# HIGH FREQUENCY ISOLATION PRE-REGULATOR FOR LOW POWER UPS APPLICATIONS

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**Abstract – A high frequency isolation pre-regulator is proposed as a viable solution for low power on-line uninterruptible power supply (UPS) applications. It's composed by one half-bridge chopper that operates in open loop with fixed duty cycle almost 0.5, and a step-up converter that operates in closed loop using the traditional average current mode control. The step-up converter control provides power factor correction to the pre-regulator stage and system. The pre-regulator is adequate for the development of low power UPSs (less than 1kVA) which few batteries are used. In such applications the battery DC link voltage, can be 24V, 36V or 48V. Principle of operation, as well as, experimental results for the pre-regulator operating in both, grid and battery modes are presented. Accordingly to the experimental results for a 750W assembled prototype, an efficiency of 85% is obtained for grid mode and 93% for the battery mode, confirming the effectiveness of the proposed circuit.**

***Keywords* - AC-DC converter, high frequency isolation, pre-regulator, UPS system.**

## I. INTRODUCTION

Nowadays uninterruptible power systems (UPS) are used to protect sensitive loads against a wide variety of utility voltage disturbances and power outages. Most of such systems consist in the double conversion UPS configuration that operates normally with a low frequency transformer using a silicon-steel core. Such transformer is placed at the input or output depending on the topology arrangement. The addition of such magnetic component increases both weight and volume, and also adds cost and difficulties in the transportation to the installation place.

In order to overcome weight and size limitations, with the evolution of semiconductors, several architectures of high frequency isolation UPS's were proposed in [1-7]. 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 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 in comparison to high frequency isolation UPS systems is its 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. Disadvantages of such systems are due to increased weight and size.

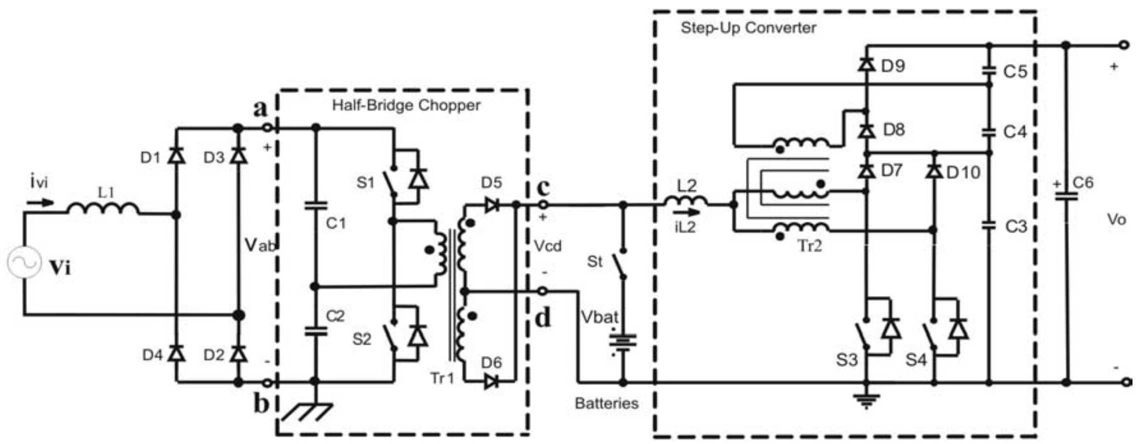



Fig. 1. Proposed pre-regulator converter.

The pre-regulator shown in Fig. 1, was obtained from the references [9-13]. The features of the circuits are soft commutation of the chopper stage, high frequency isolation, power factor correction, use of well-known conventional PWM control techniques, and utilization of few batteries in series due to the step-up stage. A theoretical disadvantage of this system is the existence of two power stages that affects its efficiency.

