A NEW CONVERTER TOPOLOGY FOR A LINE VOLTAGE CONDITIONER

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***Abstract* – This work presents the study of a new converter topology and its application in line voltage conditioner. The description of the operation, the protection against short circuit in the load and the modeling of the new topology for a line voltage conditioner are studied in this paper. The design is also presented in this article besides the experimental results of a line voltage conditioner of 10 kVA with output voltage of 220 V and a switching frequency of 20 kHz. This conditioner supplies energy for linear and non-linear loads, providing stable output voltage and with smaller harmonic content, in relation to the input.**

***Keywords* – Line conditioner, AC-AC, indirect converter.**

I. INTRODUCTION

One of the techniques used to stabilize the load voltage is by the appropriate selection of derivations of transformers. This technique is efficient, as long as the number of derivations is large, what implicates in a great number of semiconductors. Phase control stabilizers do not allow elevate the output voltage, they only have voltage down capability. Lately most of the stabilizers used tiristor technology. Such converters, however, have slow response and they need great input and output filters to attenuate the high order harmonics.

This paper presents a new topology of voltage conditioner with PWM modulation. The voltage conditioners differ from the stabilizers, because besides stabilizing the voltage they reduce its harmonic content. However, we cannot confuse voltage conditioners with the energy conditioners. The energy conditioners reduce the voltage and current harmonic contents, while the voltage conditioners reduce only the voltage harmonic content.

A recent study on line voltage conditioners is the topology studied in [1, 2], shown in Fig. 2. This voltage conditioner operates with modulation PWM in high frequency (20 kHz) and, for being the type of voltage compensator, it processes only part of the load power, increasing the total efficiency of the structure. The present work was inspired in this conditioner, in way to create a converter with two bi-directional switches in less, in other words, one branch less. However the conditioner in [1, 2] has the advantage of presenting a smaller isolation transformer in relation to the used in this work for the same load power.

The conditioner proposed in this paper and the conditioner in [1, 2] both have a great dynamic performance, because they have not energy storage part and they operate with PWM modulation in high frequency (20 kHz). Both conditioners have high efficiency for the fact they process only part of the load power.

II. DESCRIPTION AND ANALYSIS OF THE LINE VOLTAGE CONDITIONER

A. The New Converter Topology

The new converter topology in study can operate with isolated input, as shown in Fig.1, or with isolated output. For this configuration change, ideally, it is enough to change the position of the input source with the load, besides modifying the commands of the bi-directional switches. In the voltage conditioners application we use the converter with isolated input for the reasons that will be seen next.

In the converter of Fig. 1 the switches S_1, S_2, S_3 and S_4 have the function of rectifying the input voltage, the S_5 and S_6 switches operate in high frequency and they constitute the inverting part.

In applications with output voltage in the same frequency of the main, the control voltage for the modulation is synchronized with the input voltage. Therefore, during the positive semicycle of the main voltage, the switch S_5 operates with duty cycle D and the switch S_6 commutes with duty cycle (1-D). In the negative semicycle of the main voltage the duty cycle is inverted, the switch S_5 operates with duty cycle (1-D) and the switch S_6 operates with duty cycle D.

B. Chooses of Isolated Input Converter Topology

In the conditioner of the references [1, 2] is used the isolation in the converter output, as presented in Fig. 2. It is observed that in this case the transformer input voltage goes through a rectifying and inverting stage, so due to impossibility of a perfect symmetry in the command of the switches, the voltage in the transformer input has a DC value. Thus, the converter topology with isolated output needs an additional loop for the offset voltage control in the transformer, besides the output voltage control loop. However, for this configuration the transformer dispersion inductance aids the converter output voltage filtering.

From the protection against short circuit in the load point of view, in the topology with isolated output converter it is not allowed the immediate opening of the converter switches at the moment which the short circuit is detected, because the short circuit current is in series with the transformer and its interruption would provoke over voltage in the switches. So it is necessary the use of two tiristors or a triac in parallel with the transformer, shown in Fig. 2, to circulate the short circuit current before opening the converter switches.

