Study of an AC-AC Indirect Converter used as a Line Conditioner

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***Abstract* — This work presents a study and design of an AC line conditioner operating in closed loop, which can provide energy to linear and non-linear loads. The converter is able to operate as an active filter, correcting distortions in the AC mains, providing an output voltage with low harmonic distortion. In order to validate the study, the experimental results of a 10 kVA prototype are presented.**

I. Introduction

AC voltage regulators are equipment necessary to provide energy for sensitive loads or in the industrial field, when the energy quality is poor. The main difference between AC voltage converters and DC voltage converters is the difficulty in performing the commutation, which demands the presence of clampers or elaborated circuitry to command the active switches. In indirect converters [6] this problem is not present, but the quantity of switches is greater than in direct converters.

In recent years, topologies that can actuate as voltage conditioners and that solve the commutation problem due to AC-AC conversion have been sought. [1] presented converters that operate by overlapping the active switch's signals. The advantages of these topologies are their simplicity and robustness. On the other hand, they present problems of average current in the output filter inductor. In [2, 3 and 4] topologies composed by four bidirectional current switches were presented, which have the disadvantage of demanding a complex driver. In [5] a similar topology was presented with the same characteristics from [2, 3 and 4].

An AC line conditioner with the ability to step up or step down the output voltage was presented in [6]. It uses eight bidirectional current switches. Even with the high number of switches, its command is simple and robust, and the PWM sinusoidal voltage inverter techniques can be used. Considering these characteristics, this topology was chosen for the study and development of a 10 kVA conditioner, with 3-level modulation, operating as a regulator and active filter, feeding linear and non-linear loads.

The main differences that are proposed, in relation to [6] are the control structure, which is based on the instantaneous control of the output voltage, with the controller design being developed in the frequency domain. Also, in the converter modeling, developed by instantaneous averaged values, the line impedance is considered, which alters significantly the converter transfer function. A solution that will be presented is to use an input filter in the rectifier stage, permitting a better frequency response and improving the dynamic response for load variations or input voltage variations.

II. Converter Structure and Principle of Operation

The simplified circuit of the voltage conditioner is shown in Fig. 1. The switches S_1/S_2 and S_3/S_4 form a bidirectional current rectifier, with low frequency operation, in order to rectify the input voltage. Transformer T_1 has the purpose of applying the output compensation voltage, adding or subtracting from the input voltage. Capacitor C_o and inductor L_o form the voltage inverter's output filter, which is formed by switches S_5/S_6 and S_7/S_8. All switches have antiparallel diodes.

The rectifier has two operating stages, which depend on the AC mains polarity ($v_i(t)$). The full bridge inverter has five operating stages, described in [6]. Filter capacitor C_o can be positioned on the secondary side of transformer T_1, using the transformer's leakage inductance as an additional output inverter voltage filter. So, L_o represents the total inductance seen by primary side of the transformer, that is, the leakage plus the inductance of the external inductor.

The line impedance, formed by its resistance and inductance, is represented by Z_i. The converter's circuit was conceived in order to discard the use of DC link capacitors, but, due to line impedance and parasitic inductances, it is necessary to use a small capacitor, in order to avoid overvoltage across the switches.

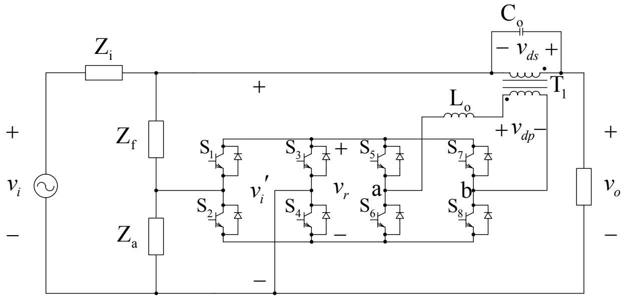

Figure 1 – Voltage conditioner circuit.

