AC-AC INDIRECT CONVERTER FOR APPLICATION AS LINE CONDITIONER

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***Abstract* – This work presents the study and design of an AC line conditioner with three levels PWM modulation. Design, simulation and experimental results of a 220V and 10kVA conditioner were presented, that can provide energy to linear and non-linear loads.**

KEYWORDS

Line conditioner, AC-AC, indirect converter.

I. INTRODUCTION

Line conditioners are different of voltage regulators. Both can regulate the output voltage, but only the conditioners can conform the output voltage, providing to the load a voltage with a very low harmonic content. In this way, conditioners operate similarly as one active filter, correcting the distortion present at the line voltage.

At the present time topologies capable to operate as voltage regulator and as active filter, solving the commutation problem inherent to the AC-AC converters has been studied. To solve this problem [1] such topologies operate overlapping the active switch's signals. They are simple and robust structures. However, they present problems of current continuity caused by the storage energy in the filter inductors. Topologies constituted by four current bi-directional switches were presented at [2], [3] and [4]. Those structures need an elaborated circuit to command the active switches. In [5] was presented a similar topology with the same characteristics of [2], [3] and [4].

A line conditioner with voltage up/down capability was presented at [6]. It uses eight current bi-directional switches. This represents a high number of active switches. However, its command circuit is simple. It has the advantage of robustness and can use the classical PWM inverters principle. Considering these characteristics this topology was chosen to design a 10kVA line conditioner, with three level modulation, operating as active filter and as voltage regulator, feeding linear and non-linear loads.

II. CONVERTER STRUCTURE AND PRINCIPLE OF OPERATION

The power circuit of the line conditioner is shown in Fig. 1.

The switches S_1/S_2 and S_3/S_4 constitute the current bi-directional rectifier. The transformer T_1 applies the compensation voltage output. The inverter is constituted by the switches S_5/S_6 and S_7/S_8 and its output filter is formed by the capacitor C_o and the inductor L_o. All the active switches have an intrinsic anti-parallel diode.

The operation stages of this structure are described below.

The bi-directional rectifier has two operating stages. They depend of the input voltage (V_i) polarity.

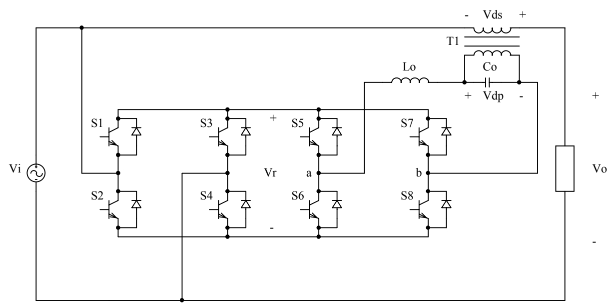

Fig. 1 – Power circuit of the line conditioner.

Stage 1 (for $V_i > 0$): S_1 and S_4 are ON. If i_o>0, the current i_{Lo} flows through D_1 and D_4. Otherwise it flows through S_1 and S_4. This stage finishes when the input voltage invert its polarity.

Stage 2 (for $V_i < 0$): S_2 and S_3 are ON. If i_o>0, the current i_{Lo} flows through D_2 and D_3. Otherwise it flows through S_2 and S_3. This stage finishes when the input voltage invert its polarity again.

The bridge inverter has five operating modes. These modes don't represent exactly the sequence stages of the converter operation. They have validity only when the converter is modulated by three levels PWM modulation.

Mode 1: S_5 and S_8 are ON. The V_{ab} voltage is positive. If i_o>0, the current i_{Lo} flows through S_5 and S_8. If not it flows through D_5 and D_8.

Mode 2: S_5 and S_7 are ON. The V_{ab} voltage is zero. If i_o>0, the current i_{Lo} flows through S_5 and D_7. Otherwise it flows through D_5 and S_7.

Mode 3: S_6 and S_7 are ON. The V_{ab} voltage is negative. If i_o>0, the current i_{Lo} flows through D_6 and D_7. If not it flows through S_6 and S_7.