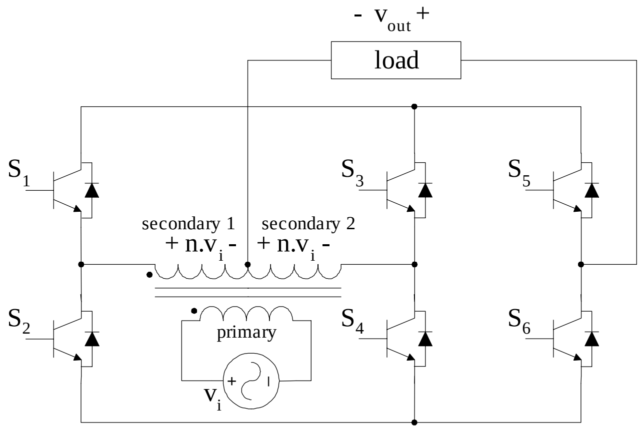

Fig. 1. Isolated input converter.

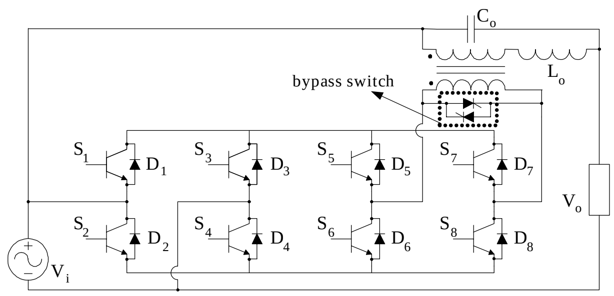

Fig. 2. Conditioner studied in the references [1, 2].

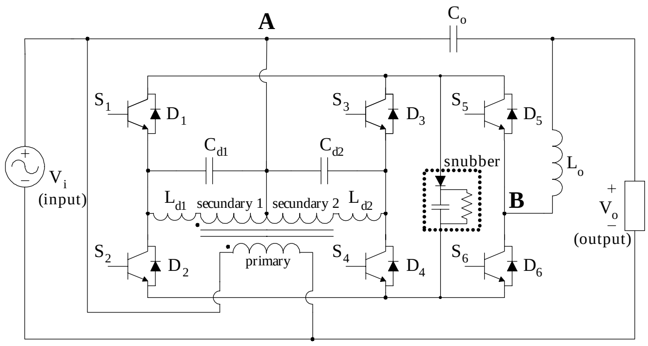

Fig. 3. Circuit of the proposed line voltage conditioner.

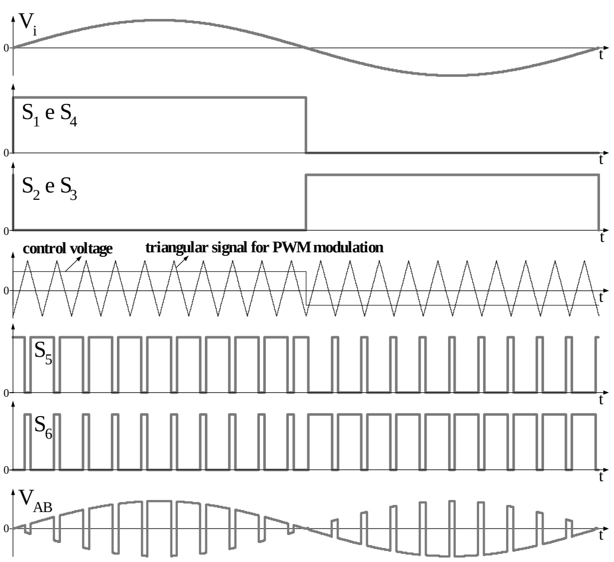

Fig. 4. Main waveforms f the conditioner proposed.

In the isolated input conditioners it is not necessary an additional loop to control the offset voltage, because the voltage supplied by the main does not have DC value. However, in this situation the leakage inductance should be uncoupled through capacitors in the transformer secondary winding to avoid overvoltage in the switches. The protection of this configuration against short circuit is simpler. The transformer is in parallel with the input source and so the converter switches can be opened in same instant which the short circuit is detected. In this way, it is necessary only a simple snubber for the filtering inductor demagnetization L_o.