## II. ANALYSIS OF THE HALF BRIDGE CHOPPER CONVERTER

### *A. Description of the Circuit*

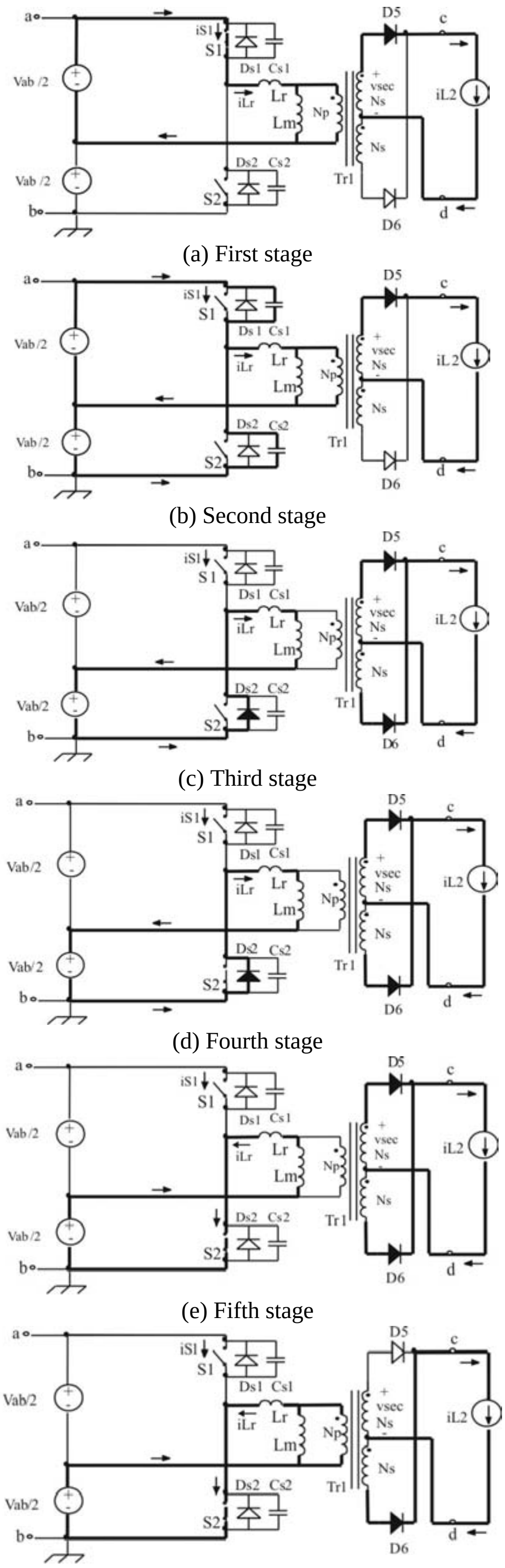
The half-bridge chopper shown in Fig. 1 consists of controlled switches $S_1$-$S_2$, filter and voltage divider capacitors $C_1$-$C_2$, high frequency transformer $T_{r1}$, and rectifier diodes $D_5$-$D_6$.

### *B. Principle of Operation*

The chopper shown in Fig. 1 is supplied by rectified sinusoidal voltage. The capacitor divisor is obtained using small polypropylene or polyester capacitors $C_1$ and $C_2$. The indicated voltage is transformed at high frequency switching using an open loop PWM half-bridge chopper. Each switch of the chopper operates with duty cycle almost 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 $D_5$ and $D_6$ to supply the step-up converter.

The chopper circuit presents five operating stages within half switching period. The operating stages are described as follows and the relevant circuits indicating the current path are shown in Fig. 2. Fig. 3 shows the corresponding theoretical waveforms.