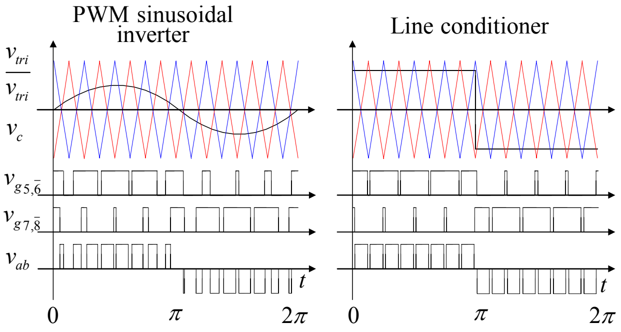

Figure 2 – Comparison between the modulation of an inverter and a line conditioner.

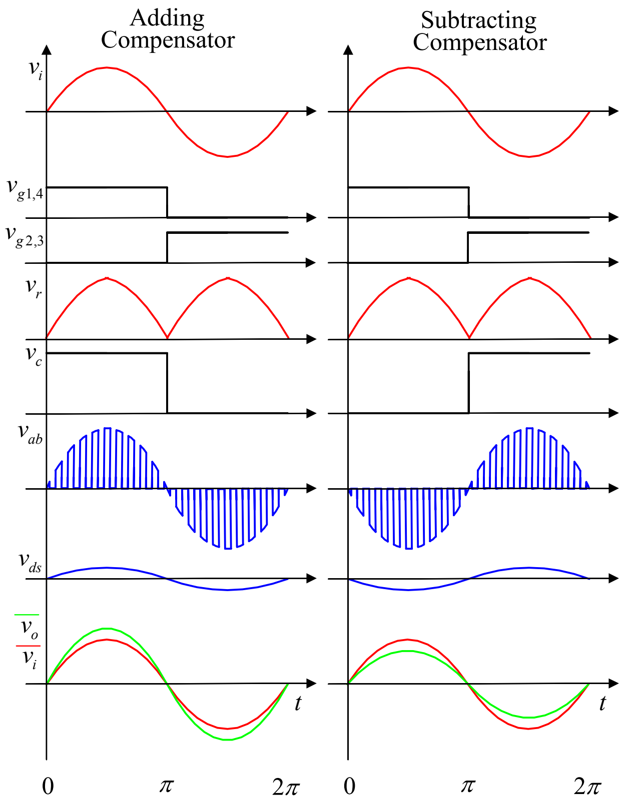

Figure 3 – Main waveforms of the power stage of the converter.

III. Modulation and Main Waveforms

The inverter modulation can be formed by two or three levels. A substantial difference between a sinusoidal PWM inverter used in an uninterruptible power supply and the studied converter is the modulating signal, which is compared to a high frequency triangular signal. That is the carrier in the modulation process. In Buck derived converters, the duty cycles ($d_1(t)$ and $d_2(t)$) can be obtained as a relation between the inverter's output ($v_{dp}(t)$) and input voltages ($v_r(t)$). Assuming that the commutation frequency is much greater than the frequency of the AC mains voltage, that is, using instantaneous average values, equation (1) can be written for a sinusoidal PWM inverter. For the studied converter, expressions (2) and (3) can be obtained, assuming that the inverter's output voltage is greater than zero and is in phase with the AC mains voltage.

$$d_1(t)=\frac{v_{dp}(t)}{v_r(t)}=\frac{V_{dp}\cdot sin(\omega_r\cdot t)}{V_r}=m\cdot sin(\omega_r\cdot t) \quad (1)$$

$$d_2(t)=\frac{v_{dp}(t)}{v_r(t)}=\frac{V_{dp}\cdot sin(\omega_r\cdot t)}{V_r\cdot|sin(\omega_r\cdot t)|}=m\cdot\frac{sin(\omega_r\cdot t)}{|sin(\omega_r\cdot t)|} \quad (2)$$

$$d_2(t)=m\cdot\begin{cases}+1 & 0\le\omega_r\cdot t<\pi\\ -1 & \pi\le\omega_r\cdot t<2\pi\end{cases} \quad (3)$$

$$m=\frac{V_{dp}}{V_r} \quad (4)$$

The modulation waveforms for a sinusoidal PWM inverter (1) and for a line conditioner (3) are shown in Fig. 2. The control voltage represents the time behavior of the duty cycle. It can be noted by Fig. 2 that the control voltage for a sinusoidal PWM inverter is a sinusoid, while for a line conditioner it is a rectangular voltage, then this modulation can be called rectangular PWM.