Soon, we chose the configuration with isolated input, presented in Fig. 3, because it does not need additional control loop and it has simpler protection against short circuit.

C. Conditioner Operation Description

The proposed voltage conditioner uses the converter presented in Fig. 1 with a low pass filter in the output, as shown in Fig. 3. As already mentioned before, the converter needs two capacitors in parallel each with secondary winding to uncouple the transformer leakage inductances.

The main waveforms of the voltage conditioner are shown in Fig. 4. It is observed that the voltage between A and B points of the Fig. 3 (V_{AB}) in the converter output is filtered and added or subtracted of the main voltage (V_i) in a way to compensate the voltage in the load (V_o), for a certain variation range of the input voltage.

D. Modulation

The modulation of the converter is accomplished with a rectangular control voltage, shown in Fig. 4, different from the traditional sinusoidal modulation that it has the control voltage in the form of a sinusoid.

E. Modeling

The instantaneous average value of the V_{AB} voltage is obtained starting from the integration of this voltage in a switching period. In this way the equation (1) is obtained.

$$\boxed{\overline{V_{AB}} = (2D-1)nV_i} \tag{1}$$

Then the conditioner static transfer characteristic is obtained starting from the input voltage sum with the instantaneous average value of the V_{AB} voltage, as shown in the equation (2).

$$\overline{V_o} = V_i + (2D-1)nV_i \Rightarrow \boxed{\overline{V_o} = V_i\left[1+n(2D-1)\right]} \tag{2}$$

The dynamic model of the voltage conditioner is obtained by considering the small signals model. In this model it can be considered the low frequency sources of alternate voltage such as DC sources.

By using the model of the PWM switch of Vorpérian [6] in the continuous mode of current, the Fig. 3 can be redrawn according to Fig. 5.

Analyzing the small signal model in steady-state, shown in Fig. 6, the values of I_x and V_x, utilized in Fig. 5, are calculated.

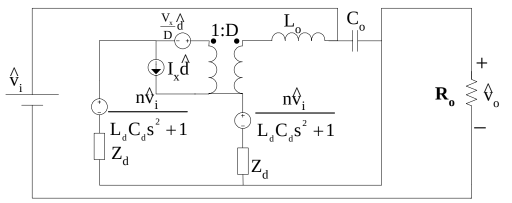

Fig. 5. Small signal model of the voltage conditioner.

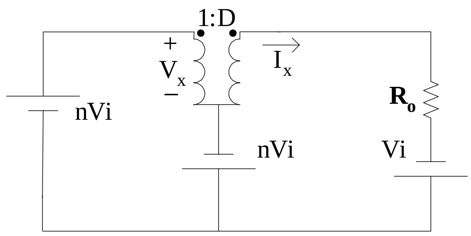

Fig. 6. Small signal model in steady-state.

So:

$$V_x = 2nV_i \tag{3}$$

$$I_x = \frac{V_i}{R_o}\left[n\left(2D-1\right)+1\right] \tag{4}$$

By making $\hat{v}_i = 0$ and analyzing the circuit of Fig. 5 it is found $\hat{v}_o(s)/\hat{d}(s)$.

$$\boxed{\frac{\hat{v}_o(s)}{\hat{d}(s)} = V_i\frac{2nR_o\left(L_dC_ds^2+1\right)+L_ds\left(1-2D\right)\left[n\left(2D-1\right)+1\right]}{\left(1+sC_oR_o\right)L_ds\left(2D^2-2D+1\right)+\left(s^2L_oC_oR_o+sL_o+R_o\right)\left(1+L_dC_ds^2\right)}} \tag{5}$$

By making $\hat{d} = 0$ and analyzing the circuit of Fig. 5 it is found $\hat{v}_o(s)/\hat{v}_i(s)$.

$$\boxed{\frac{\hat{v}_o(s)}{\hat{v}_i(s)} = R_o.\frac{n\left(2D-1\right)+L_dC_ds^2+1+L_oC_os^2\left(2D^2-2D+1\right)+L_oC_os^2\left(L_dC_ds^2+1\right)}{(sC_oR_o+1).L_ds.\left(2D^2-2D+1\right)+\left(s^2L_oC_oR_o+sL_o+R_o\right)\left(L_dC_ds^2+1\right)}} \tag{6}$$