Mode 4: S_6 and S_8 are ON. The V_{ab} voltage is zero. If i_o>0, the current i_{Lo} flows through D_6 and D_8. Otherwise it flows through S_6 and S_8.

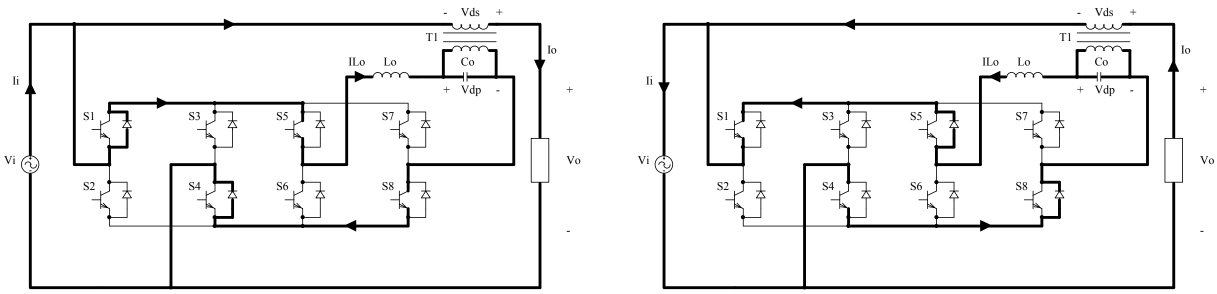

Fig. 2 – First stage.

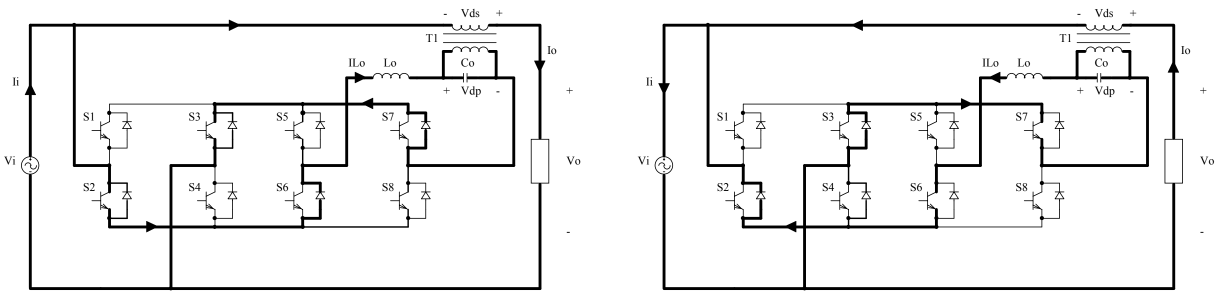

Fig. 3 – Second stage.

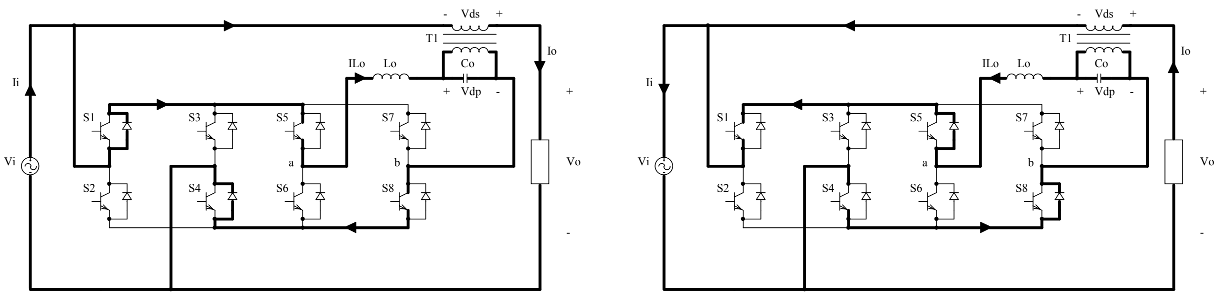

Fig. 4 – First mode.

