COMPARISON BETWEEN LINE CONDITIONERS WITH THE AC-AC CONVERTER CONNECTED AT THE LINE AND AT THE LOAD SIDE

C. A. Petry[1], T. B Soeiro[2], A. J. Perin[3], J. C. Fagundes[4], I. Barbi[5]

[1]Department of Electronics - DAELN
Federal Center of Technological Education of Santa Catarina – CEFET/SC
88020-300 – Florianópolis – SC- Brazil
[1]petry@cefetsc.edu.br

[2-5]Power Electronics Institute - INEP
Department of Electrical Engineering - EEL
Federal University of Santa Catarina – UFSC
P. O. box 5119 – 88040-970 – Florianópolis – SC- Brazil
([2]tbsoeiro, [3]arnaldo.perin, [4]fagundes, [5]ivobarbi)@inep.ufsc.br

***Abstract* – This article presents the comparison between two line conditioners with series compensation. One of them with the ac-ac converter connected at the line side, and the other with the converter connected at the load side. The placement of the converter exerts little influence over the line conditioner's operation principle and its main waveforms. On the other hand, the static gain, the T_1 transformation ratio and the current and voltage ripple at the inverter output filter differ from one configuration to the other. The control strategies and the main differences between the two conditioners are discussed in this article, pondering the problems that arise when the line impedance is considered for the line-side converter while the load-side converter presents one zero at the right-hand side of the complex plane. Experimental results for 10 kVA converters are presented showing the functionality of the conditioners.**

***Keywords* – line conditioners, ac-ac converters, line and load side connections, line impedance.**

I. INTRODUCTION

Providing energy uninterruptedly has been one of the main goals for the energy companies around the world. Therefore, the academic and industrial sectors have been paying more attention to the quality of the Electrical System over the last few years.

A great number of electronic equipments installed in residential, commercial or industrial areas need a high quality energy supply. For this reason, there have been investments from the providing side aiming to improve line voltage quality. From the consumer's side, incessant researches have tried to tackled problems of line voltage variations and waveform degradation by substituting thyristors for high frequency PWM modulated switches in voltage regulators [1, 2].

To provide high quality energy for those kinds of consumers two converter groups were studied: direct and indirect. The first has the advantage of processing energy in a direct way, but needs a precise command circuitry for the switches that need synchronism with the line or with the load [4-6]. The latter includes a special family, where the dc link bus is not present. This particular group was studied in [1-3].

The indirect converters without dc link have also been denominated direct link indirect converters [1 and 3]. The energy supply for those conditioners can be provided by connecting the ac-ac converter at the line or at the load side.

The main objective of this work is to compare the converters studied in [1] and [3] showing the main differences in their power stage and control. The experimental results for two 10 kVA conditioners will be presented at the end of this article.

II. STRUCTURES AND PRINCIPLES OF OPERATION

The two different forms of placement of the ac-ac converter are shown in Fig. 1 and Fig. 2. It can be noted that, in the first case, the rectifier is connected directly on the line side, before the transformer (T_1) which provides the necessary compensation to obtain the stabilized voltage. In the second case, the ac-ac converter is located directly on the load, after the compensation transformer.

The energy flowing from the line to the load represents the direct flow, while the energy circulating through the ac-ac converter is called the indirect flow.

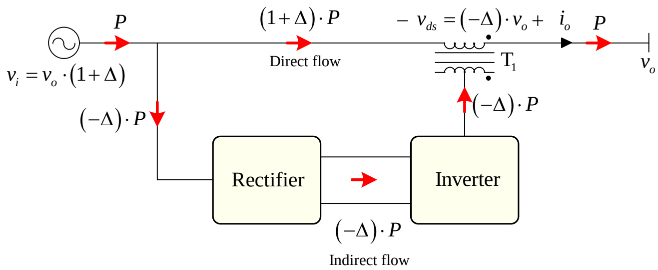

Fig. 1. Ac-ac converter connected at the line side.

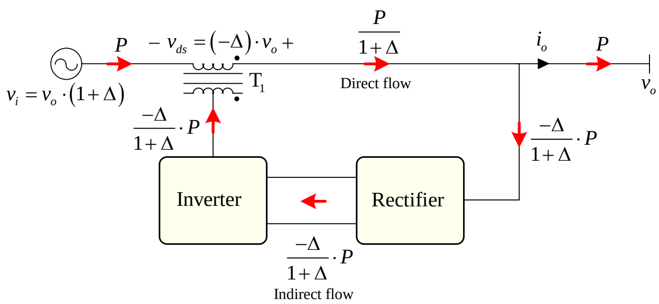

Fig. 2. Ac-ac converter connected at the load side.