In Fig. 3 the converter's main waveforms are presented, showing its operation in conditions of adding and subtracting compensation voltage.

In Fig. 2 and 3 the following variables are shown:

- $v_{tri}(t)$ and $\overline{v_{tri}}(t)$ - triangular voltages;
- $v_c(t)$ - control voltage;
- $v_{g1,4}(t)$ and $v_{g2,3}(t)$ - rectifier's command;
- $v_{g5,6}(t)$ and $v_{g7,8}(t)$ - inverter's command;
- $v_{ab}(t)$ - inverter's output voltage;
- $v_{ds}(t)$ - compensation voltage;
- $v_i(t)$ and $v_o(t)$ - input and output voltages.

IV. Analytical Study and Converter's Control

A. Main Analitical Expressions

The expressions shown in this section are valid for the converter operating with three-level modulation.

The conditioner input voltage can present a variation (Δ) of ±20% in relation to the rated input voltage, given by expression (5). The turns ratio of transformer T_1 is given by (6). The converter's static gain is shown in expression (7). D_{max} is the maximum duty cycle.

For designing the inverter output filter, it is necessary to know its voltage and current oscillations, given by expressions (8) and (9), respectively, where F_s is the commutation frequency.

B. Converter Control

Determining the transfer functions for the output voltage vs. duty cycle and output voltage vs. input voltage is necessary to study the converter control and to design the voltage controller. The closed loop converter's complete circuit is shown in Fig. 4. In this figure, $Z_i(s)$ is the line impedance, $Z_f(s)$ and $Z_a(s)$ are the series and parallel impedances of the input filter, respectively. To model the converter, the following assumptions are made:

- Switches S_1 to S_8 and transformer T_1 are ideal;

- The inductor's and capacitor's equivalent series resistances are negligible;
- The load is purely resistive;
- The commutation frequency ($\omega_s = 2\pi \cdot F_s$) is much greater than the AC mains frequency ($\omega_r = 2\pi \cdot F_r$).

Since the inverter is a Buck type converter, operating with three-level modulation, it can be modeled as a DC-DC circuit, with the maximum AC mains voltage, using Vorpérian's PWM switch model as is shown in Fig. 5. Beginning from this circuit and eliminating $Z_i(s)$, $Z_f(s)$ and $Z_a(s)$, expressions (10) and (11) can be obtained.

Bode diagrams of expression (10) are shown in Fig. 6 where it is noted the similarity to Buck and Forward converters. A PID (proportional-integral-derivative) controller allows obtaining good results in closed loop operation, for a system with transfer functions given by (10) and (11).

$$v_i(t) = V_i \cdot sin(\omega_r \cdot t) \quad (5)$$

$$n_1 = \frac{v_{dp}(t)}{v_{ds}(t)} = \frac{1-\Delta}{\Delta} \cdot D_{max} \quad (6)$$

$$g(t) = \frac{v_o(t)}{v_i(t)} = \frac{n_1 + d(t)}{n_1} \quad (7)$$

$$\Delta I_{Lo}(t) = \frac{v_i(t) - \left|\left(v_o(t) - v_i(t)\right) \cdot n_1\right|}{2 \cdot F_s \cdot L_o} \cdot d(t) \quad (8)$$

$$\Delta V_{Co}(t) = \frac{v_i(t) - \left|\left(v_o(t) - v_i(t)\right) \cdot n_1\right|}{\pi^3 \cdot F_s^2 \cdot L_o \cdot C_o} \cdot d(t) \quad (9)$$

