A PFC PRE-REGULATOR WITH 110V/220V INPUT VOLTAGE AND HIGH FREQUENCY ISOLATION FOR UPS APPLICATIONS

René P. Torrico-Bascopé[1], Demercil S. Oliveira Jr.[2], Carlos G. C. Branco[3], Fernando L. M. Antunes[4]
Energy Processing and Control Group, Electrical Engineering Department, Federal University of Ceará,
P.O. Box: 6001 – Campus of Pici - 60.455-760 - Fortaleza - CE - Brazil
[1]rene@dee.ufc.br , [2]demercil@dee.ufc.br, [3]cgustavo@ieee.org, [4]fantunes@dee.ufc.br

Abstract – **This work deals with the development of a PFC pre-regulator circuit with possibility of 110V/220V ac main input voltages, while maintaining the same efficiency for a wide load range. Other relevant features of this circuit topology are high frequency transformer isolation, soft commutation of the controlled switches, simple control strategy that can be implemented with well known integrated circuits, and uses few batteries in series due to step-up stage. This circuit is recommended for on-line UPS applications and it is convenient to the development in rack type structure due to small size and reduced weight. Qualitative analysis and experimental results obtained from 1.6kW prototype are presented.**

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

I. INTRODUCTION

Nowadays uninterruptible power supplies systems are being used to protect sensitive loads against a wide range of utility voltage disturbances and power outages. A large amount of these systems consists in the double conversion UPS configuration that operates normally with a low frequency isolation using silicon-steel core transformer. Such transformer is placed in the input or in the output depending on the topology arrangement. The addition of this magnetic component increases both weight and volume, and also adds costs and difficulties in the transportation to the installation place.

Low frequency isolation transformers sometimes presents low power factor in the input stage, and as consequence, harmonic current injection in the ac mains, contributing to the electromagnetic interference in other apparatus and I^2R power losses in electrical transmission and distribution components [1]. A relevant feature of UPS systems with low frequency transformer lies in high efficiency, not requiring additional converters to convert dc voltage or low frequency ac voltage in high frequency voltages to enable high frequency operation of the transformer.

During 1990s, the evolution of semiconductors (diodes and transistors) and other components have allowed the development of devices with near-ideal characteristics, making research on UPS systems with high frequency isolation possible [1-6].

Several topologies were studied in a bibliography review, as a brief description and comparison of pre-regulator stages, including advantages and disadvantages, are presented as follows.

The pre-regulator stage of the UPS studied in [1-2] is a current-fed full-bridge topology that presents advantages such as power factor correction, high frequency isolation and single power processing stage without considering the input bridge rectifier. However, disadvantages are hard commutation of the controlled switches degrading efficiency, complex PWM control due to discrete implementation, and many batteries placed in series to achieve the high DC bus voltage.

The pre-regulator stage of the system proposed in [3] is a modified current-fed full-bridge circuit similar to the previous one. This topology has the advantages of power factor correction, high frequency isolation, single power stage, reduced amount of semiconductors in series during power transfer, contributing for reduction of conduction losses and improving efficiency. Disadvantages are hard commutation of the controlled switches, complex PWM control strategy, and many batteries in series to achieve high DC bus voltage.

In [4], a series-parallel resonant system with galvanic isolation between the input, the output, and the battery was proposed. This system has the advantages of power factor correction, high frequency isolation, single power stage, soft commutation of the controlled switches, and few batteries in series. On the other hand, disadvantages are complex control strategy and resonant parameters adjustment. Other UPS topologies were proposed in [5-6], where each one presents inherent advantages and disadvantages.

In Brazil, utility voltage levels are commonly 110V or 220V, single-phase rms voltage. Therefore, to satisfy such requirements, a flexible input voltage pre-regulator circuit is proposed in Fig. 1. The advantages of this converter are soft commutation of the controlled switches, avoiding snubber circuits and EMI problems, power factor correction, high frequency operation of the transformer with two input voltages, use of well known conventional PWM control techniques, and few batteries in series due to step-up stage. As a disadvantage, there are two power stages, which could imply the reduction of the overall efficiency. The operation with two input voltage levels, the chopper and the boost stage in cascade configuration, and the possibility of achieving soft commutation of switches in the chopper using coupling inductors when it supplied with 110V were obtained from [3,8,9].

