PFC PRE-REGULATORS WITH HIGH FREQUENCY ISOLATION

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Abstract – This paper proposes PFC pre-regulators with high frequency isolation transformer using both half-bridge and full-bridge choppers for applications in double conversion UPS systems. They are suitable for rack type structure because they have a compact size and reduced weight. Compared to other converters revisited in literature, the proposed circuits present the following characteristics: conventional control used in both stages, few batteries in series are required due to step-up stage, and soft commutation is achieved in the chopper switches. Qualitative analysis, design example and experimental results obtained from 1.6kW prototype are presented.

***Keywords* – High frequency Isolation, AC-DC Converters, On-line UPS systems, PFC converter, soft commutation.**

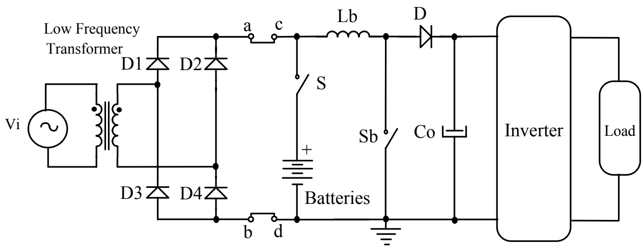
I. INTRODUCTION

The first UPS topologies were developed during the 1970's using phase-controlled rectifiers and low frequency transformers. The battery bank, composed by batteries connected in series, was connected directly to the dc link of the controlled rectifier and charged with pulsed currents causing lifetime degradation. Other disadvantages of such equipments were increased weight and size due to the low frequency transformer, harmonic current injection in the ac mains and audible noise [1, 2].

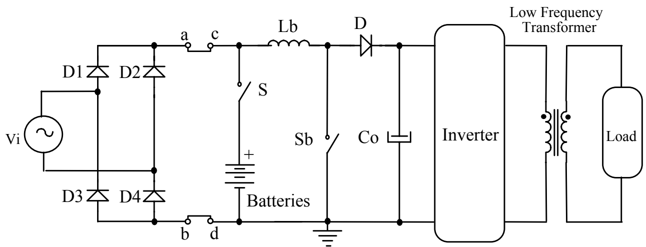
In order to overcome weight and size limitations, with the evolution of semiconductors, several architectures of high frequency isolation UPS's were proposed in [2-7]. In [2-4], the pre-regulator stages are current fed full-bridge circuits that have as advantages, power factor correction, and high frequency isolation, and as disadvantages, hard commutation of the controlled switches, complex control due to absence of dedicated integrated circuits, and many batteries in series to achieve the high bus dc voltage. The addition of batteries also implies increased cost, mainly in low power processing. The series-parallel resonant system proposed in [5] presents as advantages, soft commutation of the switches, power factor correction, and few batteries in series, and as disadvantages, complex control for the same reason explained previously, and adjustment of the resonant parameters.

The UPS circuits shown in Fig. 1 with power factor correction and separate battery charger have been developed recently by several industries in Brazil. Isolation is obtained in the input or in the output by using low frequency transformers. A relevant feature of low frequency isolation UPS systems lies in high efficiency, because it does not require additional converters to convert low frequency voltages or dc voltages to high frequency voltages in order to use high frequency transformers. A disadvantage of such systems are due to increased weight and size.

In this work, two pre-regulator circuits, which can be supplied with 220V, are proposed. The features of the circuits are soft commutation of the controlled switches avoiding snubber circuits and EMI problems, power factor correction, high frequency isolation, use of well-known conventional PWM control techniques, and few batteries in series due to step-up stage. A disadvantage of this system is the existence of two power stages that barely affects efficiency. The main idea of using chopper circuits in cascade with boost converters was obtained from [9].



(a)



(b)

Fig. 1. Double conversion UPS with low frequency transformer connected to (a) the input, and to (b) the output.