III. VOLTAGE CONDITIONER DESIGN

A. Design Specifications

For simulation and implementation of a prototype in laboratory, the following specifications of the voltage conditioner were used:

V_i = 311V ⇒ Amplitude of the input nominal voltage;
Δ = 0.2 ⇒ Variation of the input voltage (± 20%);
V_o = 311V ⇒ Amplitude of the output voltage;
P_o = 10 kW ⇒ Output nominal power;
ΔI_{Lo_Io} = 0.4 ⇒ Current variation in the inductor in relation to amplitude of the output current;
ΔV_{Co_Vo} = 0.03 ⇒ Variation of the capacitor voltage in relation to V_o;
f_s = 20 kHz ⇒ Switching frequency.

B. Relation of the Transformer

Starting from the limits of variation of the input voltage of the voltage conditioner, the following transformation relations are obtained:

$V_{i\_max} = (1 + \Delta).V_i = 373.2$ V ⇒ D = 0 ⇒ n = 0.167
$V_{i\_min} = (1 - \Delta).V_i = 248.8$ V ⇒ D = 1 ⇒ n = 0.25

So, considering a sinusoidal ideal input voltage and not considering the voltage drop, to satisfy the two situations above, the relation should be n = 0.25.

Fig. 7 shows the mathematical simulation of the equation (2) for n = 0.25 and n = 0.5.

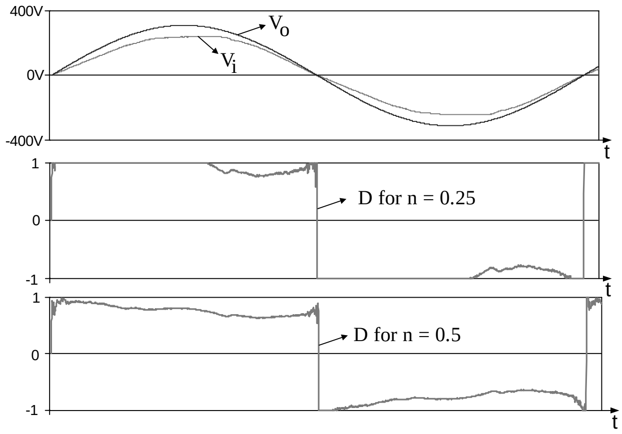

Fig. 7. Mathematical simulations of the duty cycle for different “n”.

It was considered in this simulation the ideal output voltage in the nominal value and a real input voltage with 80% of the nominal value. It is possible to observe that, due to saturation of the duty cycle for n = 0.25, we increased the transformer relation for n = 0.5. However, it is necessary to be aware that the increase of “ n ” also elevates the power of the transformer. For n = 0.5 the transformer power of this design was 4 kVA.

C. Uncoupling Capacitors

The uncoupling capacitors (C_d) were designed starting from the following specifications:

L_d = 50 μH ⇒ Transformer parasite leakage inductance;
f_s = 20 kHz ⇒ Switching frequency.
f_{od} ⇒ Frequency of resonance between L_d and C_d;

Knowing that the low pass filter L_dC_d, it attenuate approximately 40 dB per decade, to frequencies above f_{od}. Then to reduce the voltage ripple, caused by the switching, it must be used $f_{od} < f_s$.

$$f_{od} < f_s \Rightarrow \frac{1}{\sqrt{L_dC_d}} < 2\pi f_s \Rightarrow \boxed{C_d > \frac{1}{4\pi^2 f_s^{\,2} L_d}} \Rightarrow C_d > 1.27\ \mu F$$

Choosing $f_{od} \approx f_s/4$ $\quad C_d = 20.3\ \mu F \Rightarrow \boxed{C_d = 20\,\mu F}$

D. Output Filter

Starting from the relationship volt-ampere of the inductor it is found:

$$v_L = L\frac{di_L}{dt} \quad \Rightarrow \quad nV_i - V_{Co} = \frac{L_o \Delta I_{Lo} f_s}{D_o} \tag{7}$$