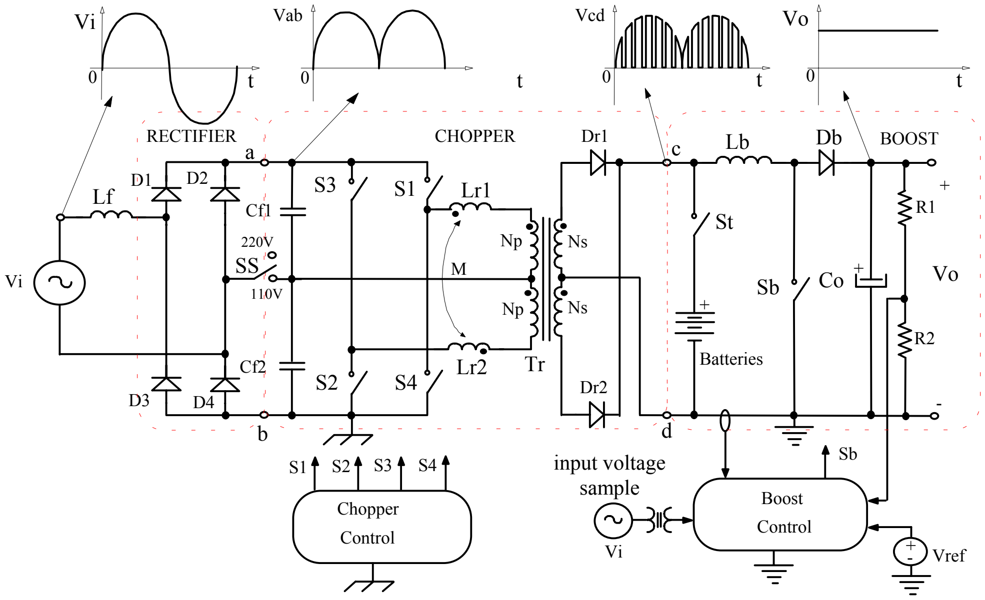


Fig. 1. Proposed pre-regulator circuit scheme.

II. DESCRIPTION OF THE PROPOSED TOPOLOGY

The proposed pre-regulator circuit shown in Fig. 1 is composed of a full-bridge rectifier using diodes D_1-D_4; a full-bridge chopper using controlled switches S_1-S_4, a high frequency transformer T_r, coupled inductors L_{r1}-L_{r2}, and rectifier diodes D_{r1}-D_{r2}. A classical boost circuit is formed by inductor L_b, switch S_b, diode D_b, filter capacitor C_o, and a high frequency input filter given by inductor L_f and capacitors C_{f1} -C_{f2}.

III. ANALYSIS OF THE CHOPPER OPERATION WITH INPUT VOLTAGE EQUAL TO 110V

A. Principle of Operation

The chopper is controlled in open loop with fixed duty cycle ($D\cong0.5$) using conventional PWM integrated circuit. The control allows the application of high frequency voltage pulses to the primary windings of the transformer T_r, enabling the use of a high frequency transformer.