A. Proposed pre-regulator topologies

B. Description of The Circuits

The pre-regulator configuration shown in Fig. 2 is composed of the following parts: full-bridge rectifier formed by diodes D_1-D_4; half-bridge chopper given by the controlled switches S_1-S_2, high frequency transformer T_r, commutation inductor L_r, rectifier diodes D_{r1}-D_{r2}; a classical boost circuit given by inductor L_b, switch S_b, diode D_b and capacitor filter C_o; and a high frequency input filter given by inductor L_f and capacitors C_{f1}-C_{f2}.

The chopper in Fig. 3 presents one additional half-bridge leg compared to the chopper shown in Fig. 2.

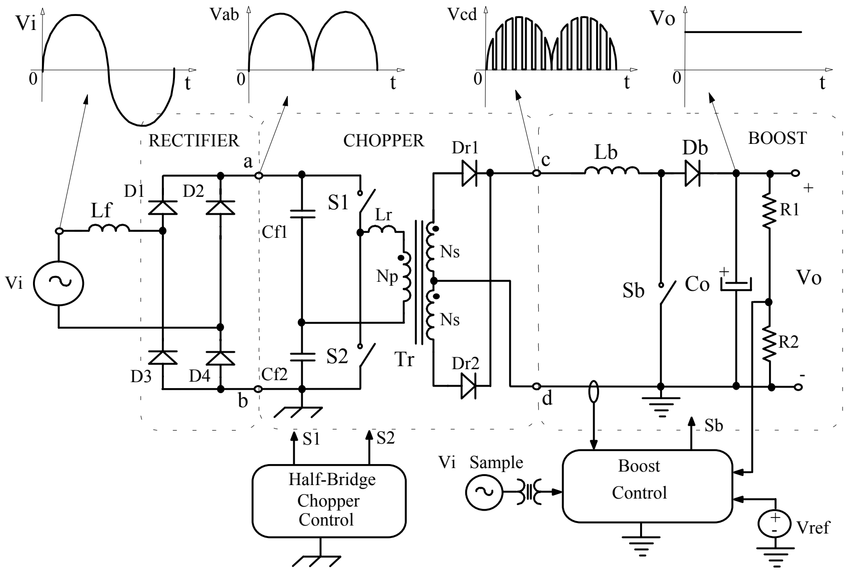


Fig. 2. Proposed pre-regulator circuit scheme with half bridge chopper.

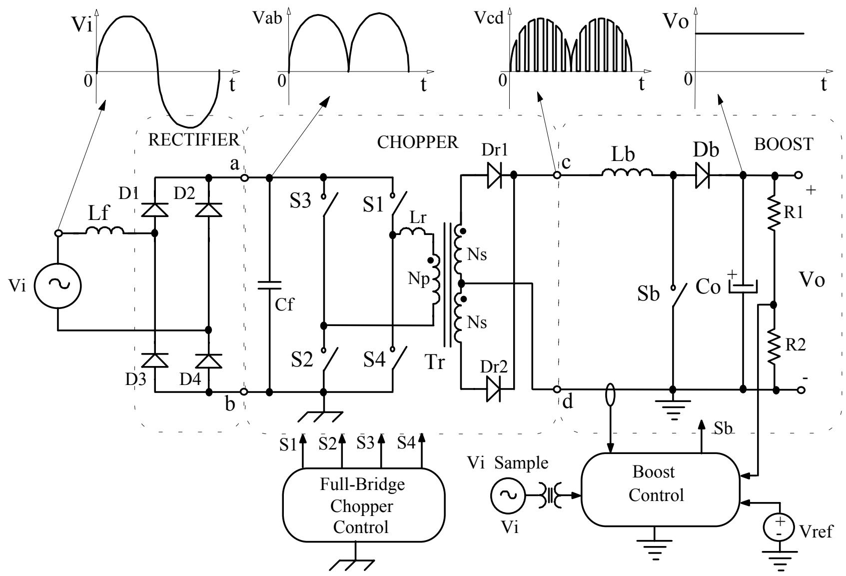


Fig. 3. Proposed pre-regulator circuit scheme with full bridge chopper.