The maximum ripple happens for $D_o = 0.5$. Therefore:

$$\boxed{L_o = \frac{nV_i 0.5}{\Delta I_{Lo} f_s}} \quad \Rightarrow \quad \boxed{L_o = 150\,\mu H} \tag{8}$$

Considering that all the current variation in the inductor will go by through the filtering capacitor, decomposing this current in series of Fourier and conserving the fundamental component, it is obtained:

$$i_{Co} = \frac{4\Delta I_{Lo}}{\pi^2}.\cos\omega t \tag{9}$$

By multiplying the current with the impedance of the capacitor:

$$v_{Co} = i_{Co}.X_{Co} = \frac{i_{Co}}{\omega C_o} \Rightarrow v_{Co} = \frac{4\Delta I_{Lo}}{2\pi^3 f C_o}.\cos\left(\omega t - \frac{\pi}{2}\right) \tag{10}$$

Then the amplitude of the alternated component of the voltage v_{Co} will be:

$$\frac{\Delta V_{Co}}{2} = \frac{2\Delta I_{Lo}}{\pi^3 C_o f} \tag{11}$$

So:

$$\boxed{C_o = \frac{4\Delta I_{Lo}}{\pi^3 f_s \Delta V_C}} \quad \Rightarrow \quad \boxed{C_o = 20\mu F} \tag{12}$$

E. Controller Design

It was used for the control of the plant a proportional integral derivative controller (PID), presented in Fig. 9, designed for the plant model of the equation (5).

The PID controller to control the voltage conditioner was designed for the worst case, when the current of the non-linear load arrives in zero to each semicycle, in other words, for $R_o = \infty$. For this reason, the controller's design is done for this situation. It is observed in the equation (5) that, by making $R_o = \infty$, the poles and the zeros of the plant move into the imaginary axis.

In the PID compensator design, a pole was placed in (0 +j.0) so that the system should have null error to step in permanent regime, two zeros on the filter resonance frequency and a pole with the frequency nine times larger than the resonance frequency to improve the dynamic response of the plant. The controller's gain was adjusted so that the plant presented the best possible dampening, by using a PID compensator. Thus, this gain was adjusted according to the root locus of the system into closed loop such as presented in Fig. 8. In the instant that the current of the non-linear load gets to zero the system oscillates, therefore the concern with the dampening.

The equation (13) presents the PID controller transfer function, where:

$V_o^* = 0.01V_o$.

$$G_{controle}(s) = \frac{v_{controle}(s)}{v_o^*(s)} = \frac{[R_2C_1s+1].[R_4C_2s+1]}{C_2(R_1+R_2)s\left[\frac{C_1R_1R_2}{R_1+R_2}.s+1\right]} \tag{13}$$

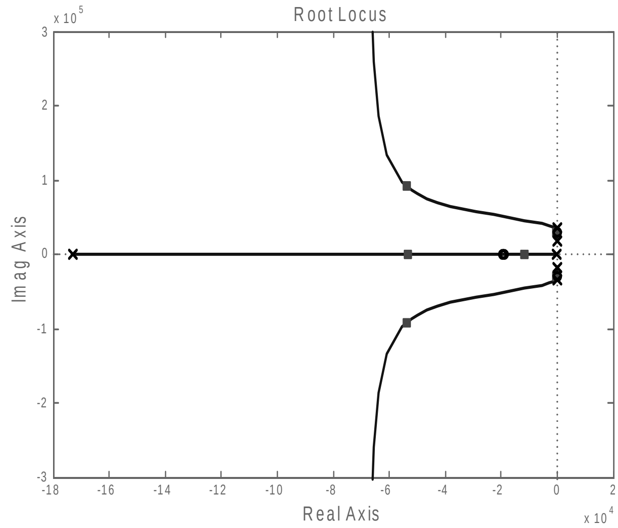

Fig. 8. Root locus of the plant with the controller.