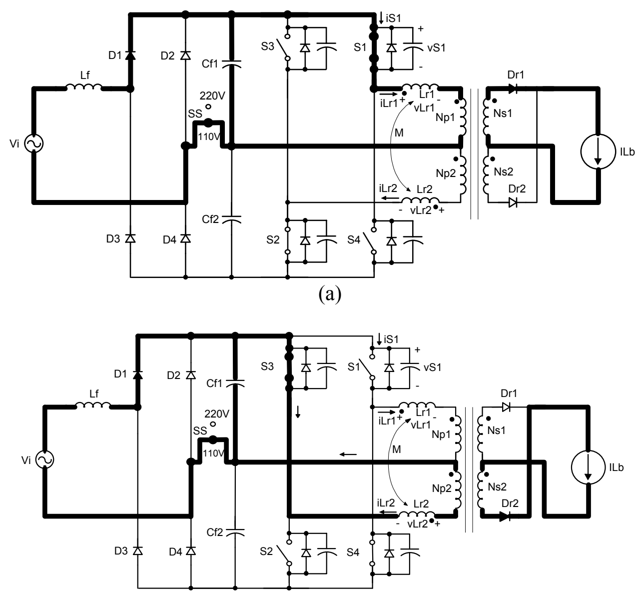
When the input voltage is 110V, the selector switch *SS* (manual or automatic) must be turned on and adjusted in 110V position point. Under this condition, diodes D_2 and D_4 are always reverse biased.

During the positive semicycle of the input voltage, in one switching period, the converter presents two power transfer stages according to the waveforms in Fig. 3, and commutation is similar to the description in [9]. The operation of the topology in the negative semicycle is analogous to the positive one.

- *Interval (t_1-t_2):* Switches S_1 and S_2 are turned on. Then, energy is transferred to the load from the voltage source through diode D_1, switch S_1, commutation inductor L_{r1}, upper primary and secondary transformer windings, and diode D_{r1}. Switches S_3 and S_4 are turned-off and the voltages across them are equal to $2V_i$. The equivalent circuit for this interval is shown in Fig. 2.a.
- *Interval (t_5-t_6):* Switches S_3 and S_4 are turned on. Analogously to the previous interval, energy is transferred to the load from voltage source V_i through diode D_1, switch S_3, commutation inductor L_{r2}, lower primary and secondary transformer windings, and rectifier diode D_{r2}. Switches S_1 and S_2 are turned off and the voltages across them are equal to $2V_i$. The equivalent circuit of the interval is shown in Fig. 2.b.

During the commutation intervals, mutual energy transference occurs between the coupled commutation inductors L_{r1} and L_{r2} in order to charge and discharge the output intrinsic capacitances of the controlled switches of the chopper, and to guarantee ZVS commutation of them.

When the input voltage is 110V, the input current is twice that in 220V, so that the output power is maintained. Luckily, as one can see in Fig. 2, only one controlled switch of the chopper is involved during energy transference, and consequently conduction losses are reduced.



(a)

(b)

Fig. 2. Operating stages of the chopper circuit when the input voltage is 110V.

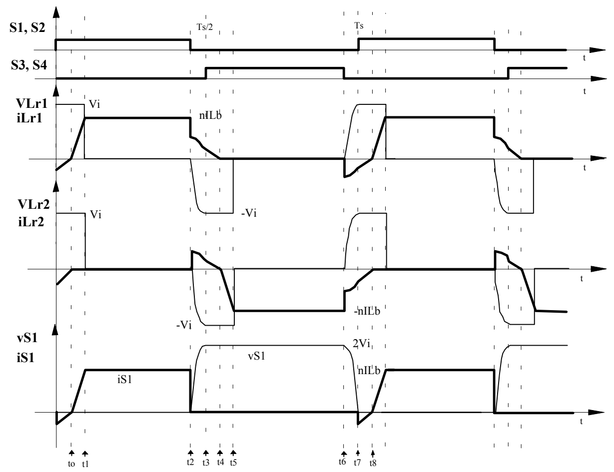


Fig. 3. Main theoretical waveforms when the input voltage is 110V.

IV. ANALYSIS OF THE CHOPPER OPERATION WITH INPUT VOLTAGE EQUAL TO 220V

A. Principle of Operation

The control strategy is the same one used when input voltage is 110V. In this mode, the selector switch, *SS* must be set in 220V point.

During the positive semicycle of the input voltage, the proposed topology presents two power transfer stages according to the waveforms in Fig. 5. The commutation process is similar to that presented for DC-DC full-bridge converters.