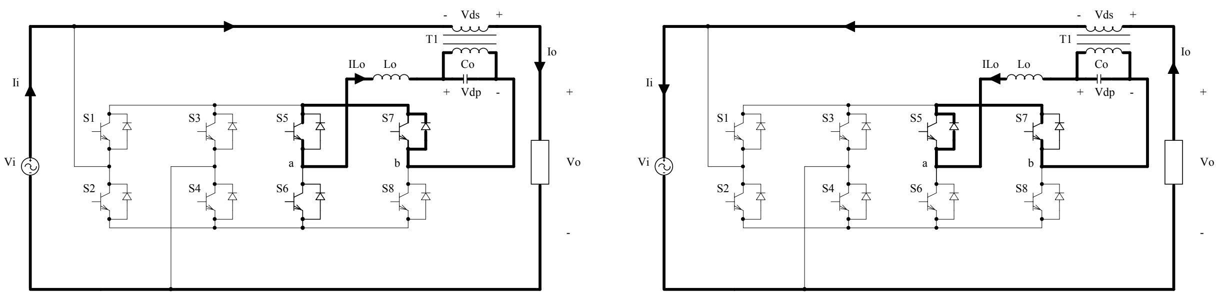

Fig. 5 – Second mode.

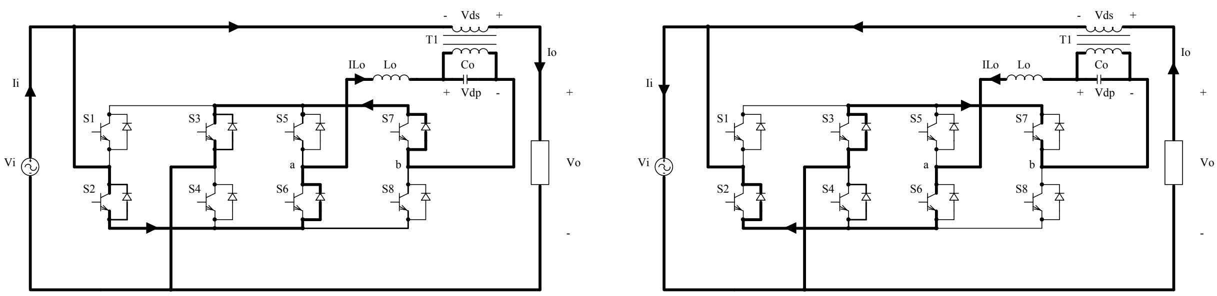

Fig. 6 – Third mode.

Mode 5: All the inverter switches are OFF. The V_{ab} voltage is positive if $i_o<0$ and negative if $i_o>0$. The current i_{Lo} flows through D_6 and D_7 if $i_o>0$ or through D_5 and D_8 if $i_o<0$.

The main wa veforms for a line period are shown in Fig. 9, Fig. 10 and Fig. 11.

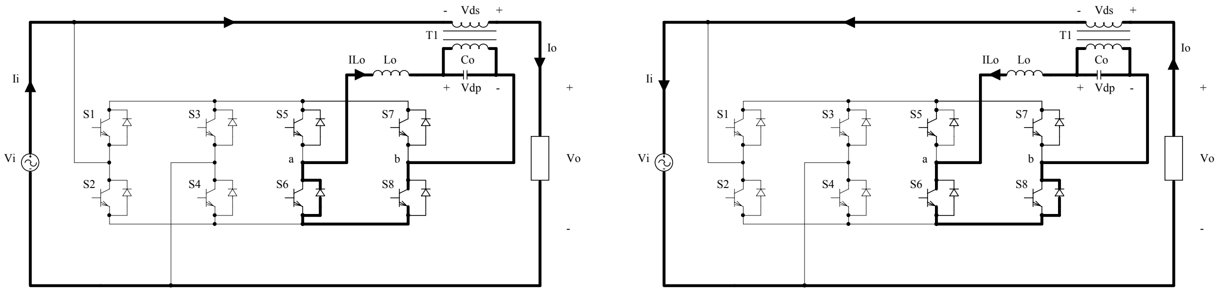

Fig. 7 – Fourth mode.