II. HALF BRIDGE CHOPPER ANALYSIS

A. Principle of Operation

The chopper given in Fig. 2 is supplied by rectified sinusoidal voltage. The capacitor divisor is obtained using small filter capacitors C_{f1} and C_{f2}. The indicated voltage is transformed high frequency switching using an open loop PWM half-bridge chopper. Each switch of the chopper operates with duty cycle near 0.5. Then, the pulsating 120Hz voltage is converted to a high frequency one in order to enable the use of a high frequency transformer. In the secondary side of the transformer, the voltage is rectified by diodes D_{r1} and D_{r2} to supply a rectified voltage to the boost converter.

The chopper analysis is performed with the following assumptions:

➔ All semiconductors are ideal;

➔ The boost inductor current I_{Lb} is constant in a switching period;

➔ The input voltage is constant in a switching period;

➔ The magnetizing current of the transformer is null;

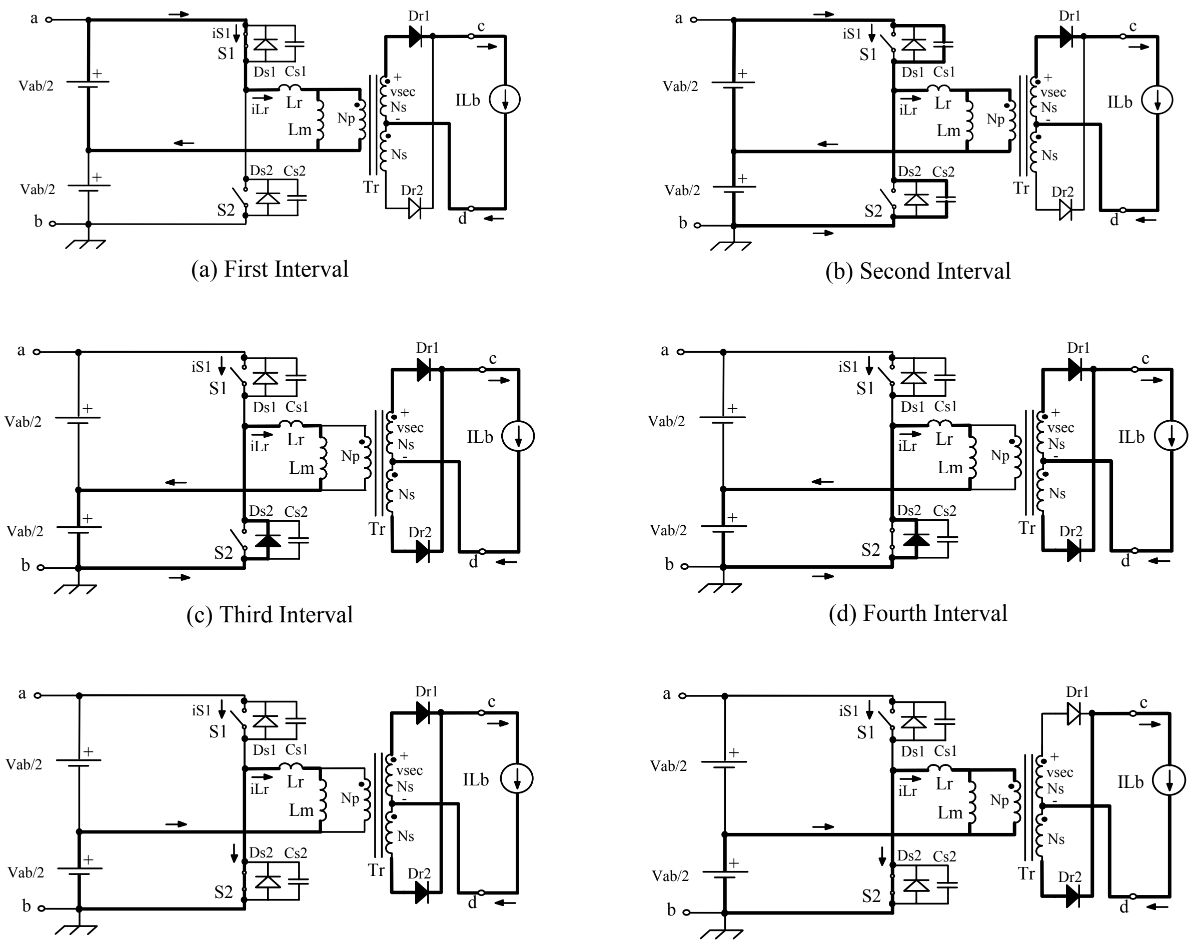
➔ The transformer leakage inductance is added to the commutation inductor L_r.