$$G(s) = \left.\frac{\widehat{v_o}}{\widehat{d}}\right|_{\widehat{v_i}=0} = \frac{V_i \cdot R_o \cdot n_1}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o \cdot n_1^2} \quad (10)$$

$$F(s) = \left.\frac{\widehat{v_o}}{\widehat{v_i}}\right|_{\widehat{d}=0} = \frac{R_o \cdot \left(s^2 \cdot L_o \cdot C_o + n_1^2 + n_1 \cdot D\right)}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o \cdot n_1^2} \quad (11)$$

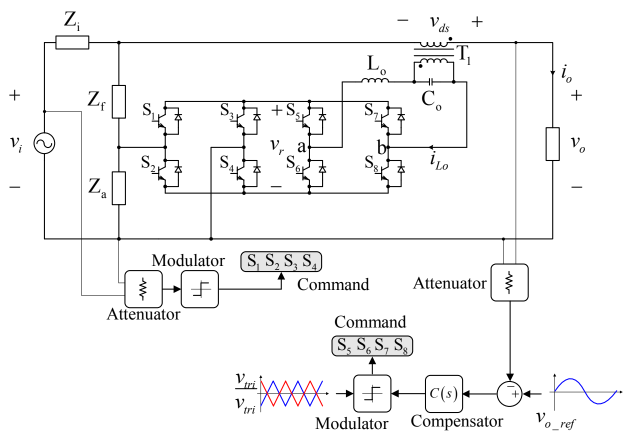

Figure 4 – Converter's control circuit.

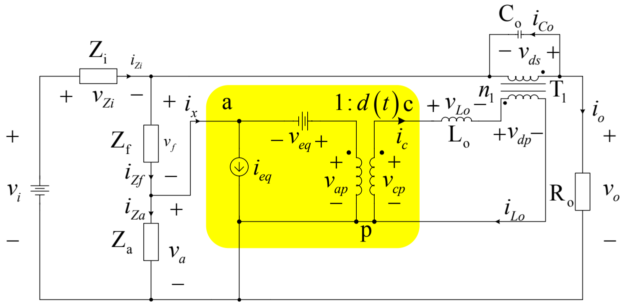
Figure 5 – Equivalent circuit for small signal model.

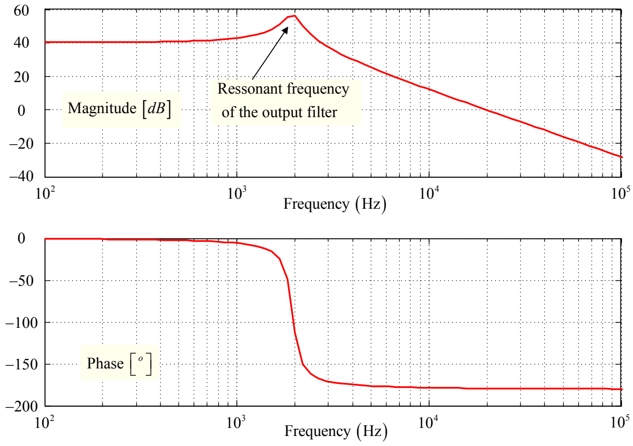

Figure 6 – Bode diagrams of magnitude and phase of expression (10).

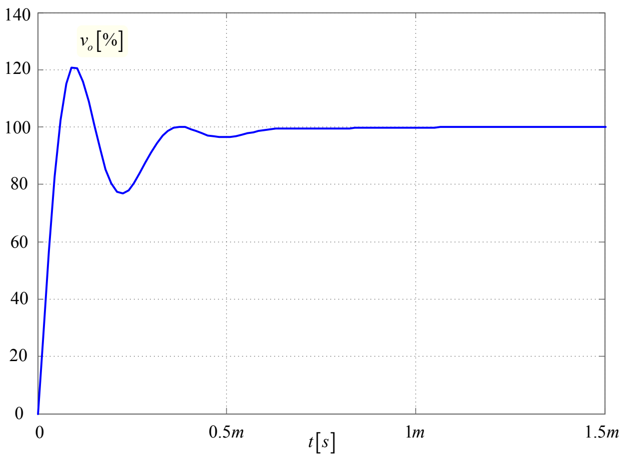

Figure 7 – Unity step response of the system in closed loop.