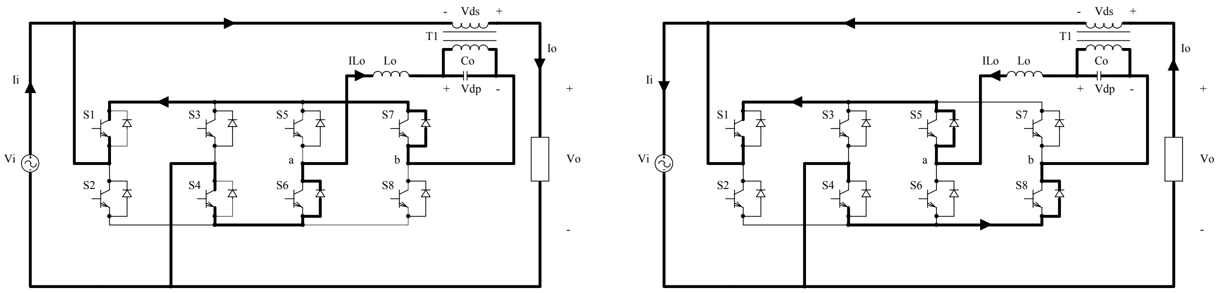

Fig. 8 – Fifth mode.

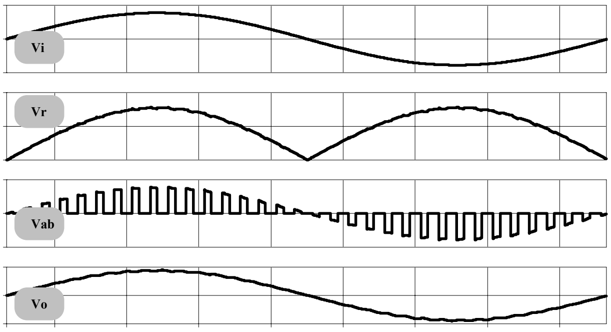

Fig. 9 – Main waveforms of the converter.

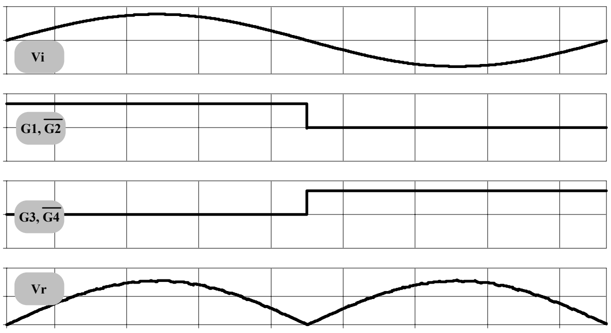

Fig. 10 – Waveforms for the bi-directional rectifier.

III. ANALYTICAL STUDY

The mathematical expressions presented in this section are valid for the converter modulated by three levels PWM modulation.

The line voltage applied in the conditioner input can have an amplitude variation of ± 20% of the rated voltage and is given by (1):

$$v_i(\omega t) = V_i \cdot \sin(\omega t) \quad (1)$$

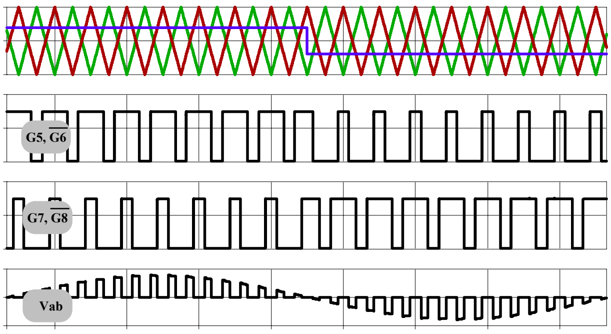

Fig. 11 – Waveforms for the bridge inverter.

The transformation ratio of the transformer T_1 is given by (2) and (3):

$$n_1 = \frac{V_{dp}}{V_{ds}} \quad (2)$$

$$n_1 = \frac{1-\Delta}{\Delta} D_{max} \quad (3)$$

Where: Δ – input voltage variation (20%);
D_{max} – maximum duty cycle.