The amount of indirect energy flow through the conditioner in Fig. 1 is greater than that through the conditioner in Fig. 2, indicating that the latter processes less power having, therefore, less volume and weight.

It is also noticeable from Fig. 1 and 2 that the transformer T_1 inserts a voltage (v_{ds}) needed to compensate the input voltage (v_i) variations (Δ) with the purpose of maintain the output voltage (v_o) regulated and with a sinusoidal pattern. This line conditioner's operation principle is illustrated in Fig. 3.

The non-linear loads demand from the line a high harmonic content current (i_o=i_F+i_H) that provokes a voltage drop over the line impedance (Z_L), causing an input voltage (v_i') distortion. Moreover, the input voltage can also have a high harmonic content (v_i=v_F+v_H). So, it is necessary for the conditioner to provide a compensation voltage with two components, the fundamental (v_{dsF}) and the harmonic (v_{dsH}), in order to have a regulated output voltage with low harmonic distortion.

From this operation principle two kinds of devices can be defined:

- A voltage regulator: a device capable of assuring a constant output RMS voltage;
- A line conditioner: a device capable of assuring a constant output RMS voltage and conforming the output voltage to a defined reference.

The scheme for the direct and indirect voltage conditioners are shown in Fig. 4 and Fig. 5 respectively. 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 the necessary signal 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 anti-parallel diodes.

The rectifier has two operating stages, that depend on the ac main polarity (v_i). The full bridge inverter has five operating stages, described in [3]. In Fig. 4 the filter capacitor C_o can be positioned on the secondary side of transformer T_1, using the transformer leakage inductance as an additional output inverter voltage filter. Thus, L_o represents the total inductance seen by the primary side of the transformer, that is, the leakage plus the inductance of the external inductor. In Fig. 5, the filter inductance is formed by L_o plus L_s and L_{ds}, which represent the external inductor, the transformer leakage and the line inductance respectively. Note that the capacitor C_o is placed over the load in Fig. 5.

The converter shown in Fig. 5 has a great advantage in comparison with that of Fig. 4 by using all the parasitic inductances of the transformer, the connection cables and the line as an output filter.

At the input side, the rectifiers used must have a voltage source due to the fact that they are commanded in low frequency. It can be verified, for the converter showed in Fig. 5, that its input is a voltage source taken from the output capacitor C_o. For the converter in Fig. 4 this does not occur because the rectifier input voltage is taken from the line and presents impedance different from zero, meaning that the use of an input filter for the rectifier is recommended.

III. MODULATION AND MAIN WAVEFORMS

The inverters in Fig. 4 and Fig. 5 are formed by S_5/S_6 and S_7/S_8 switches and can be modulated by two or three level PWM modulation. For inverters, the duty cycle ($d(t)$) is obtained as a ratio of the inverter's output voltage ($v_{dp}(t)$) and input voltage ($v_r(t)$). Considering that the switching frequency is very high in comparison with the line frequency and using instantaneous average values, the expression (1) can be obtained for a PWM sinusoidal inverter. For the line conditioner showed in Fig. 4 or in Fig. 5, expressions (2) and (3) can be obtained assuming that the line voltage is positive and in phase with the output voltage.

The duty cycle waveforms for a PWM sinusoidal inverter (expression (1)) and for the line conditioners (expression (3)) are shown in Fig. 6. It can be seen that the inverter output voltage (v_{ab}) has an amplitude variation for the line conditioner but not for the PWM sinusoidal inverter.

Fig. 7 shows the line conditioners' main waveforms. It can be observed that the converter acts increasing the input voltage or decreasing it in order to regulate the output voltage. The unique difference between the line conditioner connected at the line side and the same one connected at the load side is the rectifier input voltage. In the first case this voltage is v_i and for the second one it is v_o.

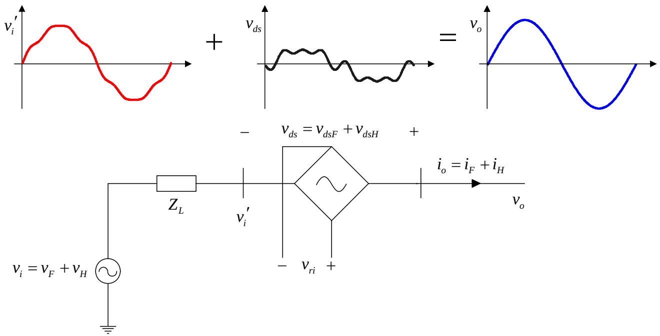

Fig. 3. Line conditioner principle of operation.