- *Interval (t_1-t_2):* Switches S_1 and S_2 are turned on. Energy is transferred to the load from the input voltage source V_i through rectifier diodes D_1 and D_4, switches S_1 and S_2, coupled inductors L_{r1} and L_{r2}, both transformer primary windings, upper transformer secondary winding, and rectifier diode D_{r1}. Switches S_3 and S_4 are turned off and the voltages across them are equal to V_i. The equivalent circuit for this interval is shown in Fig. 4.a.
- *Interval (t_5, t_6):* Switches S_3 and S_4 are turned-on. Energy is transferred to the load from input voltage source V_i through rectifier diodes D_1 and D_4, switches S_3 and S_4, coupled inductors L_{r1} and L_{r2}, both primary transformer windings, lower transformer secondary winding, and rectifier diode D_{r2}. Switches S_1 and S_2 are turned off and the voltages across them are equal to V_i. The equivalent circuit for this interval is shown in Fig. 4.b.

Although the current flows simultaneously through both inductors when the chopper operates with 220V, the equivalent commutation inductance, considering the mutual inductance and coupling coefficient next to unity, is equal to four times L_{r1} or L_{r2} i.e. $L_{req} = 4L_{r1} = 4L_{r2}$.

The operation of the topology in the negative semicycle is analogous to the positive one.

According to Fig. 4, there are always two controlled semiconductors involved in power transference. Although the input voltage is twice that in Section III, the current through the semiconductors is reduced to a half. Therefore, losses are approximately equal when the converter operates with 110V or 220V.

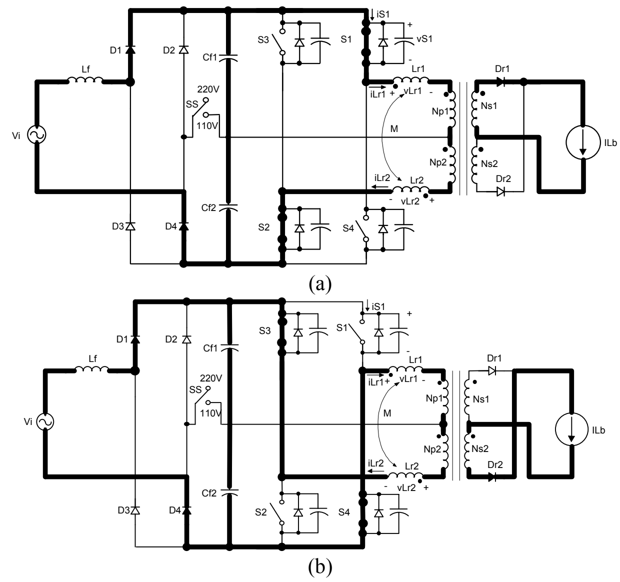


Fig. 4. Operating stages of the chopper circuit when the input voltage is 220V.

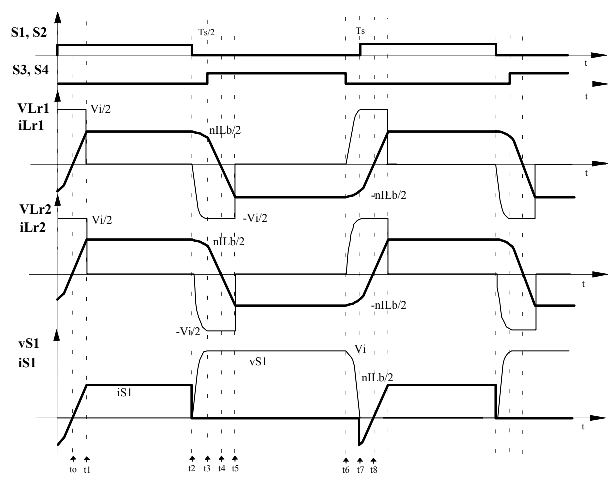


Fig. 5. Main theoretical waveforms when the input voltage is 220V.

