PROPOSAL OF A LOW COST HIGH FREQUENCY ISOLATION HIGH POWER FACTOR AC-DC-AC POWER SUPPLY

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Abstract – **This paper proposes a low cost double conversion power line conditioner with high frequency isolation, high input power factor, full-range input voltage varying among 90Vac-264Vac and 115Vac output voltage. The rectifier with power factor correction is based on flyback converter using the critical current mode control. The inverter is based on full-bridge topology with digital control implemented in a DSPic30F2020 microcontroller. This system is suitable for application with loads which require a high quality sinusoidal voltage. System description, theoretical analysis and experimental results for a 500W implemented prototype are shown in this paper.**

Keywords – **Power Factor Correction, DC-AC converter, Flyback Converter, Inverter.**

I. INTRODUCTION

Uninterruptible Power Supply (UPS) systems provide uninterrupted, reliable, and high quality power for vital loads. They, in fact, protect sensitive loads against power outages as well as overvoltage and undervoltage conditions. UPS systems also suppress line transients and harmonic disturbances [1]. Most of such systems consist in the true on-line UPS configuration. In general, this is the most reliable UPS configuration due to its capacitor tank in the bus that mitigates input disturbances. This kind of UPS provides total independence between input and output voltage amplitude and frequency, and, thus, high output voltage quality can be obtained [2], [3].

On the other hand, when the load does not require a continuously fed, but it needs just reliable and high quality power, a power line conditioner is already enough. It has the same reliability and capability to provide high quality output voltage of UPS system, however it presents lower cost compared to UPS system since the lack of battery bank. This kind of system is wide applied to computer system in Brazil.

In the most of cases, the classical power line conditioner is based on appropriate selection of derivations of low frequency transformer [4], or based on AC-AC converter, as reported in [5] and [6].

The first technique is efficient, as long as the number of derivations is large, what implicates in a great number of semiconductors or relays [4]. However, the time response in this kind of system is still high, decreasing the quality power. It is usual to use few number of tap in the transformer, which cause weak regulation (>5%).

The second technique presents better regulation when compared with the first technique as explained in [5], [6]. On the other hand, this solution uses a low frequency transformer, increasing the volume, weight and cost. A fixed input voltage is also a characteristic of this system. To make possible the operation with a wide range of input voltage, the low frequency transformer structure must be changed.

This paper proposes an AC power supply based on double conversion power supply and its block diagram is shown in Fig. 1. It means that there is a high frequency isolated rectifier stage and an inverter stage. As in UPS system, this structure has the feature of output voltage independently of the input voltage, presenting higher reliability and quality power. Furthermore, power factor correction is embedded is this structure. This kind of system presents also a feature to operate in high frequency, reducing its size and weight. However, the cost may be a problem in this structure, due the possibility to use high number of active switch. In order to achieve low cost, a converter with low number of switches and with small magnetic should be selected. Thus, the flyback converter is the most suitable for this application, being chosen to be responsible for AC-DC conversion and power factor correction. The topology full-bridge is used on the inverter. To reduce the output filter, the PWM unipolar modulation is used. The proposed power line conditioner presents 115Vac output voltage, which implies in 180Vdc for DC link, due to the inverter structure.

The proposed power supply description, theoretical analysis of each stage, procedure design, as well as experimental results is show in this paper.

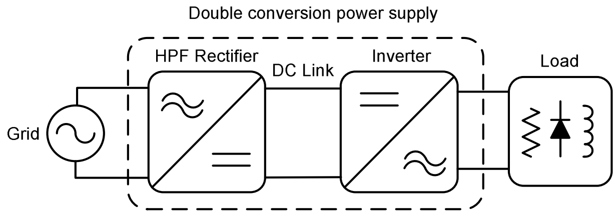

Fig. 1. Block diagram of proposed structure.

II. PROPOSED POWER SUPLLY DESCRIPTION

The proposed power line conditioner system is shown in Fig. 2. It is composed by the following parts: a full-bridge rectifier formed by diodes D1-D4; a high frequency input filter formed by inductor L1 and capacitors C1; a flyback converter formed by controlled switch S1, high frequency transformer T1, rectifier diode D6 and an output capacitor filter C3; and a full-bridge inverter formed by controlled switches S2-S5, inductor L2, and capacitor C4.