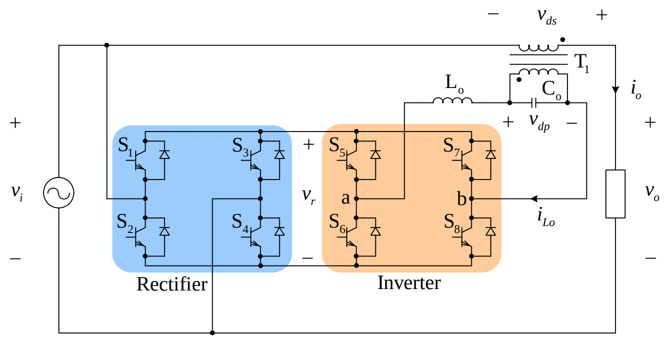

Fig. 4. Line conditioner circuit with the ac-ac converter connected at the line side [1].

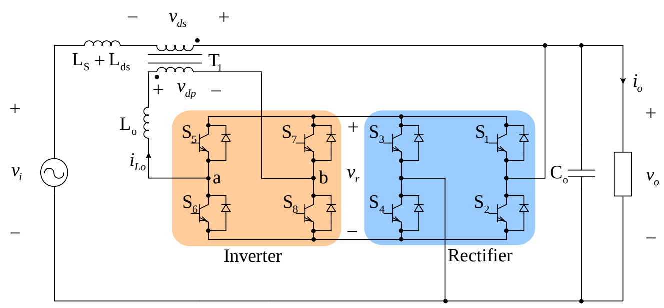

Fig. 5. Line conditioner circuit with the ac-ac converter connected at the load side [3].

$$d(t) = \frac{v_{dp}(t)}{v_r(t)} = \frac{V_{dp} \cdot sen(\omega_r \cdot t)}{V_r} = m \cdot sen(\omega_r \cdot t) \qquad (1)$$

$$d(t)=\frac{v_{dp}(t)}{v_r(t)}=\frac{V_{dp}\cdot sen(\omega_r\cdot t)}{V_r\cdot\left|sen(\omega_r\cdot t)\right|}=m\frac{sen(\omega_r\cdot t)}{\left|sen(\omega_r\cdot t)\right|}\tag{2}$$

$$d(t)=\begin{cases}+m & 0\le\omega_r\cdot t<\pi\\ -m & \pi<\omega_r\cdot t\le 2\pi\end{cases};\quad m=\frac{V_{dp}}{V_r};\quad \omega_r=2\pi\cdot F_r\tag{3}$$

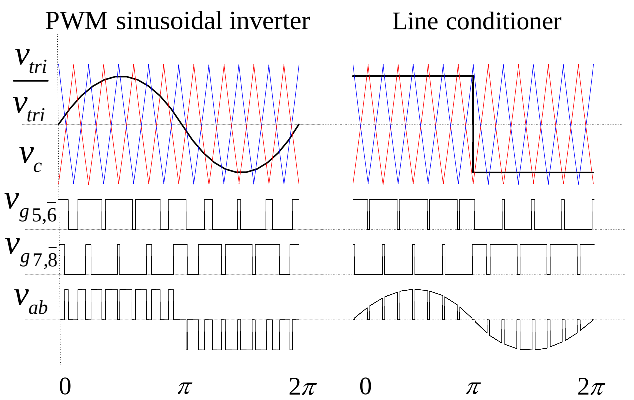

Fig. 6. Comparison between the modulation of an inverter and a voltage conditioner.

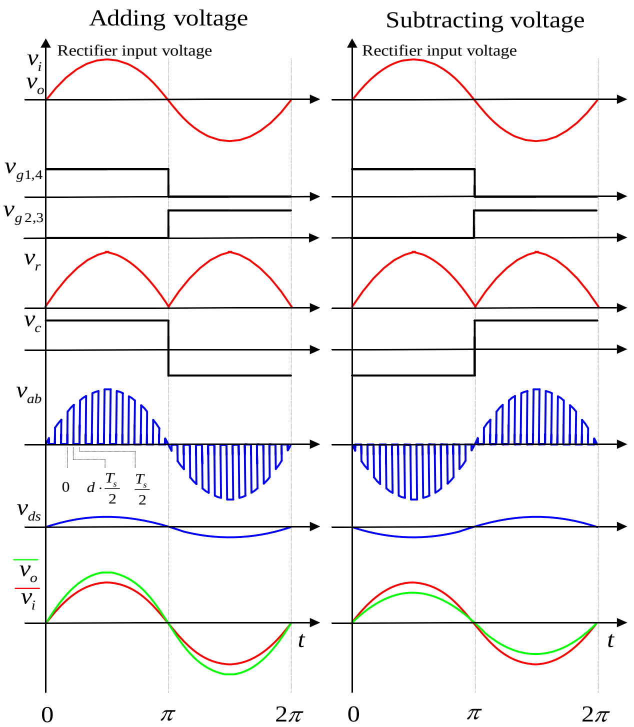

Fig. 7. Main power stages waveforms for the converters using three level RPWM modulation [3].