Verifying the converter operation in closed loop, a controller can be determined using the classical methodology of design in the frequency domain. In Fig. 7, the system response to a unity step disturbance is shown, where it can be noted its dynamic performance. $F_s/4$ is the open loop cross frequency.

C. *The Line Impedance Problem*

For a converter connected to AC mains, the line impedance $Z_i(s)$ will not be zero, and transfer functions from expressions (10) and (11) will no longer be valid. Moreover, new expressions for $G(s)$ and $F(s)$ are complex and present zeros on the right-hand side of the complex plane. The right-hand side zero problem, typical of Boost converters in voltage mode was studied in [7 and 8]. In Fig. 8, a converter simplified circuit is shown in order to help clarify this problem.

In a converter without line impedance, when a positive duty cycle step (*d(t)*) is applied, the output voltage will increase instantaneously. For AC-AC converters connected to the AC mains an increase in *d(t)* implies on an increase in the compensation voltage and also in the converter input current. This current flowing through impedance Z_i implies in a voltage drop, and so, during Δt, the output voltage decreases, and, after this, increases as desired. In this way, the line impedance effect can be interpreted as a delay on output voltage response due to duty cycle variations. In terms of control, this is modeled as a zero in converter transfer function *G(s)*.

From Fig. 9, it can be noted that the ideal system, without line impedance, has no delay and the output voltage increases instantaneously with the increase in *d(t)*. The converter with line impedance has the delay and, moreover, has an output voltage oscillation due to the voltage drop in Z_i from converter's high frequency current. Both effects can be attenuated by using an input filter with the rectifier which is shown in Fig. 10. It is noted that the filter is positioned at the rectifier input, sustaining only this rectifier current.

The input filter performs basically two functions in this operation. The first is to filter the converter's current, therefore, improving the power factor seen by the grid, it also attenuates the voltage drop due to the converter's high frequency current through impedance Z_i and which would appear in the output and flow through the output voltage sensor and possibly cause problems to the structure's control. The second is to cause a phase displacement in the grid line current required by the converter. This second function is better understood by observing in Fig. 11 that a DC voltage bus converter, where the rectifier's input current is controlled, has the effect of decoupling the current required by the converter ($i_{Zf}(t)$) and the inverter's output current ($i_{Lo}(t)$) and, consequently, the compensation voltage ($v_{ds}(t)$). If the converter has no DC bus, then it is said that the rectifier and the inverter are directly coupled and the input and output currents are directly proportional. The input filter has the ability of partially decoupling the rectifier and the inverter, that is, $i_{Zf}(t)$ and $i_{Lo}(t)$.

Another solution to avoid the problem caused by line impedance, but not using the input filter with the converter, is to design a slower controller, limiting the converter's dynamic response and inhibiting the active filtering action.

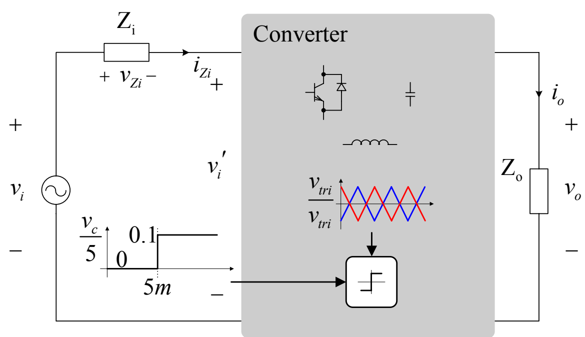

Figure 8 – Converter's simplified circuit.