The flyback is responsible for AC-DC conversion with input current control to realize the power factor correction. It also regulates the voltage of DC link. Its control is based on critical current mode control, implemented with a dedicated integrated circuit.

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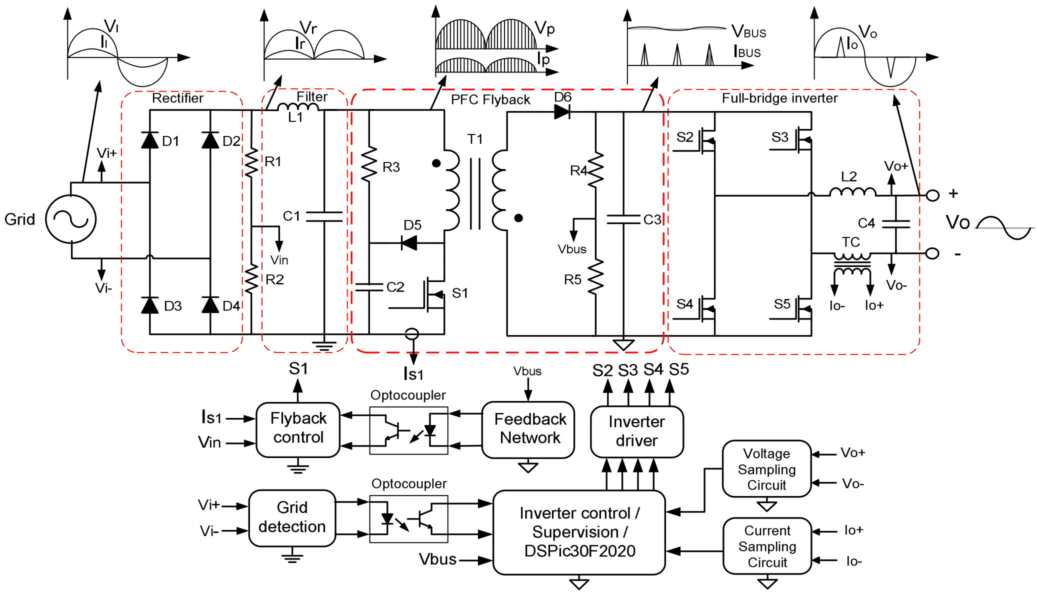

Fig. 2. Proposed structure.

The inverter is responsible for DC-AC conversion, generating a high quality sinusoidal waveform voltage, with low total harmonic distortion (THD). The inverter control is implemented digitally in a microcontroller.

The power line conditioner has a supervision system based on 16 bits DSPic30F2020 microcontroller. It is responsible for input overvoltage and undervoltage protection, output short-circuit protection, DC link voltage verification, user interface and inverter control.

III. FLYBACK ANALISYS

The first stage is based on flyback converter responsible for AC-DC conversion, input power factor correction, DC link voltage regulation independently of the input voltage. Fig. 3 shows the power circuit and control block diagram of the flyback. The converter is designed to operate with large range of input voltage, varying among 90Vca to 264Vca. The voltage stress in the semiconductors and the total harmonic distortion (THD) of the input current may vary as function of the input voltage value. The flyback converter works between the limit of the continuous and discontinuous conduction mode – named as critical conduction mode (CRM) [7-10]. Despite the discontinuity of the flyback input current, the low-pass input filter should to eliminate the high frequency harmonic content, providing high power factor. The crossover frequency of input filter should be one decade lower than the switching frequency. The inductor L1 operates in high frequency, presenting low volume.

The modulation strategy is based on constant conduction time of switch and variable off time, which results in variable frequency operation. This conduction time, T_{ON}, and off time, T_{OFF}, are given by (1) and (2), respectively.

$$T_{ON} = \frac{L_P \cdot I_{pPK}}{V_{pPK}} \quad (1)$$

$$T_{OFF} = \frac{L_P \cdot I_{pPK}}{n \cdot V_{BUS}} \cdot |\sin\theta| \quad (2)$$

Where:

V_{BUS} - Output voltage.
n - Transformer turns ratio.
Lp - Magnetizing inductance of the transformer primary side.
I_{pPK} - Peak current through the transformer primary side.
V_{pPK} - Peak current across the transformer primary side.