The converter static gain is expressed by (4):

$$\frac{V_o}{V_i} = \frac{n_1 + D}{n_1} \quad (4)$$

To design the output filter elements it is necessary to know the mathematical expressions that give the current and the voltage ripple. So, (5) and (6) give the L_o current ripple and the C_o voltage ripple, respectively.

$$\Delta I_{Lo} = \frac{V_i - \left|(V_o - V_i) \cdot n_1\right|}{2 \cdot f_s \cdot L_o} D \quad (5)$$

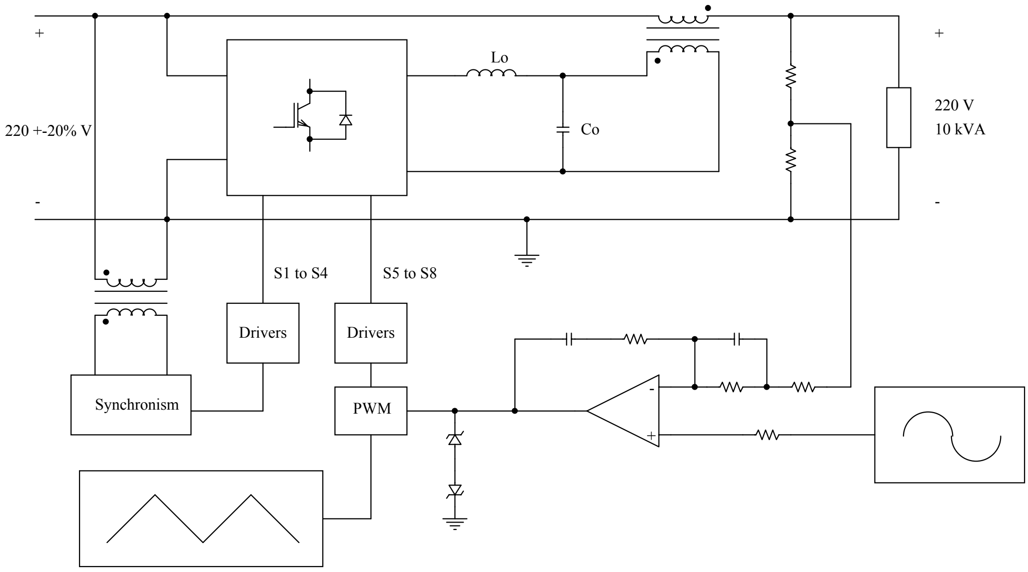

Fig. 12 – Converter diagram.

$$\Delta V_{Co} = \frac{V_i - \left|(V_o - V_i)\cdot n_1\right|}{\pi^3 \cdot f_s^{\,2} \cdot L_o \cdot C_o} D \qquad (6)$$

The converter transfer function, necessary to design the control circuit, is given by (8):

$$\frac{V_o(s)}{D(s)} = \frac{V_i}{n_1} \frac{1}{s^2 \cdot L_o \cdot C_o + s \cdot \dfrac{L_o}{R_o \cdot n_1^{\,2}} + 1} \qquad (7)$$

$$G(s) = \frac{V_o(s)}{V_s(s)} = \frac{V_i}{n_1 \cdot V_S} \frac{1}{s^2 \cdot L_o \cdot C_o + s \cdot \dfrac{L_o}{R_o \cdot n_1^{\,2}} + 1} \qquad (8)$$

Where V_s is the triangular peak voltage and R_o is the load resistance.

IV. DESIGN EXAMPLE AND SIMULATION RESULTS

In order to demonstrate the operation of the line conditioner and to validate the analytical study previously presented, a converter with the following parameters was design:

$$V_i = 220 \pm 20\%\,V \qquad V_o = 220\,V \qquad P_o = 10\,kVA$$

Using the classical methodology, a PID compensator was designed for the closed loop operation. Fig. 12 shows the designed converter diagram.

Fig. 13, 14, 15 and 16 show the main waveforms for the converter operating under line variation and feeding linear and non-linear loads. From these figures it can be verified the good operation and performance of the line conditioner.