V. BOOST CONVERTER STAGE

A classical boost converter, shown in Fig. 6, was connected to the output of the chopper. It is responsible for regulation of the output voltage, power factor correction, and the step of battery bank voltage up to the output voltage V_o. Additionally, this stage provides an active filtering to block the pulsating current of the nonlinear load (inverter stage) from the battery bank. Switch S_b operates with zero voltage switching in a wide range of output power using a passive nondissipative snubber circuit [10]. The Boost converter is controlled using conventional average current-mode-control implemented with the well-known PWM integrated circuit for power factor correction [7].

VI. BATTERY CHARGER STAGE

The battery charger is based on a small nonisolated buck converter as shown in Fig. 7. The converter operates in continuous conduction mode (CCM) of the current through the filter inductor, and is supplied with the output voltage of the boost converter.

As the voltage between terminals *cd* is chopped and modulated in 120Hz, a controlled switch S_t is necessary due to the voltage characteristic at this point. For this application, the thyristor device is adequate. Switch S_t is turned-on when AC main voltage is off or out of input voltage specification levels, and it is turned-off when AC main voltage is suitable for on-line operation.

In the practical implementation, eight batteries in series can be used in order to obtain the desired output voltage V_o specified in Table I.

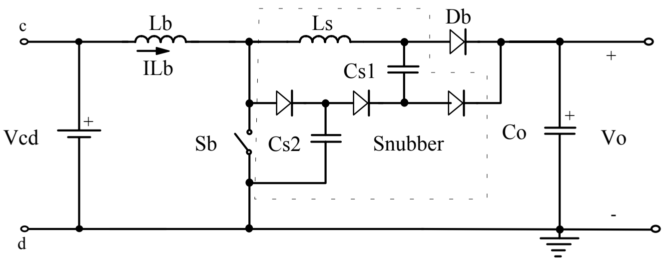


Fig. 6. Boost converter.

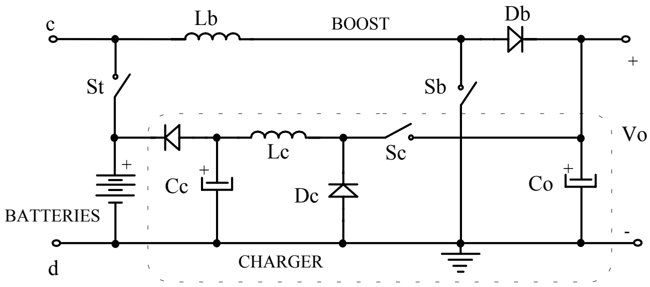


Fig. 7. Battery charger.

VII. SIMPLIFY DESIGN EXAMPLE

A. Preliminary specifications

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

TABLE I
Pre-regulator Specifications

Input voltage	V_i = 110Vac / 220Vac
Output voltage	V_o = 220V_{dc}
AC Main Frequency	f_r = 60Hz
Output Power Capacity	P_o = 1600W

The remaining parameters are: maximum boost inductor current ripple $\Delta IL_{b\,max} = 0.15 IL_{b(pk)}$; transformer turns ratio $n = N_s / N_p = 1$; maximum fixed duty cycle of the chopper switches $D_{max} = 0.48$; maximum duty cycle reduction $\Delta D_{max} = 0.048$ and, input filter resonant frequency $f_o = 0.15 f_s$.

B. Design Procedure of The Chopper

The output voltage of the chopper can be calculated by

$$V_{cd(rms)} = nV_{i(rms)_{110V}} \sqrt{2\left(D_{\max} - \Delta D_{\max}\right)} = 102.25V \quad (1)$$

$$V_{cd(rms)} = \frac{nV_{i(rms)_{220V}}}{2} \sqrt{2\left(D_{\max} - \Delta D_{\max}\right)} = 102.25V \quad (2)$$