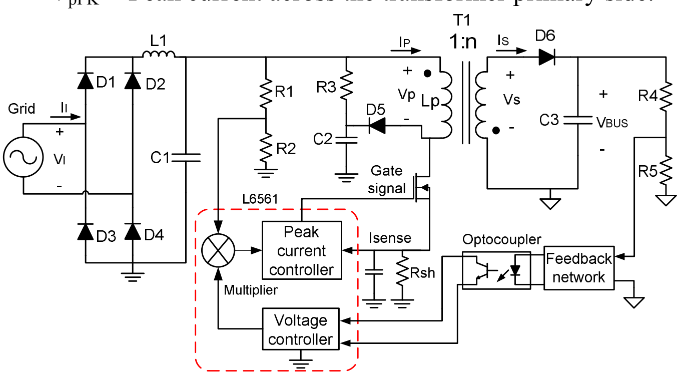

Fig. 3. Power circuit and block diagram of flyback converter.

Duty-cycle variation is given by:

$$D(\theta) = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{1}{1 + \frac{V_{pPK}}{n \cdot V_I} \cdot |\sin(\theta)|} \quad (3)$$

Fig. 4 shows the duty-cycle variation according to grid sinusoidal voltage angle, θ.

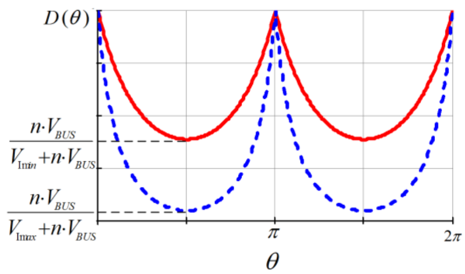

Fig. 4. Duty-cycle variation.

A. High Frequency Transformer Design

The root-mean-square value and peak value current of primary side and secondary side is important to its design and also to switch S1 and diode D1 design Then, according to [11-13], the peak value of transformer primary side current is given by (4).

$$I_{pPK} = \frac{2 \cdot P_I}{V_{pPK} \cdot \frac{1}{\pi} \cdot \int_0^{\pi} \frac{\sin(\theta)}{1 + \frac{V_{pPK}}{n \cdot V_I} \cdot |\sin(\theta)|} \cdot d\theta} \tag{4}$$

The RMS value of current of transformer primary side and secondary side are calculated according to [11-13] and given by (5) and (6), respectively. The peak current of transformer secondary side is obtained from $I_{sPK} = n \cdot I_{pPK}$.

$$I_{pRMS} = I_{pPK} \cdot \sqrt{\frac{\frac{1}{\pi} \cdot \int_0^{\pi} \frac{\sin^2(\theta)}{1 + \frac{V_{pPK}}{n \cdot V_I} \cdot |\sin(\theta)|} \cdot d\theta}{3}} \tag{5}$$

$$I_{sRMS} = I_{sPK} \cdot \sqrt{\frac{\frac{V_{pPK}}{n \cdot V_{BUS}} \cdot \frac{1}{\pi} \cdot \int_0^{\pi} \frac{\sin^3(\theta)}{1 + \frac{V_{pPK}}{n \cdot V_I} \cdot |\sin(\theta)|} \cdot d\theta}{3}} \tag{6}$$

The magnetizing inductance of the primary side Lp, is calculated in way that the converter operates in a minimum switching frequency, $f_{s\,min}$ [14]. Then Lp is given by (7).

$$L_P \leq \frac{1}{2} \cdot \frac{V_{pPK\,min}^{\;2}}{f_{s\,min} \cdot P_I} \cdot \frac{\frac{1}{\pi} \cdot \int_0^{\pi} \frac{\sin^2(\theta)}{1 + \frac{V_{pPK}}{n \cdot V_I} \cdot |\sin(\theta)|} \cdot d\theta}{\frac{V_{pPK\,min}}{n \cdot V_{BUS}} + 1} \tag{7}$$

B. Semiconductors Design

The maximum voltage across the switch S1 is

$$V_{S1} \leq V_{pPK} + n \cdot V_{sPK} \tag{8}$$

The current through the switch S1 is the same of transformer primary side. Then, the maximum value of RMS current through the switch S1 is given by (9).