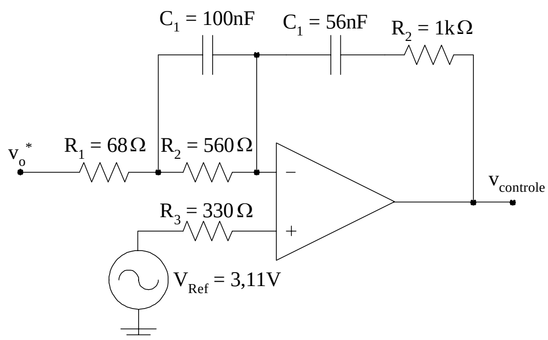

Fig. 9. Circuit of the PID compensator.

IV. CONDITIONER EXPERIMENTAL RESULTS

A. Analysis with Linear and Non-linear Load

Fig. 10 and Fig. 11 show the analysis with resistive load for input voltage -14% of the nominal value and +14% of the nominal value, respectively. These specific values of input variation were used, because the voltage source, used in the linear load testing, disposed only this voltage variation in the input.

It was verified in the analysis of resistive load, with nominal power and variation of the input voltage of -14% to +14% of the nominal value, that the output voltage is corrected in 220 V±0,5%.

Fig. 12 shows the analysis with non-linear load in the nominal power and with crest factor CF = 3.0.

In both analysis, with linear and non-linear load, the total harmonic distortion (THD) of the output voltage were below 5% and any harmonic component had not larger value than 3%, Fig. 13, attending to the limits of THD of the norm IEEE 519/92 [4].

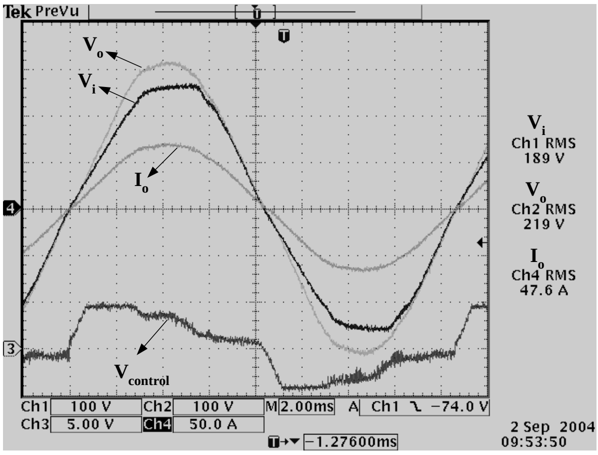

Fig. 10. v_i (-14%), v_o, $v_{control}$ and i_o for P_o = 10 kW.

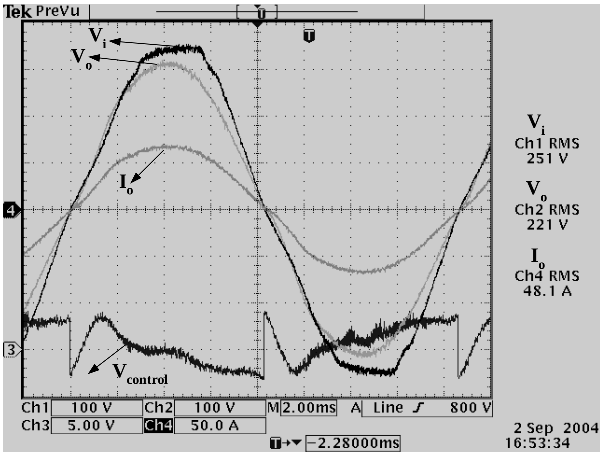

Fig. 11. v_i (+14%), v_o, $v_{control}$ and i_o for P_o = 10 kW.

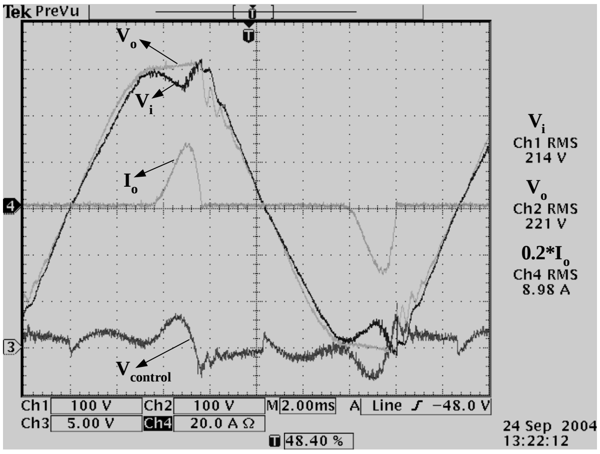

Fig. 12. v_i, v_o, $v_{control}$ and $0.2i_o$ for P_o = 10 kVA.