The chopper circuit presents five operating intervals within half a switching period. The intervals are described as follows and the relevant circuits indicating the current path along each interval are shown in Fig. 4.

• *First Interval (t_0, t_1):* Switch S_1 is turned on and energy transference from the input source $V_{ab}/2$ to the load occurs, through the high frequency transformer T_r and rectifier diode D_{r1}. Switch S_2 remains turned off and the voltage across it is V_{ab}. Rectifier diode D_{r2} is reversed biased. The interval finishes when switch S_1 is turned off under ZVS guaranteed by the intrinsic capacitance of the switch.

• *Second Interval (t_1, t_2):* Switches S_1 and S_2 are turned off. Capacitors C_{s1} and C_{s2} are charged and discharged, both with constant current $nI_{Lb}/2$, respectively. Therefore, the voltage transition is linear. The interval finishes when the voltage across capacitor C_{s1} is equal to V_{ab} and voltage across the capacitor C_{s2} is equal to zero.

- *Third Interval (t_2, t_3):* At instant t_2, the antiparallel diode D_{s2} is forward biased and allows the current through commutation inductor L_r to increase linearly. The output current i_{Lb} starts freewheeling through diodes D_{r1} and D_{r2} and through secondary windings. Switches S_1 and S_2 remain turned off.
- *Fourth Interval (t_3, t_4):* Switch S_2 is turned on under ZVS condition, since diode D_{s2} is directly biased. The interval finishes when the current through inductor L_r reaches zero. Additionally, output current i_{Lb} remains in freewheeling.
- *Fifth Interval (t_4, t_5):* At instant t_4, the current through inductor L_r changes its direction and varies linearly due to voltage $V_{ab}/2$ across it. Current i_{Lr} starts flowing through switch S_2 and output current i_{Lb} remains in freewheel mode. This interval finishes when current i_{Lr} is equal to $n*I_{Lb}$.
- *Sixth Interval (t_5, t_6):* The energy transference occurs as described in the first interval.



(a) First Interval (b) Second Interval

(c) Third Interval (d) Fourth Interval

(e) Fifth Interval (f) Sixth Interval

Fig. 4. Operating intervals of the proposed half-bridge chopper.

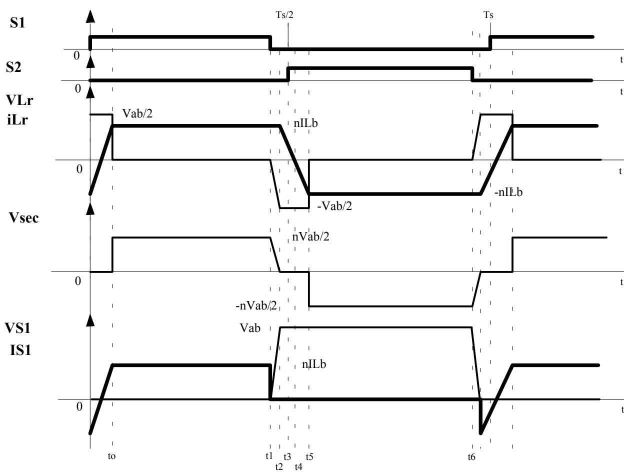


Fig. 5. Main waveforms of the half-bridge chopper.

III. FULL-BRIDGE CHOPPER ANALYSIS

A. Principle of Operation

The full-bridge chopper, like the half bridge chopper, is controlled in open loop with conventional PWM modulation. The fixed duty cycle of each switch is near 0.5.