$$I_{S1} = I_{pRMS} \tag{9}$$

The maximum voltage across the diode D6 is

$$V_{D6} \leq \frac{V_{pPK}}{n} + V_{BUS} \tag{10}$$

The current through the diode D6 is the same of transformer secondary side. Then, the maximum rms value and maximum average value of current through the diode D6 are given by (11) and (12), respectively.

$$I_{D6RMS} = I_{sRMS} \tag{11}$$

$$I_{D6AVG} = \frac{Po}{\eta \cdot V_{BUS}} \tag{12}$$

C. Control Strategy

The control strategy is based on critical current mode control implemented with the power factor correction IC L6561 [11], [12] and [13].

The control is based on multiplication of the output voltage controller error and the rectified input voltage sample. The output signal of the multiplier is compared with series resistor, Rsh, voltage signal using a comparator. When the voltage across Rsh is equal to the multiplier output, S1 is turned-off. When current through the magnetizing inductance achieve zero, S1 is turned-on. The multiplier guarantees that the slope of the current through the primary side of the transformer will have a sinusoidal shape, obtaining a high power factor. An external control loop was implemented using the TL431 and it is responsible for regulated the DC link voltage. The design control was performed according to [11] and [13].

IV. INVERTER ANALISYS

The DC-AC is based on classic full-bridge voltage source inverter with three level sinusoidal PWM modulation. The output voltage is 115Vca with frequency of 60Hz and supplied by the 180Vcc DC link voltage. The inverter control is implemented through a digital microcontroller DSPic30F2020 with two control loops – one for output voltage control and other for output current control. Fig. 5 shows the inverter power circuit and scheme control.

The first loop is based on digital PID controller and it act during the normal operation of the converter, providing a high quality sinusoidal output voltage. The second one is based on digital PI controller and it act during an output short-circuit to limit the peak value of current. In an output short-circuit, the current loop take the inverter act, and the inverter start to operates as a current source. If the short-circuit persist, the inverter is turned off after eight output voltage periods.

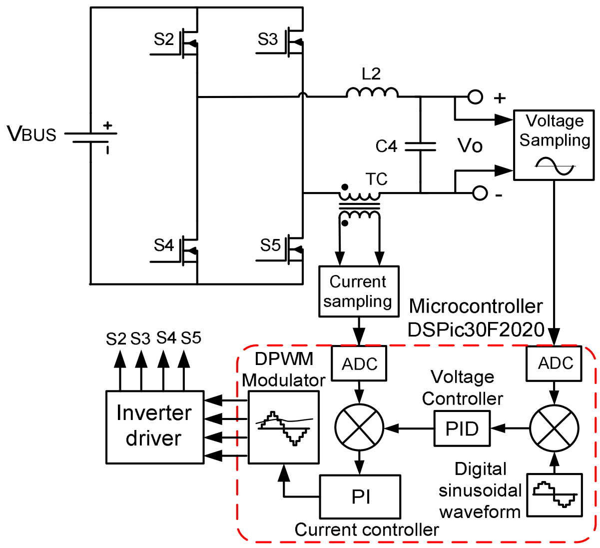

Fig. 5. Power circuit and block diagram.

V. EXPERIMENTAL RESULTS

The proposed power line conditioner design specification is shown in Table I. Tables II and III show the components used in the assembled prototype.

The experimental results consist of relevant voltage and current waveforms and also curves that demonstrate the performance of the proposed structure. As the system operates with a large range of input voltage the experimental results are presented just for the minimum and maximum nominal voltage, i.e. input voltage of 110 Vac and 220 Vac. Fig. 15 shows a picture of implemented prototype.

A. Experimental Waveform

Fig. 6 to 8 show the voltage and current waveforms corresponding of the system operation with 110V input voltage and nominal output power.