- ***First Stage ($t_0$, $t_1$):*** Switch $S_1$ is turned on and energy transference occurs from the input source $V_{ab/2}$ to the load, through the high frequency transformer $T_{r1}$ and rectifier diode $D_5$. Switch $S_2$ remains turned off and the voltage across it is $V_{ab}$. Rectifier diode $D_6$ is reversed biased. The stage finishes when switch $S_1$ is turned off under ZVS guaranteed by the intrinsic capacitance of the switch.
- ***Second Stage ($t_1$, $t_2$):*** Switches $S_1$ and $S_2$ are turned off. Capacitors $C_{s1}$ and $C_{s2}$ are charged and discharged, both with constant current $n.I_{L2}/2$, respectively. Therefore, the voltage transition is linear. The stage 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 Stage ($t_2$, $t_3$):*** 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 $I_{L2}$ starts freewheeling through diodes $D_5$ and $D_6$ and through secondary windings. Switches $S_1$ and $S_2$ remain turned off.
- ***Fourth Stage ($t_3$, $t_4$):*** Switch $S_2$ is turned on under ZVS condition, since diode $D_{s2}$ is directly biased. The stage finishes when the current through inductor $L_r$ reaches zero. Additionally, output current $I_{L2}$ remains in freewheeling.
- ***Fifth Stage ($t_4$, $t_5$):*** 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 $I_{L2}$ remains in freewheeling mode. This stage finishes when current $i_{Lr}$ is equal to $n.I_{L2}$.
- ***Sixth Stage ($t_5$, $t_6$):*** The energy transference occurs as described in the first stage.




(a) First stage

(b) Second stage

(c) Third stage

(d) Fourth stage

(e) Fifth stage

(f) Sixth Stage

Fig. 2. Stages of the half-bridge chopper converter.

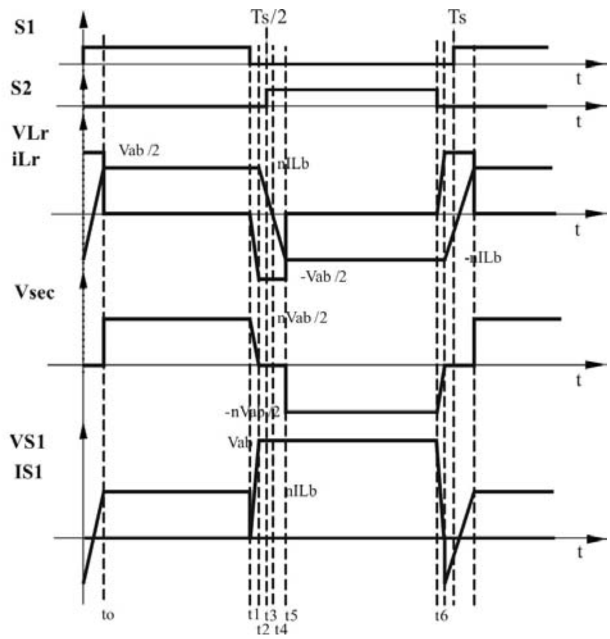



Fig. 3. Main waveforms of the half-bridge chopper converter.

## III. ANALYSIS OF THE STEP-UP CONVERTER

### *A. Description of the Circuit*

The step-up converter shown in Fig. 1 is composed by the following devices: voltage source $V_{cd}$ represented by the output voltage of the chopper, storage inductor $L_2$, transformer $T_{r2}$, controlled switches $S_3$ and $S_4$, rectifier diodes $D_7$, $D_8$, $D_9$ and $D_{10}$, and output filter capacitors $C_3$, $C_4$, $C_5$. It's important to note that when $V_{cd}$ is purely continuous DC voltage, the output filter capacitors $C_3$, $C_4$, and $C_5$ can be substituted by polyester capacitors in order to reduce series equivalent resistance of electrolytic capacitors, and one DC link electrolytic capacitor as shows the Fig. 1. For this work application $V_{cd}$ is 120Hz pulsating voltage in grid mode, therefore, electrolytic capacitors for $C_3$, $C_4$, and $C_5$ were used.

### *B. Principle of Operation*

The step-up converter shown in Fig. 1 is connected to the output of half bridge chopper circuit. It is used for the inverter DC link voltage regulation, power factor correction, and stepping the battery voltage up to the output voltage $V_o$. Additionally, this stage provides an active filtering to block the pulsating current of the nonlinear load (i.e. the inverter stage for example) from the battery bank. In this structure, the switches $S_3$ and $S_4$ operates with hard switching.

The boost converter is controlled using conventional average current mode control implemented with the well-known PWM IC UC3854 [8].