The coupled inductors can be obtained by

$$L_{r1} = L_{r2} = \frac{\sqrt{2}V_{i(rms)_{110V}} \Delta D_{\max}}{2 f_s n IL_{b(pk)}} \cong 3.4\mu H \quad (3)$$

$$L_{r1} = L_{r2} = \frac{\sqrt{2}V_{i(rms)_{220V}} \Delta D_{\max}}{4 f_s n IL_{b(pk)}} \cong 3.4\mu H \quad (4)$$

where,

$$IL_{b(pk)} \cong \frac{\sqrt{2}P_o}{V_{cd(rms)}} \cong 22.13A \quad (5)$$

The input filter capacitances are arbitrarily chosen as $C_{f1} = C_{f2} = 6.6\mu F$. Therefore, the filter inductance is:

$$L_f = \frac{1}{C_{f(eq)}\left(0.94 f_s\right)^2} \cong 137.18\mu H \quad (6)$$

C. Design Procedure of The Boost Converter

The boost inductor and filter capacitor are obtained according to [7].

$$L_b = \frac{\sqrt{2}V_{cd(rms)} D_{boost}}{f_s \Delta IL_{b\,max}} = 296.22\mu H \quad (7)$$

$$C_o = \frac{2 \cdot P_o \cdot \Delta t}{V_o^2 - V_1^2} = 2167.9\mu F \quad (8)$$

where $\Delta t = 8.333x10^{-3} s$, $V_1 = 190V$ and:

$$D_{boost} = 1 - \frac{\sqrt{2}V_{cd(rms)}}{V_o} = 0.34 \quad (9)$$

VIII. EXPERIMENTAL RESULTS

The experimental results consist of relevant voltages and current waveforms, and also curves that demonstrate the performance of the converters.

A. Waveforms and Curves When The Input Voltage is 110V

Fig. 8 shows the input voltage and input current waveforms where high power factor is observed. Fig. 9 presents the voltage and the current waveforms of switch S_1, where soft commutation detail is observed. Fig. 10 depicts the current through the boost inductor, where an optimum symmetry between the semicycles is verified. In Fig. 11, the chopper input voltage V_{ab}, is presented which is chopped and modulated in 120Hz. Fig. 12 shows efficiency curve, as a function of output power. Finally, Fig. 13 illustrates the power factor behavior as a function of the output power.

B. Waveforms and Curves When The Input Voltage is 220V

The waveforms corresponding to the operation when the input voltage 220V are shown in Figs. 14 to 19. The analysis of the waveforms and curves is similar to the case where the input voltage is 110V input voltage.

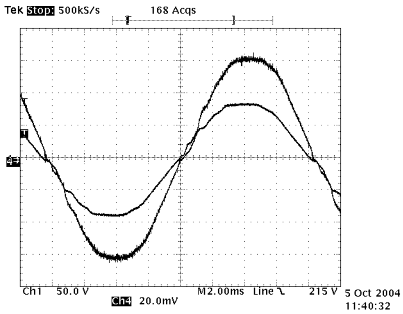


Fig. 8. Input voltage and input current of the pre-regulator stage (50V/div.; 10 A/div.; 2ms/div.)

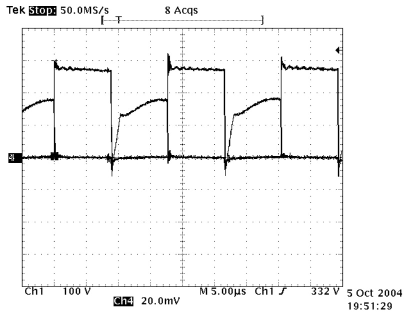


Fig. 9. Voltage and current waveforms of switch S_1 (100V/div.; 10 A/div.; 5us/div.)

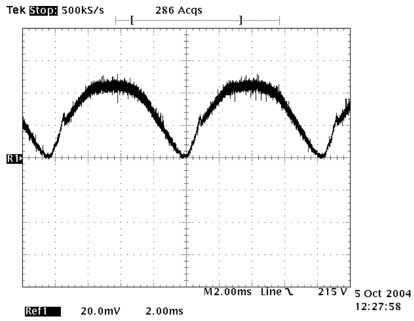


Fig. 10. Current through the Boost inductor (10 A/div.; 2ms/div.)