TABLE I
Power Line Conditioner Specification

Output power	500W
Input voltage	90 ~ 264 Vac
Input voltage frequency	60 Hz
Input power factor	≈ 1
Output voltage	115 Vac
Output voltage frequency	60 Hz
DC bus	180 Vdc
Minimum flyback switching frequency	40kHz

TABLE II
Flyback Parameters

Full-Bridge Rectifier	GSIB1580
Capacitor C1	Polypropylene - 3.3µF/250Vac
Inductor L1	L1 = 50µH NEE - 30/15/7 N = 72 turns (1x26AWG) lg =1.4mm
Switch S1	STW18NK80Z
Diode D6	HFA16TB120
Capacitor C3	Electrolytic – 1000µF/250Vdc
Transformer T1	Lp = 50µH NEE – 55/28/21 Np = 15 turns (18x26AWG) Ns = 18 turns (13x26AWG) lg =2.2mm

TABLE III
Inverter Parameters

Filter Inductor L2	L4 =710µH Core - 77076-A7 type Koll Mm From Magnetics. N= 116 turns (6x26AWG)
Filter Capacitor C4	6µF/250Vac
Switches S2, S3, S4, S5	IRF640FP

Fig. 6 shows the input voltage and input current waveforms. It is observed a high power factor of structure, due to the shape of input current and voltage.

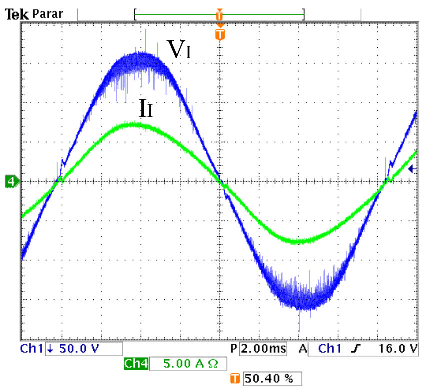

Fig. 6 – Input voltage and current for Vo=220V (Ch1: 50V/div.; Ch4: 5A/div.; 2ms/div.).

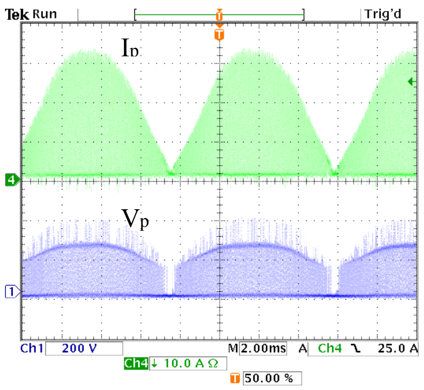

Fig. 7 – Voltage and current on S1 switch. (Ch1: 200V/div.; Ch4: 10A/div.; 2ms/div.)

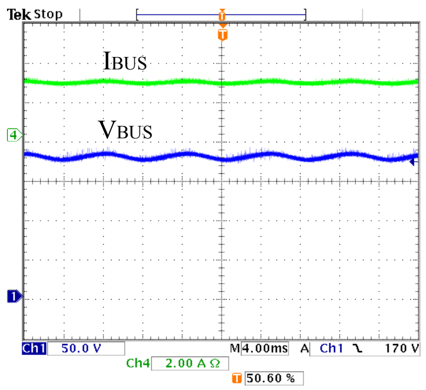

Fig. 8 – DC link voltage and current (Ch1: 50V/div.; Ch4: 2A/div.; 4ms/div.)

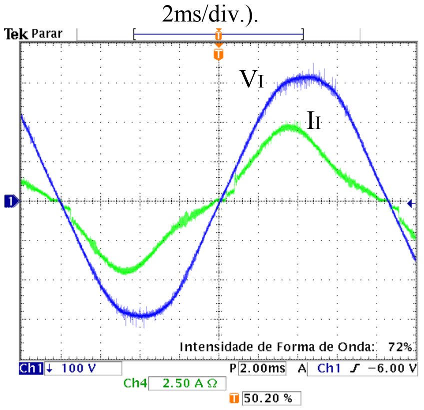

Fig. 9 – Input voltage and current (Ch1: 100V/div.; Ch4: 2.5A/div.; 2ms/div.)

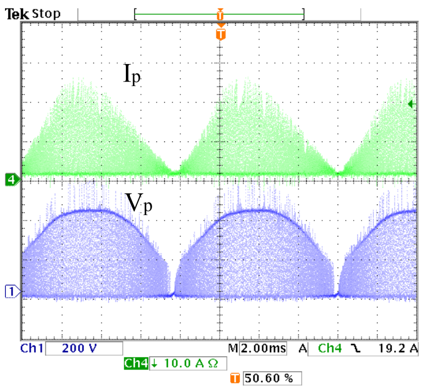

Fig. 10 – Voltage and current on S1 switch. (Ch1:200V/div.; Ch4:10A/div.; 2ms/div.)