The chopper presents five operation intervals in half a commutation period. The operation intervals are described as follows and the equivalent circuits, indicating the current path, are shown in Fig. 6.

- *First Interval (t_0, t_1)*: Energy is transferred to the load from the input source V_{ab} through turned on switches S_1 and

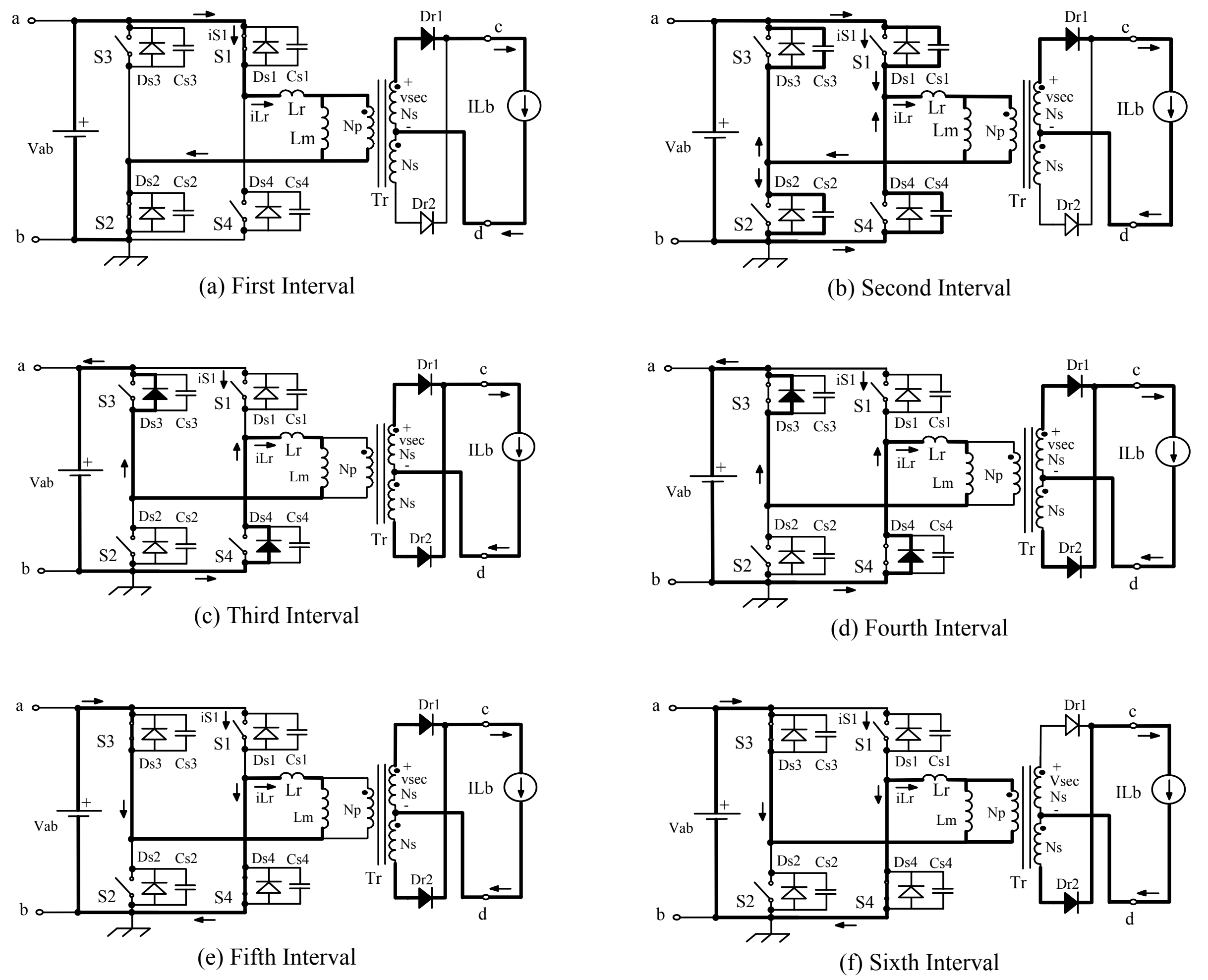


Fig. 6. Operating intervals of the proposed full-bridge chopper.