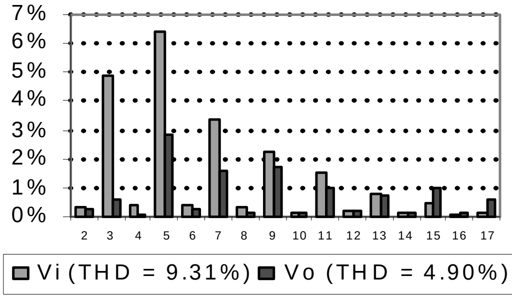

Fig. 13. Harmonics of v_i and v_o for non-linear load.

B. Efficiency

For the fact of the voltage conditioner process only part of the nominal power, the same presents a high efficiency.

The behavior of the voltage conditioner efficiency curve practically did not modify in all the range of the input voltage. The efficiency only varied in agreement with the load power, according to Fig. 14. In the nominal power the efficiency was around 97%.

C. Disturbances in the input voltage

Analyzes were accomplished with instantaneous disturbances of input voltage, with variations of -20% and +20% of the nominal voltage, shown in Fig. 15 and Fig. 16 respectively, for the conditioner operating without load. For these situations the correction of the output voltage was practically instantaneous.

D. Disturbances in the Load

In the test of instantaneous increment of 50% of the load (0 to 5 kVA), the output voltage presents a small oscillation and it is stabilized in 1/8 of the period of the input voltage, shown in Fig. 17.

During the decrement instantaneous of 50% of the load (5 kVA to 0), for any angle of load current interruption attempt, the current only extinguishes when the sinusoid of the output current goes by zero, as shown in Fig. 18. Therefore, this disturbance does not influence the output voltage.

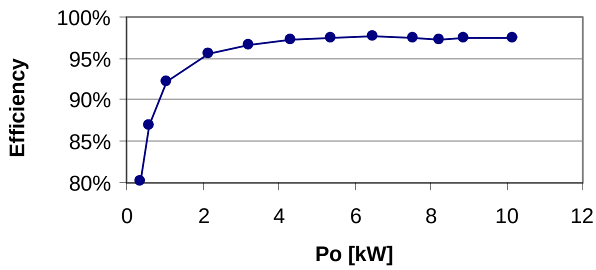

Fig. 14. Efficiency of the voltage conditioner.

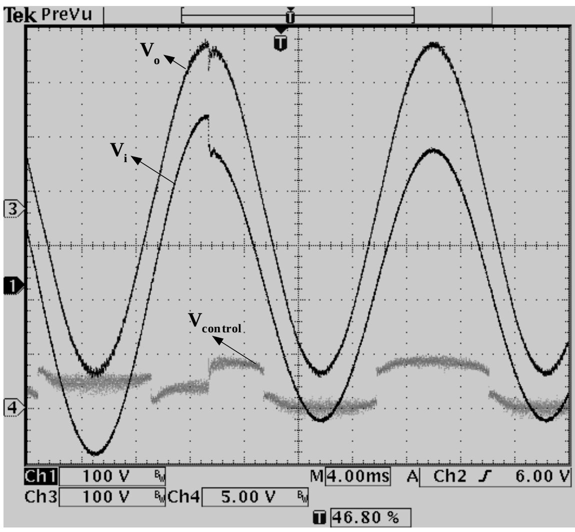

Fig. 15. Input voltage disturbance of -20%.