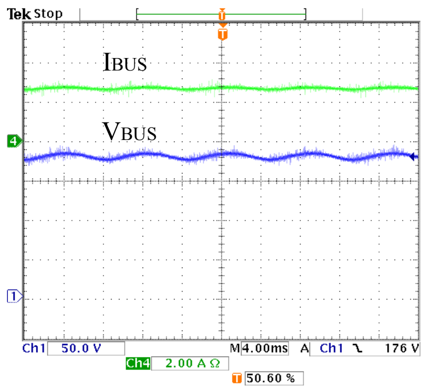

Fig. 11 – DC link voltage and current (Ch1: 50V/div.; Ch4: 2A/div.; 4ms/div.)

Fig. 7 shows the voltage and current waveform in the primary coil of high frequency transformer T1, where can be seen high frequency commutation detail. The DC link current and voltage are shown in Fig. 8, where is observed a constant value with low voltage ripple (≈ 9V).

The corresponding waveforms for 220V input voltage are shown in Figs. 9 to 11. The analysis of waveforms is similar to the case when the system operates with 110V input voltage. Then, it can be concluded that the system presents high input power factor and a stable voltage with low variation in the DC link, independently of input voltage of the system.

Fig. 12 and 13 show the output voltage and output current when the system feeds linear and non-linear load respectively. It is observed a high quality of output voltage waveform with low THD (≈ 3.4%) when the system supplies linear load. On the other hand, for non-linear load, the output voltage presents distortion. These waveforms were obtained for input voltage of 110V. For 220V input voltage the results are similar. Fig. 15 shows the input voltage variation from 110V to 220V and the output voltage response. It is observed that the response time of output voltage is zero. The output voltage is independently of input voltage, presenting no difference of input voltage range.

Fig. 16 shows the input voltage, output voltage and output voltage of system, when is applied to it a short-circuit. It can be seen that at the moment of short-circuit, the capacitor C4 discharged, causing a high current peak. Then, the inverter current control acts, turning it in a current source inverter. After eight periods of voltage grid, the output voltage is turned off.

B. Experimental Curves

Fig. 14 and 17 show the overall efficiency and input power factor curve as a function of output voltage for input voltage equal to 110V and 220V, respectively. It is observed a high input power factor for all operation range of power, when input voltage is equal to 110V. On the other hand, when the system operates with input voltage equal to 220V, the input power factor is lower, being above 0.9 for output power higher than 200W, due the low amplitude of input current. The overall efficiency is around 79% for input voltage of 110V and around 81% for input voltage of 220V.

The low efficiency is a characteristic of the structure of flyback converter [10]. The major sources of losses are the transformer and the switch S1. It is important to note that the MOSFET high conduction resistance (due to high voltage switch specification) associated with high rms switch current (due to critical conduction mode) generates high conduction switch losses, which implies in power processing limitation of the structure.

The higher efficiency for high input voltage is due the lower current through the component of flyback converter, increasing the efficiency of this converter.

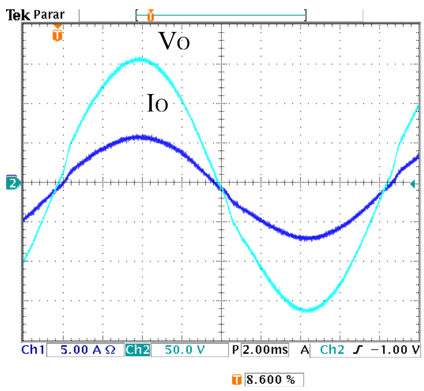

Fig. 12 – Output voltage and current for linear load (Ch1: 5A/div.; Ch2: 50V/div.; 2ms/div.).