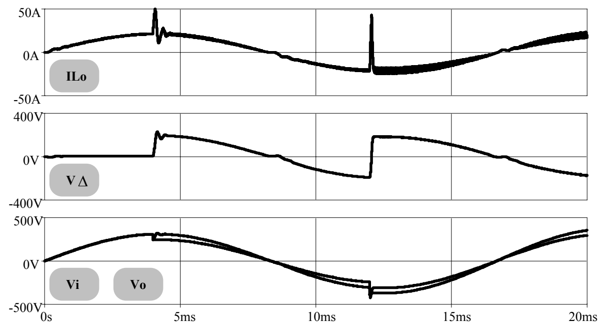

Fig. 13 – Input voltage variation.

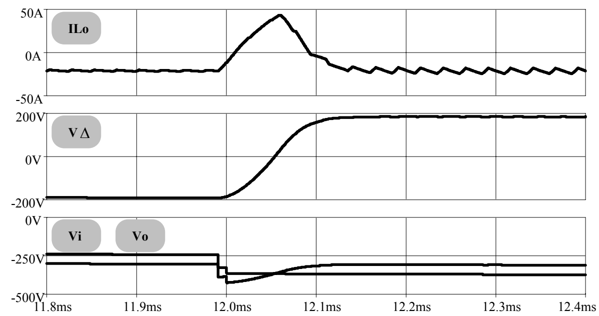

Fig. 14 – Detail of the input variation.

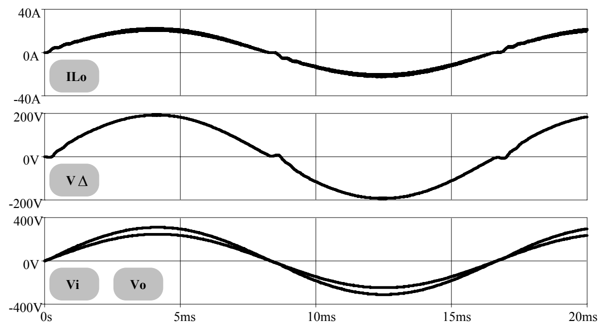

Fig. 15 – Feeding linear load.

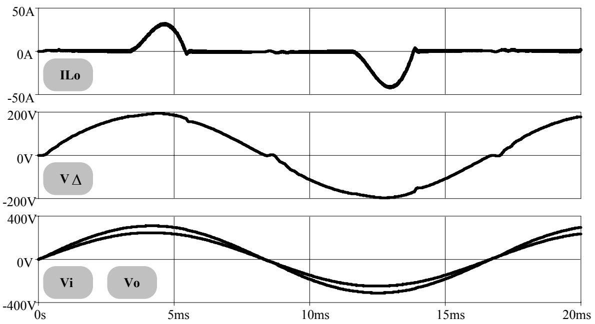

Fig. 16 – Feeding non-linear load.

V. EXPERIMENTAL RESULTS

In order to verify experimentally the principle of operation, some tests were made on a 10kW prototype with open loop control.

Fig. 17 shows the input voltage, the voltage after the rectifier and the gate signals for the switches S_1 to S_4.

Fig. 18 shows the input voltage and the control voltage that is compared with the saw-tooth voltage to generate the gate signals for the switches S_5 to S_8. The same figure shows the output converter voltage (V_{ds}) and the system output voltage (V_o). Fig. 18 shows the converter operating in addition way and Fig. 20 in subtraction way.

Input voltage, PWM ac voltage (V_{ab}), secondary transformer voltage (V_{ds}) and inductor current are shown in Fig. 19 for operating in addition way and in Fig. 21 for subtraction way.

Fig. 22 shows the input voltage, the output voltage and the input current for the converter. It can be observed that the input current has a good quality and small harmonic distortion.

The voltage after the rectifier and the inductor current are shown in Fig. 23 for operation with 10kW.