S_2, transformer T_r and rectifier diode D_{r1}. Switches S_3 and S_4 are turned off and the voltages across them are equal to V_{ab}. Rectifier diode D_{r2} is reverse biased. The interval finishes when switches S_1 and S_2 are turned off under ZVS commutation.

- *Second Interval (t_1, t_2):* Capacitors C_{s1} and C_{s2} are charged and capacitors C_{s3} and C_{s4} are discharged with constant current equal to $n*I_{Lb}/2$. The voltage across each capacitor varies linearly. The interval finishes when the voltages across capacitors C_{s1} and C_{s2} are V_{ab} and the voltages across capacitors C_{s3} and C_{s4} are null.
- *Third Interval (t_2, t_3):* At instant t_2, antiparallel diodes D_{s3} and D_{s4} are forward biased to conduct the current though the commutation inductor, which decreases linearly. The output current I_{Lb} starts freewheeling through rectifier diodes D_{r1} and D_{r2} and transformer secondary windings. Switches S_3 and S_4 remain turned off.
- *Fourth Interval (t_3, t_4):* At instant t_3, switches S_3 and S_4 are turned on in ZVS mode due to antiparallel diodes D_{s3} and D_{s4}, that are forward biased. The interval finishes when current through commutation inductor I_{Lr} is null. The output current I_{Lb} remains in freewheeling mode.
- *Fifth Interval (t_4, t_5):* At instant t_4, commutation inductor current I_{Lr} increases linearly in opposite direction from zero due to input voltage V_{ab}. The current flows through switches S_3 and S_4. The interval finishes when current I_{Lr} equals $n*I_{Lb}$. Additionally, output current I_{Lb} remains freewheeling.
- *Sixth Interval (t_5, t_6)*: Energy transference occurs as described in the first interval.

The theoretical waveforms of the full-bridge chopper are shown in Fig. 7.

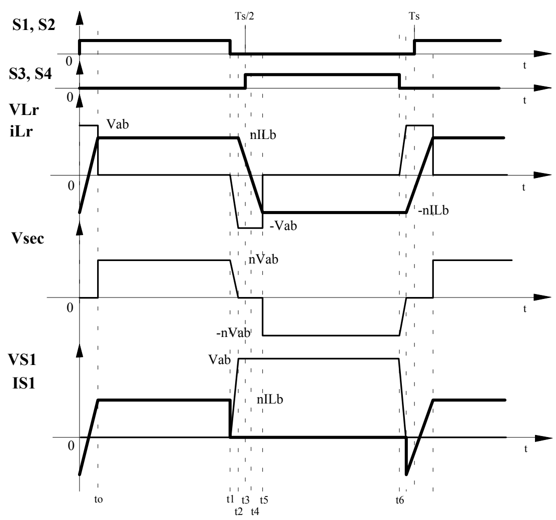


Fig. 7. Main waveforms of the full-bridge chopper.

IV. BOOST STAGE

A classical boost converter was connected to the output of the half-bridge and full-bridge choppers. It performs the following functions: regulation of the output voltage, power factor correction, and step of battery bank voltage up to the output voltage. Additionally, this stage acts as an active filter to block the pulsating current of the nonlinear load (inverter stage). The boost circuit shown in Fig. 8 is controlled by conventional average current-mode-control implemented with the known PWM integrated circuit for power factor correction [8].

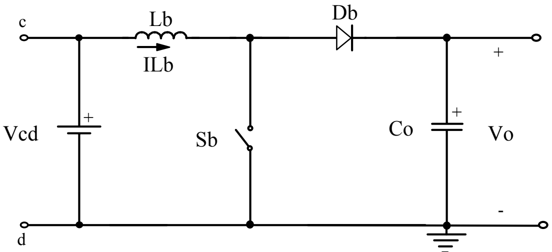


Fig. 8. Boost converter

V. EXPERIMENTAL RESULTS

A. Pre-regulator specifications

The design specifications of the proposed pre-regulator circuit are shown in Table I. The switching frequency of both converters was assumed f_s=50kHz.