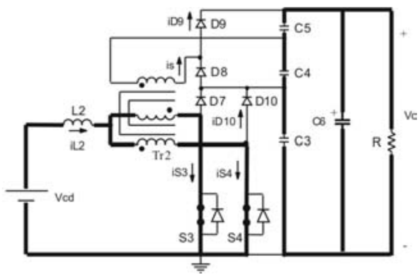
During one commutation period of the converter operation, it presents four operating stages, as shown in Fig. 4, that are described as follows and theoretical waveforms are depicted in Fig. 5.

• ***First Stage ($t_0$, $t_1$):*** The switches $S_3$ and $S_4$ are turned-on. The energy is stored only in the inductor $L_2$ and is not transferred to the load. This stage is finished when switch $S_3$ is turned-off.

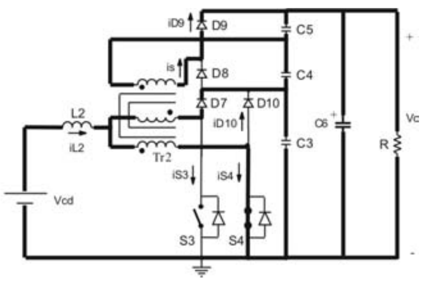
• ***Second Stage ($t_1$, $t_2$):*** In this stage the switch $S_4$ remains turned-on. The voltage across switch $S_3$ is equal to the voltage across capacitor $C_3$. The diodes $D_7$ and $D_9$ are directly biased. The energy stored in the inductor in the first stage, as well as, the energy from the voltage source are transferred to the filter capacitors $C_3$ and $C_5$, so as to the load.

• ***Third Stage ($t_2$, $t_3$):*** This stage is similar to the first one, where switches $S_3$ and $S_4$ are turned-on, and the energy is only stored in the inductor $L_2$. It is finished when switch $S_4$ is turned-off.

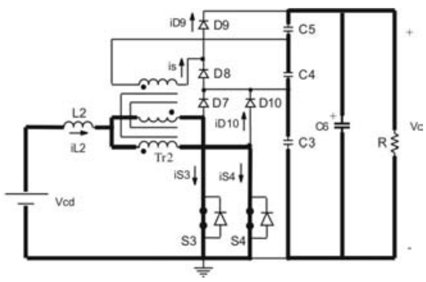
• ***Fourth Stage ($t_3$, $t_4$):*** During this stage, the switch $S_3$ remains turned-on. The voltage across switch $S_4$ is equal to the voltage across the capacitor $C_3$. The diodes $D_8$ and $D_{10}$ are directly biased. The energy stored in the inductor during the third stage, as well as, the energy from the voltage source are transferred to the filter capacitors $C_3$, $C_4$, and the load.



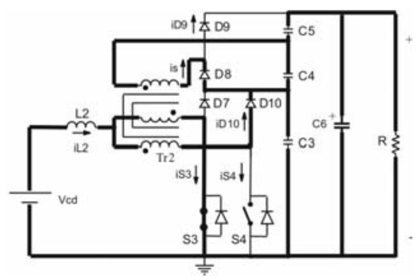
(a) First stage



(b) Second stage



(c) Third stage



(d) Fourth stage

Fig. 4. Stages of the step-up converter.

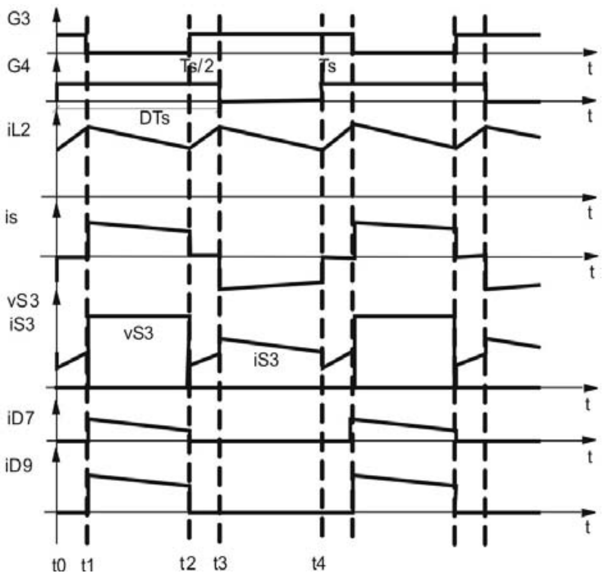



Fig.5. Theoretical waveforms of the converter.