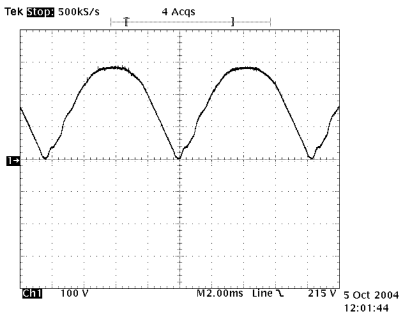


Fig. 11. Input voltage V_{ab} of the chopper (100V/div., 2ms/div.)

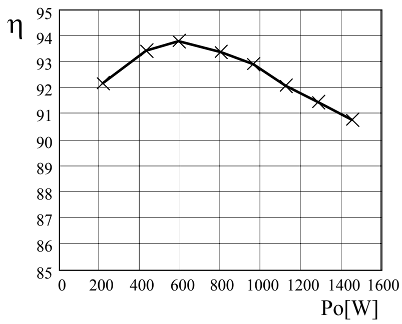


Fig. 12. Efficiency of the pre-regulator circuit as a function of the output power.

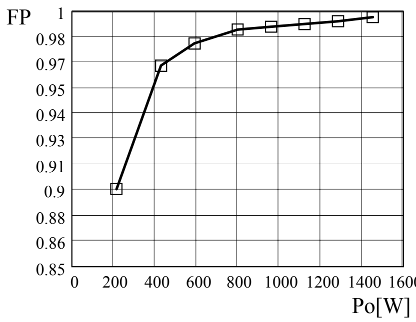


Fig. 13. Power factor as a function of the output power.

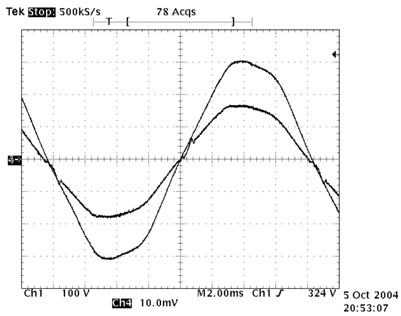


Fig. 14. Input voltage and input current of the pre-regulator stage (100V/div.; 5 A/div.; 2ms/div.)

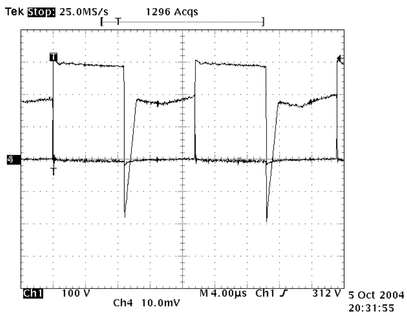


Fig. 15. Voltage and current waveforms of switch S_1 (100V/div.; 5 A/div.; 4us/div.)

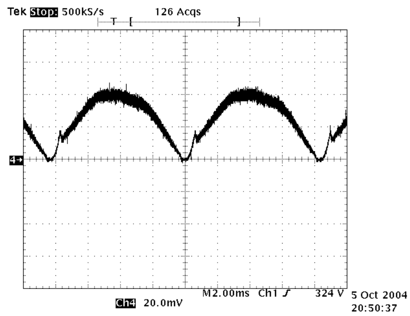


Fig. 16. Current through the Boost inductor (10 A/div.; 2ms/div.)

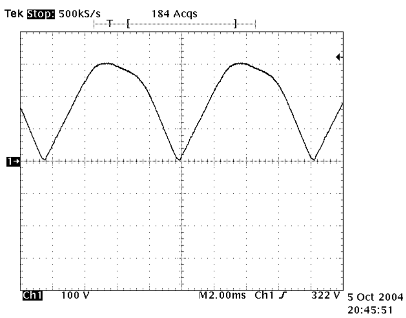


Fig. 17. Input voltage V_{ab} of the chopper (100V/div., 2ms/div.)