TABLE I
Design Specifications

Input voltage	V_i = 220Vac
Output voltage	V_o = 220V$_{dc}$
AC Mains Voltage Frequency	f_r = 60Hz
Output Power	P_o = 1600W

The design procedure of both pre-regulator circuits is presented in [9, 10].

The components used in the laboratory prototype of the pre-regulator circuit using a half-bridge chopper are listed in table II.

TABLE II
Components used in pre-regulator circuit with half bridge chopper

Rectifier Diodes	GBPC3508A
Input Filter Inductor	L_f = 100μH/NEE-30/14 NL_f = 25 turns
Input Filter Capacitors	C_{f1} = C_{f2} = 5μF / 400Vdc
Switches S_1 - S_4 and S_b	IXFX44N60
Resonant Inductor	L_r = 3.5μH/NEE-30/14 N_{Lr} = 6 turns
High Frequency Transformer	NEE–65/39, N_p = N_s = 12 turns
Diodes D_{r1} and D_{r2}	HFA30PA60C
Boost Inductor	L_b = 276μH/NEE-65/26 N_{Lb} = 40 turns
Diode D_b	HFA15PB60
Output Capacitor	C_o = 3 x 680μF / 450V

The prototype of the pre-regulator circuit using a full-bridge chopper employs the same semiconductor devices listed in Table II. Table III shows specifications of additional components.

TABLE III
Components used in pre-regulator with full bridge chopper

Input Filter Capacitor	C_f = 2.5μF / 400Vdc
Resonant Inductor	L_r = 12μH/NEE-30/14 N_{Lr} = 10 turns
High Frequency Transformer	NEE–65/39, N_p = 24 turns, N_s = 12 turns

B. Waveforms and Curves for Pre-regulator Circuit with Half-Bridge Chopper

Fig. 9 shows the input voltage and input current waveforms where high power factor is observed. In Fig. 10, one can see the total input voltage, which is chopped. Fig. 11 presents the drain-to-source voltage and current waveforms regarding switch S_1 of the chopper, as soft commutation obtained. Fig. 12 corresponds to the current through the

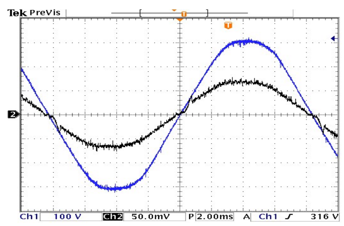


Fig. 9. Input voltage and input current (100V/div; 5A/div; 2ms/div)

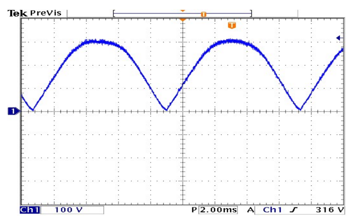


Fig. 10. Voltage across the input dc link of the chopper circuit. (100V/div; 2ms/div)

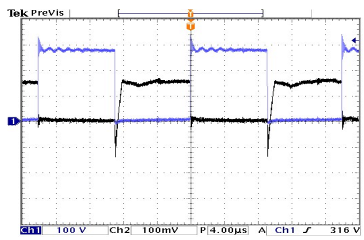


Fig. 11. Voltage and current waveforms regarding switch S_1 (100V/div; 10A/div; 2ms/div)

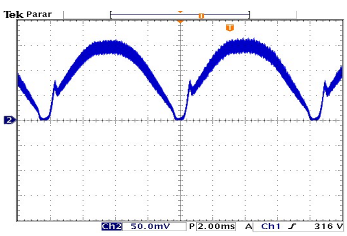


Fig. 12. Current through the boost inductor. (5 A/div; 2ms/div)

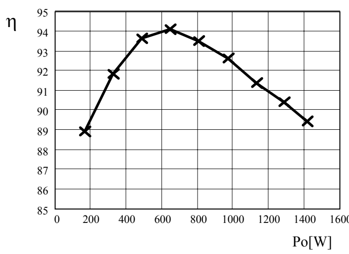


Fig. 13. Efficiency (*chopper+boost*).