## IV. EXPERIMENTAL RESULTS

### *A. Pre-regulator Specifications*

The proposed pre-regulator has been tested under both grid mode and battery mode conditions, accordingly the design specifications that are shown in Table I.

**TABLE I**
**Specifications of the pre-regulator**

| | | |
|---|---|---|
| Utility voltage | $V_i$ | 220 [V] |
| Utility frequency | $f_r$ | 60 [Hz] |
| DC link output voltage | $V_o$ | 300 [V] |
| Output power | $P_o$ | 750 [W] |
| Battery set voltage (equivalent to 4 batteries connected in series) | $V_{bat}$ | 48 [V] |
| Switching frequency assumed for the chopper stage | $f_{s\_chopper}$ | 50 [kHz] |
| Switching frequency assumed for the step-up stage | $f_{s\_boost}$ | 30 [kHz] |

The components used for experimental implementation are listed in Tables II and III.

**TABLE II**
**Parameters of the chopper stage**

| | |
|---|---|
| Rectifier Diodes | GBPC3508A |
| Input Filter Inductor | $L_1$ = 110µH |
| Input Filter Polyester Capacitors | $C_1$, $C_2$ = 3×2.2µF/400Vdc |
| Switches $S_1$–$S_4$ | IRGP35B60PD |
| Commutation inductor | $L_r$ = 7.5µH |
| Diodes $D_5$ and $D_6$ | HFA30PA60C |

**TABLE III**
**Parameters of the step-up converter**

| | |
|---|---|
| Boost Inductor | $L_2$ = 100µH |
| Output Electrolytic Capacitors | $C_3$, $C_4$, $C_5$ = 470µF/250V |
| Output Electrolytic Capacitor | $C_6$ = 470µF/400V |
| Diodes $D_7$-$D_{10}$ | HFA15PB60 |
| Switches $S_3$-$S_4$ | IRFP260N |

### *B. Waveforms of the Pre-regulator – Grid Mode*

The Fig. 6 shows the input voltage and input current waveforms where high power factor is observed. In Fig. 7, the total rectified input voltage $V_{ab}$ is shown, which will be chopped by the chopper stage in order to the utilization of a high frequency transformer. Fig. 7 also shows the output voltage of the chopper $V_{cd}$, which feed the step-up stage. It's important to step on that this waveform is chopped in high frequency but isn't clearly this characteristic in Fig. 7 due to the oscilloscope resolution. Fig. 8 corresponds to the current through the boost inductor where an optimum symmetry between the semicycles is verified. Also in Fig. 8, the DC link voltage is shown, regulated in 300V as expected, with a low voltage ripple. Fig. 9 shows the behaviour of voltages across capacitors $C_3$, $C_4$ and $C_5$. Accordingly these waveforms, it presented a good voltage balance.

Fig. 13 represents the efficiency curve as a function of output power. It's important to emphasize that efficiency also could be improved substituting lower reverse voltage diodes $D_5$ and $D_6$ of the chopper stage, and lower on-state resistance MOSFETs of the step-up stage. Finally, Fig. 10 depicts the power factor behavior as a function of the output power.

