[4] Hua, G., Leu, C.-S., Lee, F. C., "Novel Zero-Voltage-Transition PWM Converters", in *IEEE Power Electronics Specialists Conference*, pp. 55-60, 1992;

[5] Xinxiang, Y., Seckold, A., Patterson, D., **"**Development of a zero-voltage-transition bidirectional dc-dc converter for a brushless dc machine ev propulsion system**",** *in IEEE Power Electronics Specialists Conference*, pp. 1661–1666, 2002.

[6] Ho, W., Lin, M., Feng, W., "A New Single-Phase On-line UPS Structure Pre-staged with PFC-and-Boost Converter", *in IEEE Power Electronics and Drive Systems*, pp.133-138, 1997.

[7] Filho, N. P., Farias, V. J., Freitas, L. C., "A Novel Family of DC-DC PWM Converters Using the Self-Resonance Principle", *in IEEE Power Electronics Specialists Conference*, pp. 1385-1391, 1994;

[8] L. Schuch, C. Rech, H. L. Hey, H. Pinheiro, H. A. Gründling, J. R. Pinheiro "Analysis and design of a new high-efficiency bi-directional ZVT PWM converter for DC bus and battery bank interface," in *IEEE Applied Power Electronics Conference*, pp. 567-573, 2002.

[9] L. Schuch, C. Rech, H. L. Hey, H. Pinheiro, H. A. Gründling, J. R. Pinheiro "A Battery ZVT Bi-Directional Charger for Uninterruptible Power Supplies," in *IEEE Power Electronics Specialists Conference*, pp. 1841-1846, 2002.