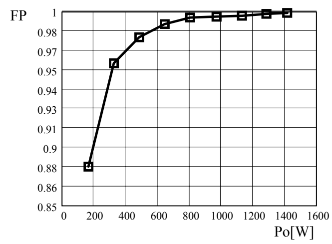


Fig. 14. Power factor as a function of the output power.

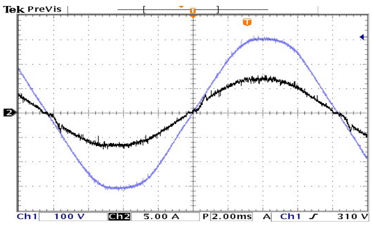


Fig. 15. Input voltage and input current (100V/div; 5A/div; 2ms/div)

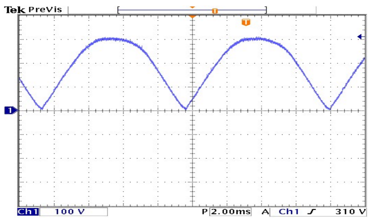


Fig. 16. Voltage across the input dc link of the chopper circuit. (100V/div; 2ms/div)

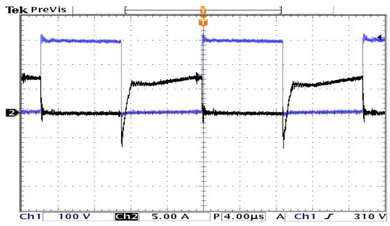


Fig. 17. Voltage and current waveforms regarding switch S_1 (100V/div; 5A/div; 2ms/div)

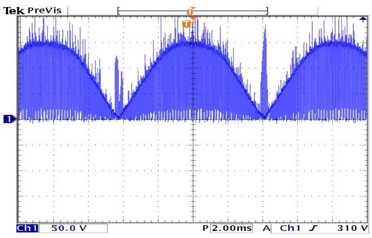


Fig. 18. Input voltage V_{cd} of the boost stage. (100V/div; 2ms/div)

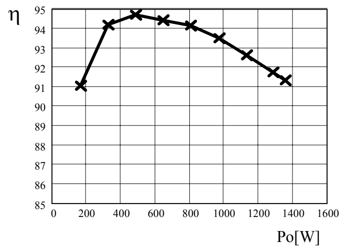


Fig. 19. Efficiency (*chopper+boost*).

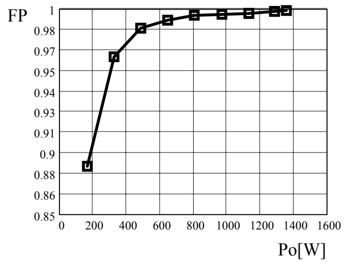


Fig. 20. Power factor as a function of the output power.

boost inductor, where an optimum symmetry between the semicycles is verified. Fig. 13 shows the efficiency curve, as a function of output power, and Fig. 14 demonstrates power factor curve, as a function of output power.

C. Waveforms and Curves for Pre-regulator Circuit with Full-Bridge Chopper

The relevant waveforms and curves are shown in Figs. 15 to 20. The analysis of the results is similar to that presented in item B.

VI. CONCLUSION

This paper presents new pre-regulators topologies with high power factor and high frequency transformer isolation, adequate to UPS systems that require high power density. The description of the operating principles, as well as some experimental results, was presented.

The controlled switches in both pre-regulator circuits present soft commutation avoiding the use of snubber circuits. The chopper stage operates in open loop with fixed duty cycle. The boost stage operates in closed loop control, and as main functions of this converter are regulation of the output voltage and voltage step-up of the battery bank. The converter is controlled with a PFC dedicated integrated circuit commercially available.

The efficiencies of the circuits are about 88% and 89%, if the half-bridge and full-bridge choppers are used, respectively, but they can be improved by optimising the performance of the circuits.

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