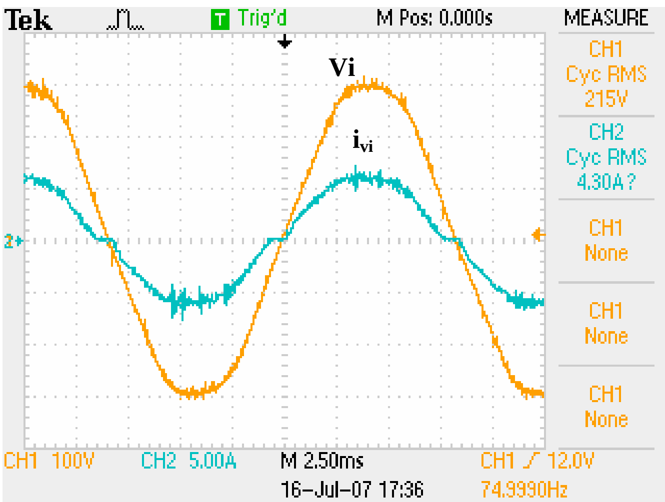



Fig. 6. AC line input voltage *Vi* and input current $i_{vi}$.
(100V/div.; 5A/div.; 2.5ms/div.)

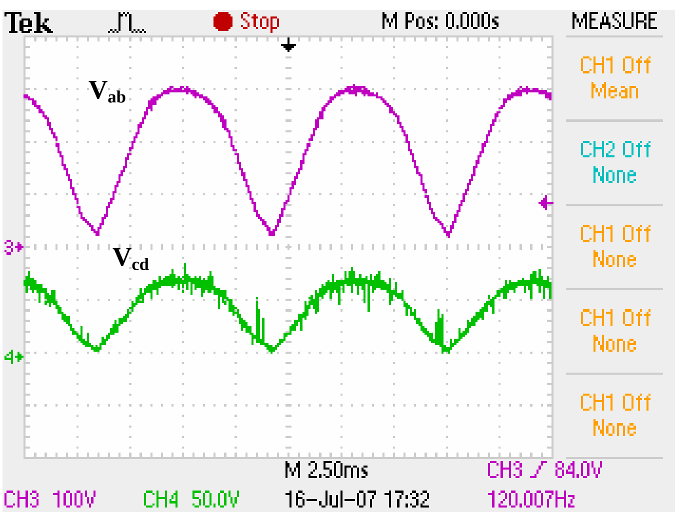



Fig. 7. Chopper input voltage $V_{ab}$ and chopper output voltage $V_{cd}$.
(100V/div.; 50V/div.; 2.5ms/div.)

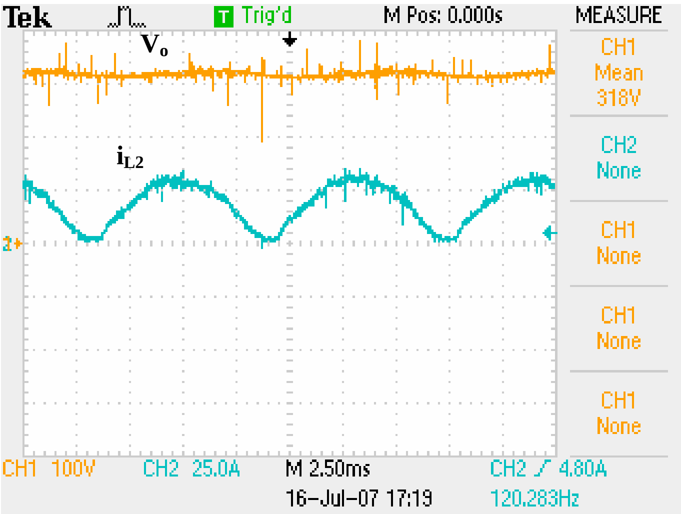



Fig. 8. Current through the boost inductor $L_2$ and DC link output voltage $V_o$. (25A/div.; 100V/div.; 2.5ms/div.)