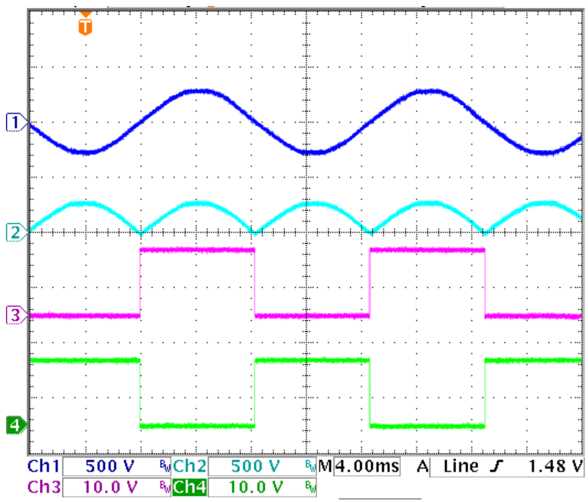

Fig. 17 – 1: input voltage, 2: voltage after rectifier, 3: gate voltage of S_1/S_4 and 4: gate voltage of S_2/S_3.

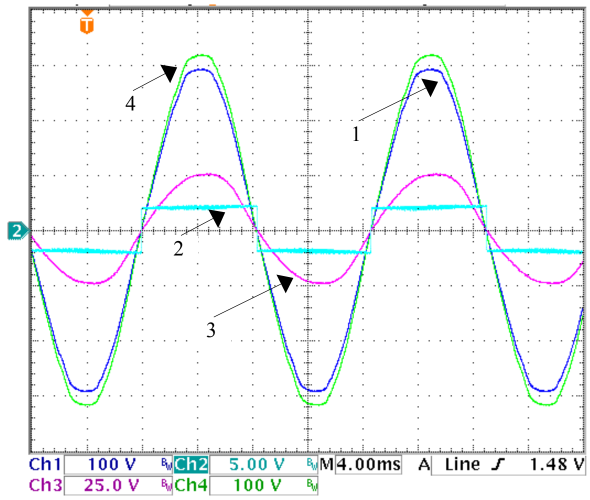

Fig. 18 – 1: input voltage, 2: inverter control voltage, 3: secondary transformer voltage (V_{ds}) and 4: output voltage.

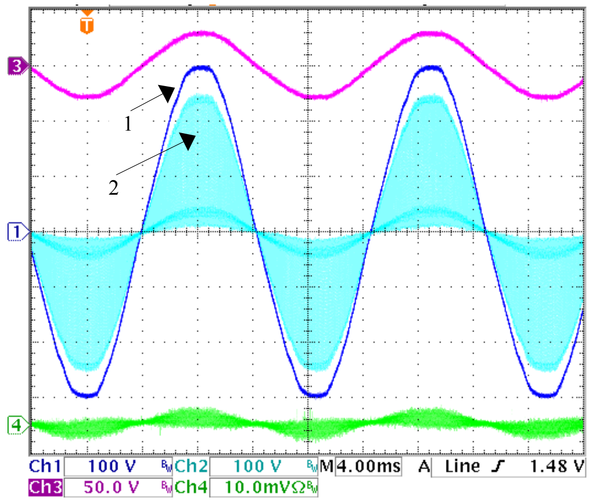

Fig. 19 – 1: input voltage, 2: PWM ac voltage (V_{ab}), 3: secondary transformer voltage (V_{ds}) and 4: inductor current (10A/div).

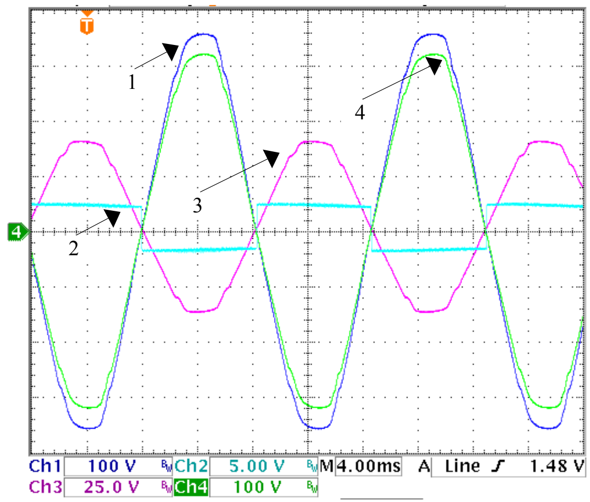

Fig. 20 – 1: input voltage, 2: inverter control voltage, 3: secondary transformer voltage (V_{ds}) and 4: output voltage.