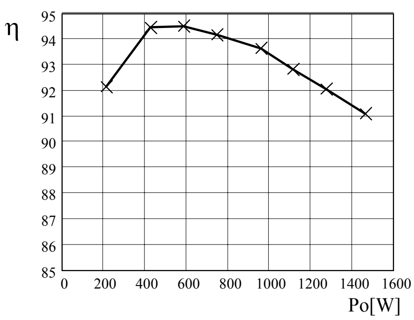


Fig. 18. Efficiency of the pre-regulator circuit as a function of the output power.

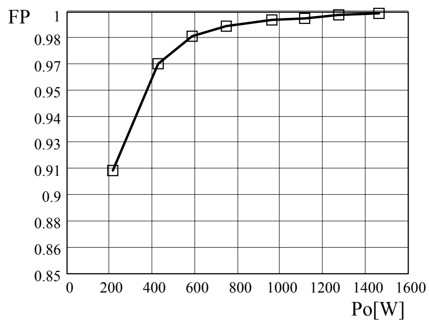


Fig. 19. 13. Power factor as a function of the output power

The main components used in the laboratory prototype are listed in table II.

TABLE II
Main components used in pre-regulator prototype.

Rectifier Diodes	GBPC3508A
Input Filter Inductor	L_f = 137.18µH/NEE-55 NL_f = 20 turns
Input Filter Capacitors	$C_{f1} = C_{f2}$ = 3 x 2.2µF / 400Vdc
Switches S_1 - S_4 and S_b	IXFX44N60
Coupled Inductors	$L_{r1} = L_{r2}$ =3.4µH/NEE-42/15 $NL_{r1} = NL_{r2}$ = 4 turns
High Frequency Transformer	NEE-65/39 Np=12 turns; Ns=12turns
Diodes D_{r1} and D_{r2}	HFA30PA60C
Boost Inductor	L_b = 296.22µH/NEE-65/26 NL_b = 40 turns
Diode D_b	HFA15PB60
Output Capacitor	C_o = 3 x 680µF / 450V

A photograph of the tested prototype is shown in Fig. 20.

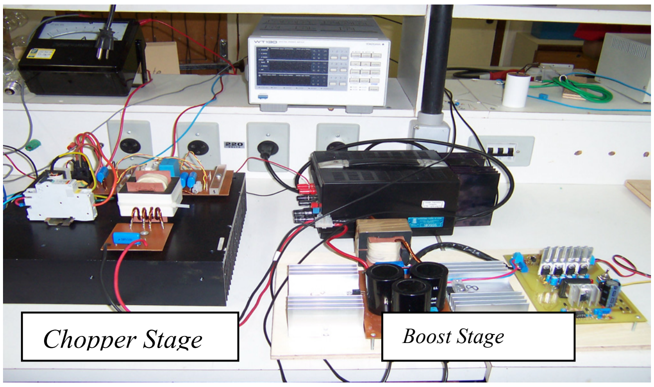


Fig. 20. Photograph of the proposed pre-regulator stage.

IX. CONCLUSIONS

This paper has proposed a new pre-regulator operating with input voltages equal to 110V/220V, high power factor correction, and high frequency isolation using conventional control technique. High frequency isolation reduces the volume and weight of the circuit. The qualitative analysis of chopper when input voltage is 110V and 220V, and also experimental results obtained from 1.6kW output power prototype have also been presented.

For both input voltages, chopper switches S_1–S_4 present zero voltage switching, avoiding the use of snubber circuits. The efficiency for both input voltages is the same, because semiconductors losses on the primary side of the transformer are almost the same as well. The chopper is controlled in open loop using fixed pulses with $D \cong 0{,}5$ obtained from conventional PWM integrated circuit.

The boost converter performs power factor correction, regulates the output voltage and the steps the battery bank voltage up to the output voltage. It is controlled in closed loop using average current-mode control, and implemented with conventional PWM integrated circuit.

The efficiency of the converter can be improved if the design is optimized, and also if MOSFETs are replaced for IGBTs.

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