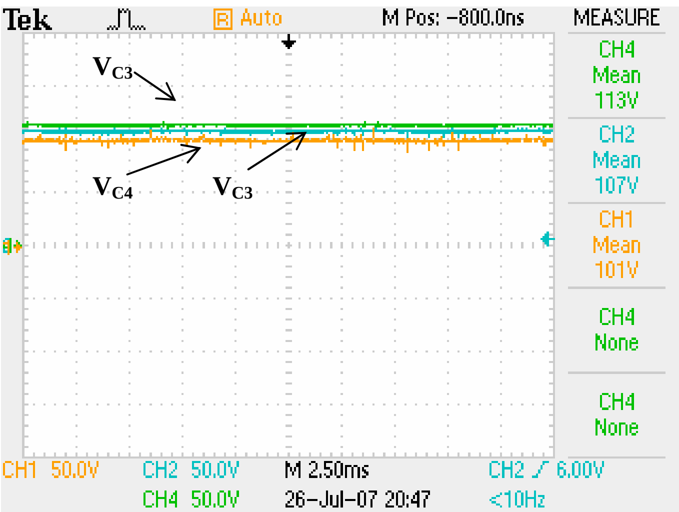



Fig. 9. Voltage across output filter capacitors $C_3$, $C_4$ and $C_5$. (50V/div.; 50V/div.; 50V/div.; 2.5ms/div.)

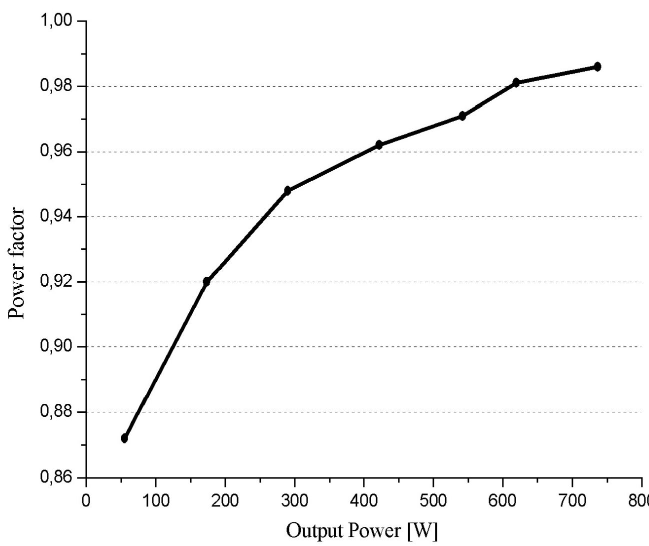



Fig. 10. Power factor of the pre-regulator for grid mode operation, as function of the output power.

## C. Waveforms of the Pre-regulator – Battery Mode

The experimental results for the battery powered mode were carried out for the same load as used in grid mode operation. In the battery mode the chopper stage is off. The waveforms description is similar to the presented for grid mode with except of current through the boost inductor $L_2$, that is almost continuous, as shown in Figs. 11 and 12.

The current in the boost inductor $L_2$ presents a low ripple. Thus, the adopted control strategy enhances the reliability and life of the battery set.

Also in the Fig. 11, is shown the battery bank voltage corresponding to four batteries in series (48V) as specified in Table I. In Fig. 12 the DC link voltage is shown, presenting the same characteristics of the Fig. 8 for the grid mode operation.

Fig. 13 represents the measured efficiency curve as a function of output power for both grid and battery modes. For the battery mode operation, it has reached a final efficiency of 93%, that is satisfactory for UPS applications.

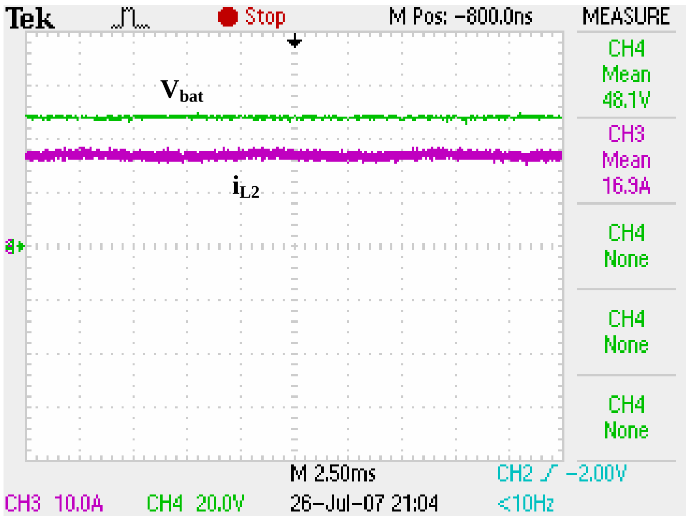



Fig. 11. Battery bank voltage $V_{bat}$ and current through the boost inductor $L_2$. (20V/div.; 10A/div.; 2.5ms/div.)