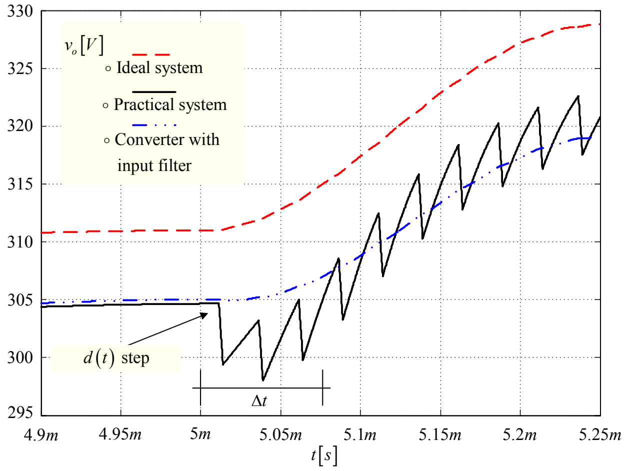

Figure 9 – Converter's responses to a step in duty cycle.

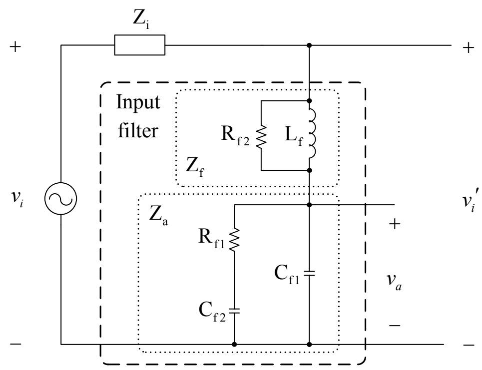

Figure 10 – Converter's input filter.

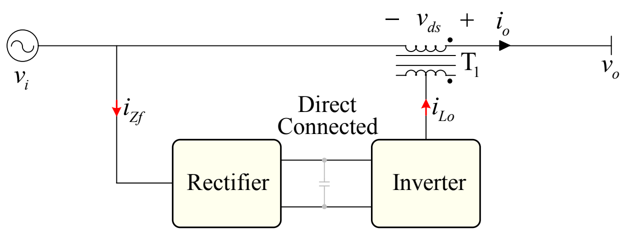

Figure 11 – Coupling between the rectifier and the inverter.

V. Design Example and Experimental Results

A. Converter specifications

The conditioner built in the laboratory has the following specifications:

- $v_i = 220 \pm 20\%[V]$ - input voltage;
- $v_o = 220[V]$ - output voltage;
- $S_o = 10[kVA]$ - output power;
- $F_r = 60[Hz]$ - AC mains frequency;
- $F_s = 20[kHz]$ - commutation frequency;
- $n_1 = 3$ - T_1's transforming ratio;
- $L_o = 570[\mu H], C_o = 120[\mu F]$ - output filter;
- $L_f = 100[\mu H], C_{f1} = 60[\mu F], R_{f1} = 1[\Omega]$
  $C_{f2} = 10[\mu F], R_{f2} = 1.2[\Omega]$ - input filter;

- Fig. 12 – voltage compensator;
- Fig. 13 – non-linear load.

B. *Operation with linear load*

In Fig. 14, output voltage waveforms with a 10 kVA linear load and using fast and slow compensators are shown, both with the converter operating with an input filter. It must be noted that the slow compensator can be used whether the converter has the input filter or not, but the fast compensator can be used only in the presence of the input filter.

The voltage reference for the converter control must be synchronized with the input voltage and in case it varies its frequency, the reference must follow these variations, since the output voltage must always be in phase with the input voltage.

C. *Operation with non-linear load*

The greatest requirements in terms of dynamic response are during the operation with non-linear load. As can be seen in Fig. 15 the output voltage is a sinusoid with a very low harmonic distortion (2.05%).

In Fig. 16, the output voltage waveforms with slow and fast controllers are shown. It is noted the superior performance of the fast system, which effectively behaves as an active filter. The non-linear load's crest factor is 3.