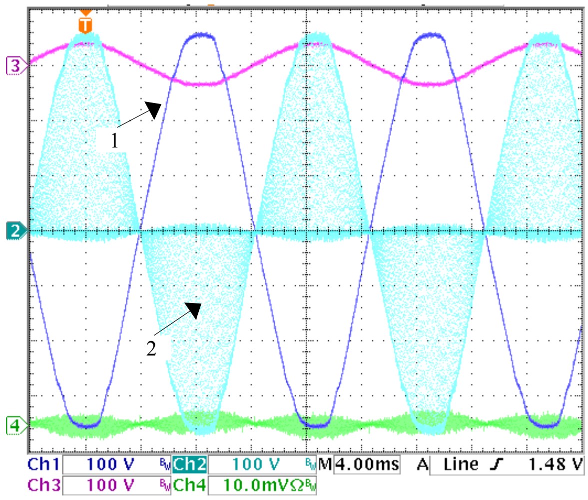

Fig. 21 – 1: input voltage, 2: PWM ac voltage (V_{ab}), 3: secondary transformer voltage (V_{ds}) and 4: inductor current (10A/div).

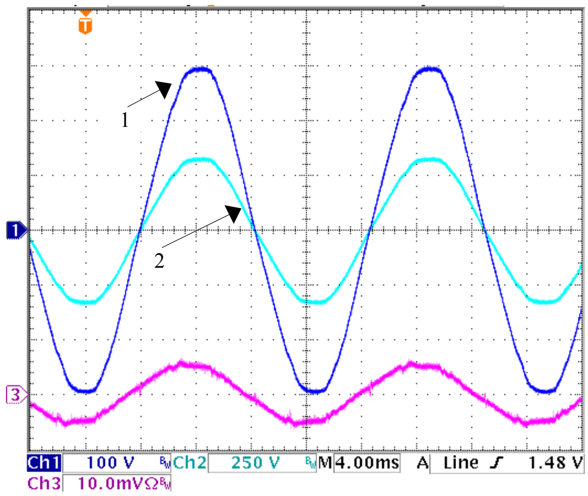

Fig. 22 – 1: input voltage, 2: output voltage and 3: input current (5A/div).

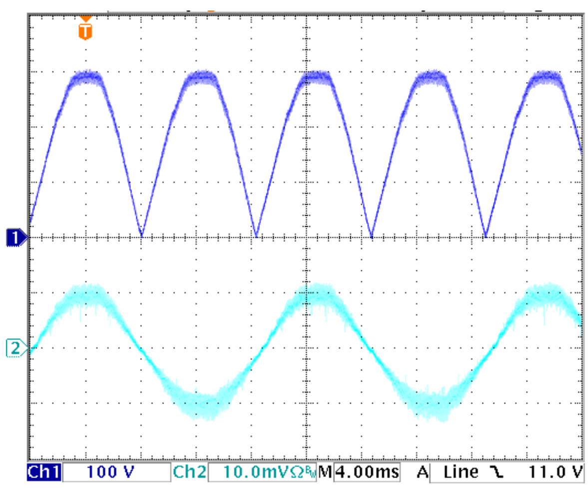

Fig. 23 – 1: voltage after rectifier and 2: inductor current (20A/div).

III. CONCLUSIONS

In this paper a line conditioner operating at high frequency (20kHz) and providing energy to linear and non-linear loads was presented. The operation stages and main waveforms were also shown. A 10kVA conditioner was designed and the simulation and experimental results proved the good operation as voltage regulator and as active filter.

The use of three levels PWM modulation in this case leads to a small size output filter. The main advantages of this topology are: simplicity of the command circuit, possibility of the use of classical inverter snubbers, robustness, small size and exploitation of the parasitic elements of the transformer T_1.

The harmonic content of the output voltage is very small and the dynamic behavior of the converter is very good, with a transient time of about 0,6ms to regulate the output voltage, when submitted to an input voltage variation. So, this topology is adequate to implement line conditioners.

ACKNOWLEDGEMENT

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