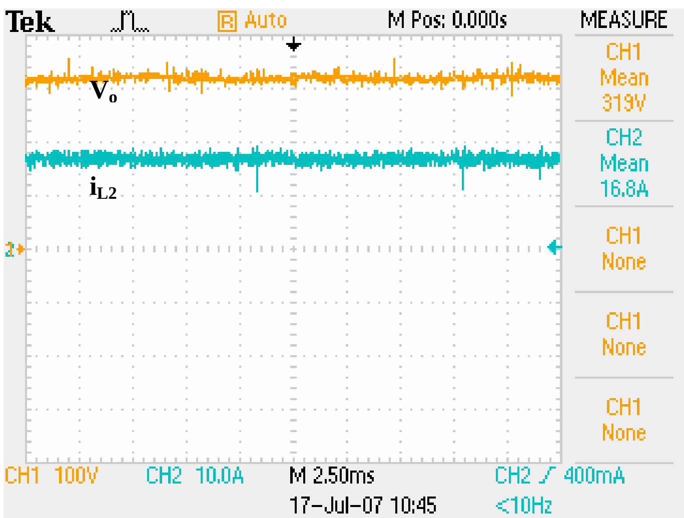



Fig. 12. Current through the boost inductor $L_2$ and DC link output voltage $V_o$. (10A/div.; 100V/div.; 2.5ms/div.)

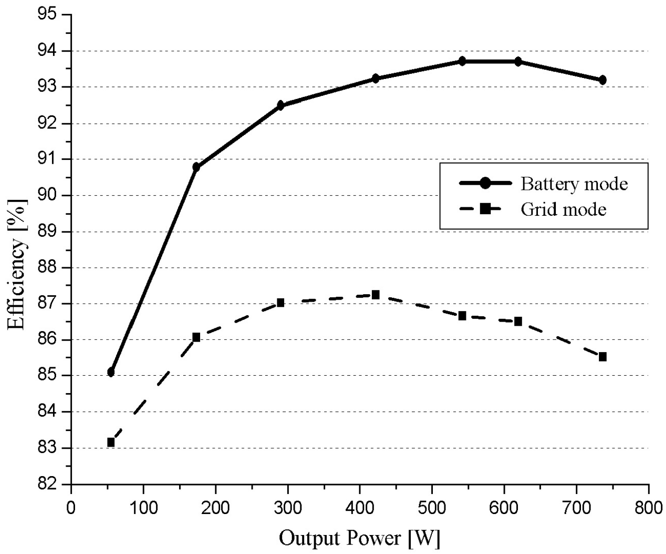



Fig. 13. Measured efficiency of the pre-regulator as function of the output power.

## V. CONCLUSION

This paper presents a new pre-regulator topology, with high power factor and high frequency transformer isolation, suitable for development of low output power on-line UPSs, which normally are designed with few batteries. The descriptions of the operating principles, as well as experimental results, were presented.

The controlled switches of the chopper circuit present soft commutation, avoiding the use of snubber circuits. The chopper stage operates in open loop with fixed duty cycle, and their main functions are: to provide electrical isolation between AC line and the load, and to permit a high frequency transformer utilization in order to reduce both weight and size. The step-up converter operates in closed loop using average current mode control, and its main functions are: to regulate its output voltage, to provide power factor correction to the pre-regulator circuit, and to raise the battery bank voltage up to the regulated DC link output voltage.

Both stages are controlled using well-know commercial integrated circuit available at the market, simplifying the control board implementation.

Accordingly to the experimental results for both grid and battery modes, waveforms and curves for the pre-regulator showed the effectiveness of the proposed structure. It's important to emphasize that efficiency also could be improved if diodes $D_5$ and $D_6$ of the chopper stage were changed by a lower reverse voltage ones and switches in step-up stage were chosen with a lower on-state resistance.

## ACKNOWLEDGEMENT

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