D. *Load and input voltage transients*

Output voltage and control waveforms for a +10% transient in input voltage can be observed in Fig. 17. The converter with input filter and fast compensator has a faster response than the converter without a filter and a slow compensator. However, both correct quickly the output voltage, maintaining it within safe values for the load.

A load transient of +50% was applied to the converter operating with an input filter and a fast compensator and the results are shown in Fig. 18. It is verified that the output voltage is quickly corrected, showing that the system is practically insensitive to load variations.

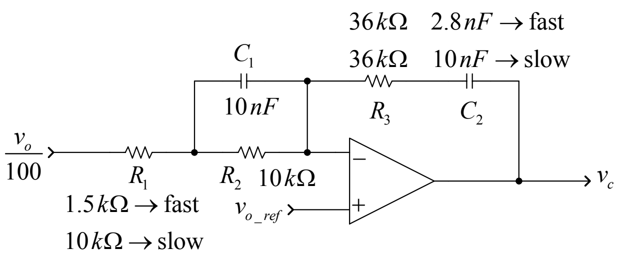

Figure 12 – Voltage compensator.

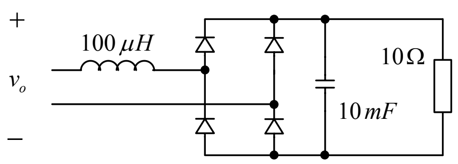

Figure 13 – Non-linear load.

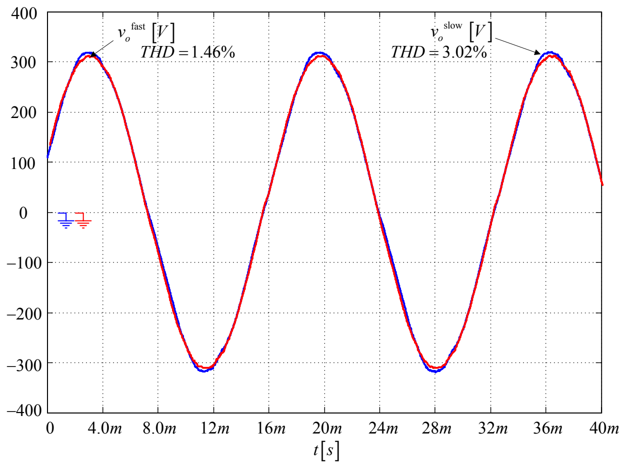

Figure 14 – Operation with a linear load.

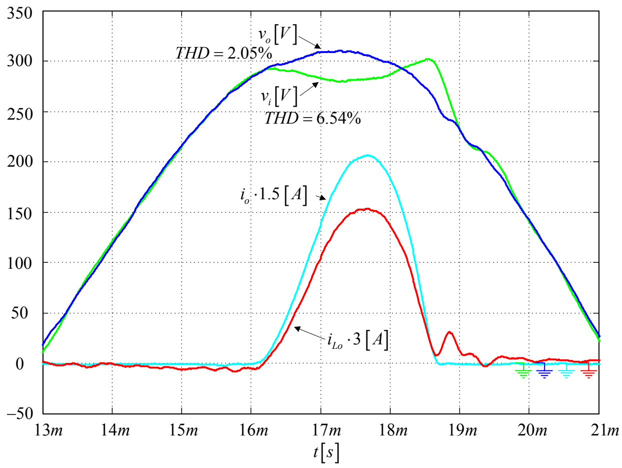

Figure 15 – Operation with a non-linear load.