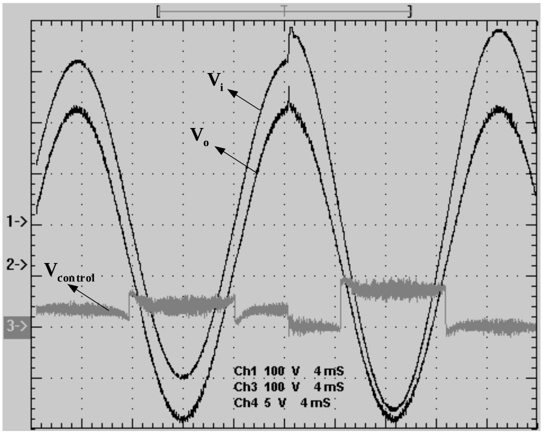

Fig. 16. Input voltage disturbance of +20%.

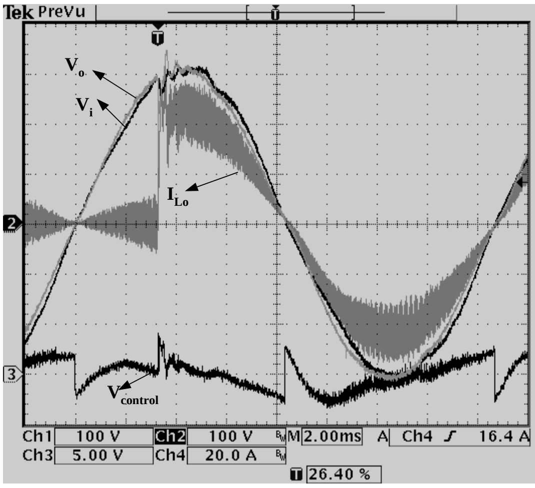

Fig. 17. Load disturbance of 0 to 50%.

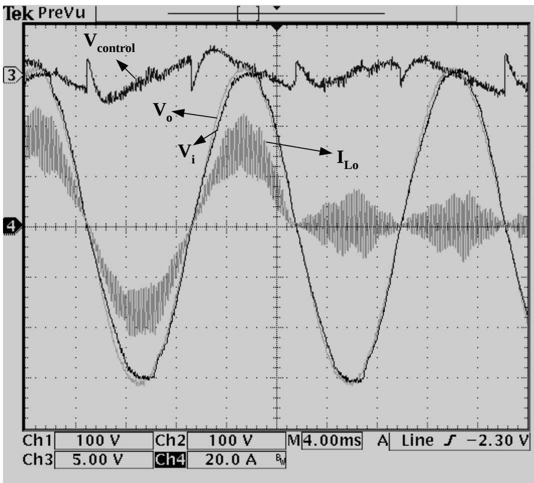

Fig. 18. Load disturbance of 50% to 0.

V. CONCLUSIONS

In this work was presented the study of a new converter topology applied in line voltage conditioner. To prove the correct operation of the new converter, a line voltage conditioner was implemented to feed linear and non-linear load with power of 10 kVA.

An important commitment in the design of the voltage conditioner is with the transformation relationship, the range of the input voltage variation and the output voltage static error. If larger the secondary voltage, larger is the input voltage variation range that the conditioner can regulate with low static error. However, the whole load current goes by the transformer, what implicates in the power of the same to be directly related to the secondary voltage.

Besides the input voltage variation range, the deformation of the main voltage can to saturate the control voltage, demanding high voltage on the secondary winding to correct this distortion. Besides, for non-linear loads the current derived increase produces a drop of significant voltage in the filtering inductor.

For the fact of the conditioner process only part of the load power, the same presented an excellent efficiency, around 97%.

The voltage conditioner has presented practically instantaneous correction of the output voltage, face the load and input voltage variations, what avoids overvoltage and failure for the consumers.

For input voltage around ±15%, the output voltage RMS was corrected in 220 V±0,6%. During all the tests accomplished with the prototype the ripple in high frequency of the output voltage was around 3% and the output total harmonic distortion was always reduced in relation to the input. In this way, the converter presented is appropriate for implementation in line voltage conditioners.

To continue stabilizing with small error (±0.6%), with main voltage out of the ±15% range, the transformer relation (n) must be increased in a way to also increase the voltages in the secondary. So must be calculated again the L_oC_o filter.

However, an increase in the transformer relation causes an increase in the power processed by the transformer.

By virtue of the independence between the phases, this design can be used in three-phase voltage conditioners of 30 kVA that have neutral.

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