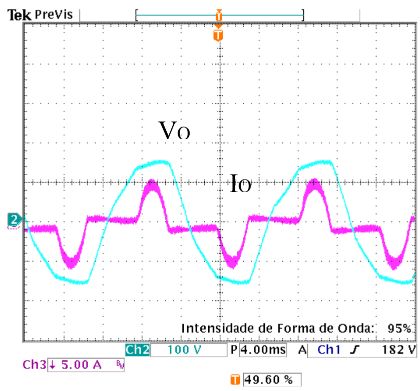

Fig. 13 – Output voltage and current for non-linear load (Ch2:100V/div.; Ch3: 5A/div.; 4ms/div.).

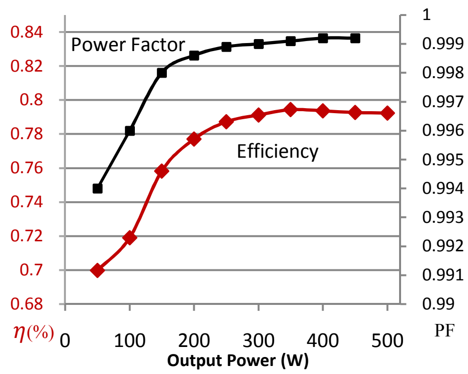

Fig. 14 – Variation of input power factor and global efficiency of the system with the output power for 110V input voltage.

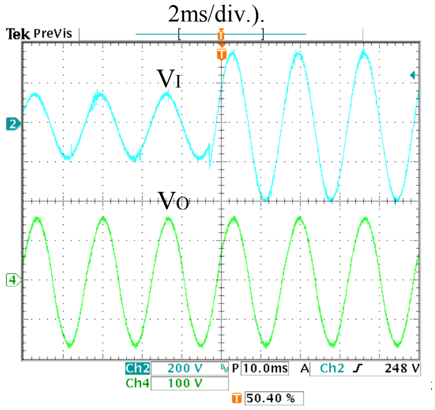

Fig. 15 – Input voltage variation and output voltage response (Ch2: 200V/div.; Ch3: 100V/div.; 10ms/div.).

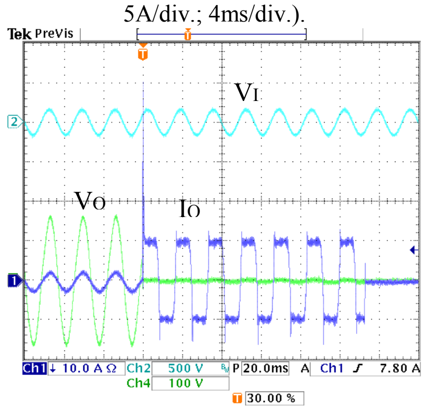

Fig. 16 – Output voltage and current during output short circuit (Ch1: 10A/div.; Ch2:500V/div.; Ch4: 100V/div.; 4ms/div.).

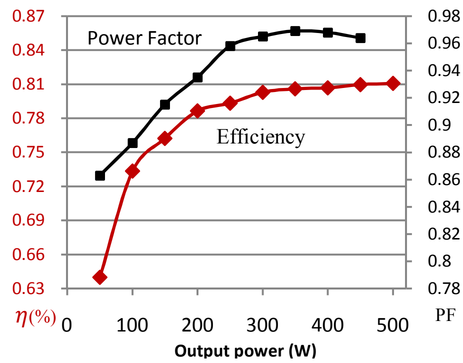

Fig. 17 – Variation of input power factor and global efficiency of the system with the output power for 220V input voltage.

VI. CONCLUSION

This paper has proposed a low cost AC-DC-AC power supply with power factor correction and high frequency isolation, which is suitable to operate with rms input voltage varying from 90Vac to 264Vac. The proposed system is based on two converters. For low cost purposes an AC-DC flyback converter and a full-bridge inverter was chosen.

Theoretical analysis of each stage, as well as the circuit control description was presented. A 500W prototype was implemented and tested for input voltage of 110V and 220V, with linear and non-linear load.

The experimental results show a high input power factor, mainly for low input voltage, a non-variation of output voltage, independently of input voltage, and high performance of short-circuit protection. The overall efficiency is around 80%, due the low efficiency of flyback structure. This system performance could be enhanced if same technique of soft switching be applied, as active clamp, to reduce the switching losses.

An optimized design of magnetic flyback can be performed to also increase the overall efficiency of the system. On the other hand, the increase of efficiency causes the increase of cost.

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