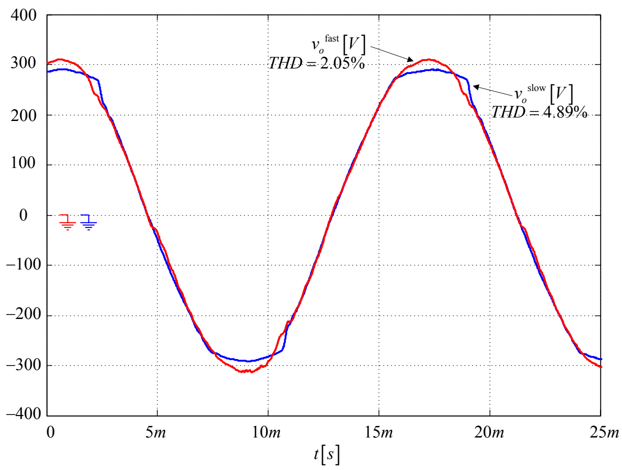

Figure 16 – Output voltage comparison with non-linear loads.

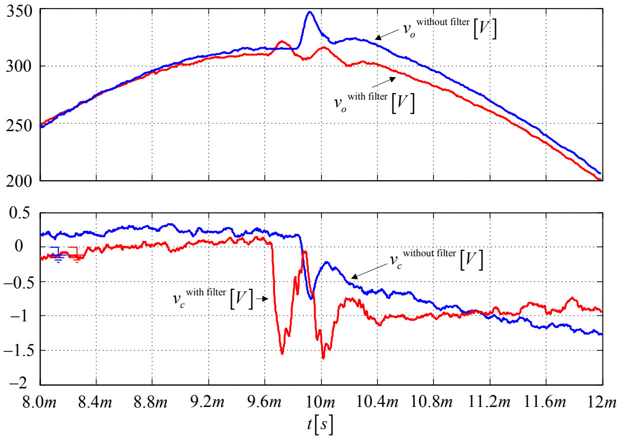

Figure 17 – +10% input voltage transient.

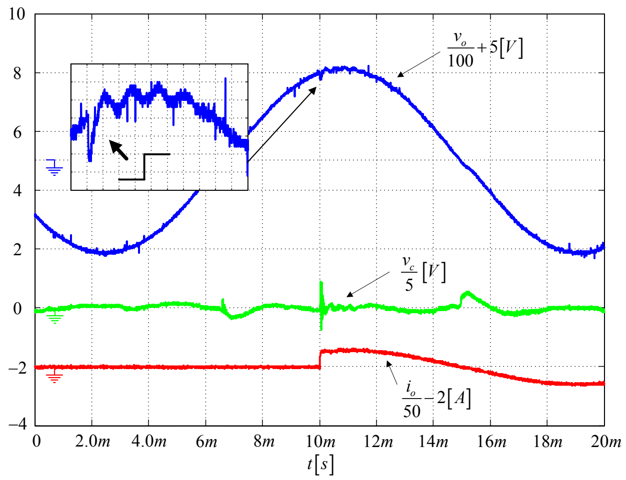

Figure 18 – +50% load transient.

VI. Conclusions

In this article, a 10 kVA indirect line conditioner, operating in closed loop, which processes only a part of load power, was studied. Briefly, the converter's operation was shown, focusing on the modulation used and on the system control in closed loop.

The use of three-level modulation allows the converter output filter to be reduced and the topology's main advantages are: simple driving, the possibility of using snubbers used in classical voltage inverters, robustness, and reduced size.

The effect of line impedance in the converter control was studied and the use of an input filter was proposed in order to allow the use of a classical fast PID controller. The experimental results proved the optimal performance of the system with fast control, operating with a non-linear load and obtaining a sinusoidal output voltage with low harmonic distortion. In addition, it is noted that with a non-linear load the input voltage presents a harmonic distortion of 6.54% and the output voltage 2.05%.

The dynamic responses for load and input voltage transients indicated that the proposed system have a good performance. The structure efficiency is greater than 97%. The output voltage error for input voltage variations is lower than 0.5%.

AC voltage conditioners without power storage elements in the bus have direct coupling between inverter and rectifier, enhancing the problem of line impedance. Using the output voltage instantaneous control with classical controllers it cannot impose an output voltage with desired shape. It was made possible in this work by using an input filter in the rectifier.

Acknowledgments

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