In Fig. 6 and 7 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 OF THE CONVERTERS POWER STAGES

In this section some expressions will be presented for the studied power stage converters. This study is valid for three-level PWM modulation.

A. Static Gain

The static gain (g) is the ratio between the conditioner output voltage and its input voltage. It is given by expression (4) for the line side connected converter and by equation (5) for the load side connected converter. In expression (4) and (5) N_1 is T_1 transformation ratio.

$$g(t)=\frac{v_o(t)}{v_i(t)}=\frac{N_1+d(t)}{N_1}\qquad \text{(Fig. 4)}\tag{4}$$

$$g(t)=\frac{v_o(t)}{v_i(t)}=\frac{N_1}{N_1-d(t)}\qquad \text{(Fig. 5)}\tag{5}$$

B. Transformer T_1

To determine T_1, the transformation ratio (N_1) is needed. The relations are given by expression (6) and (7) for the line and for the load side connected converters respectively. It is observed that expression (6) gives a N_1 inferior to that given by expression (7). This demonstrates that the ac-ac converter processes more power when it is connected at the line side, in accordance with Fig. 1 and Fig. 2.

$$N_1=\frac{1-\Delta}{\Delta}D_{\max}\qquad D_{\max}\to 1\tag{6}$$

$$N_1=\frac{1}{\Delta}D_{\max}\qquad D_{\max}\to 1\tag{7}$$

C. Output Filter

The output filter, formed by an inductor (L_o) and a capacitor (C_o), is determined by the maximum current and voltage ripple specification on these elements.

In terms of current ripple the obtained expressions for the two conditioners are very similar as shown by expressions (8) to (11), where F_s is the switching frequency.

For the line side connected converter (Fig. 4):

$$v_{Lo}(t)=\begin{cases}v_i(t)-\left(v_i(t)-v_o(t)\right)\cdot N_1 & \to\ d(t)\ge 0\\ v_i(t)-\left(v_o(t)-v_i(t)\right)\cdot N_1 & \to\ d(t)\le 0\end{cases}\tag{8}$$

$$\Delta i_{Lo}(t)=\frac{v_{Lo}(t)}{2\cdot L_o\cdot F_s}\cdot d(t)\tag{9}$$

For the load side connected converter (Fig. 5) the following expressions are obtained, where the inductor L_{eq} represents the total inductance of T_1 referred to the secondary side (Fig. 5).

$$v_{Leq}(t)=\begin{cases}v_i(t)+v_o(t)\cdot\dfrac{1-N_1}{N_1} & \to\ d(t)\ge 0\\ v_i(t)-v_o(t)\cdot\dfrac{1+N_1}{N_1} & \to\ d(t)\le 0\end{cases}\tag{10}$$

$$\Delta i_{Leq}(t)=\frac{v_{Lo}(t)}{2\cdot L_{eq}\cdot F_s}\cdot d(t)\tag{11}$$

The determination of the voltage ripple of C_o is very different for the two conditioners. That is due to the different positions of C_o in the two conditioners, considering the fact that for the load side converter the current through capacitor C_o is not only the alternate part of inductor L_{eq} current.

The voltage ripple over capacitor C_o on the secondary side of T_1, for the line side conditioner (Fig. 4) is given by expression (12), while for the load side conditioner (Fig. 5) this ripple is given by expression (13).

$$\Delta v_{Co}(t) = \frac{2 \cdot \Delta i_{Lo}(t)}{\pi^3 \cdot F_s \cdot C_o} \tag{12}$$

$$\Delta v_{Co\max}(t) = \frac{1}{C_o}\left[\frac{i_o(t)^2 N_1 L_{eq}}{2v_o(t)(N_1-1)(N_1-d)} + \frac{v_o(t)d(1-d)(N_1-d)}{32F_s^2 L_{eq} N_1^2}\right] \tag{13}$$

The capacitor voltage ripple will be bigger in the load side converter implying the use of a larger capacitor than for the line side conditioner's case.

D. Input Filter

Both converters can use input filters to reduce the high frequency current ripple introduced by the line. This filter would eliminate the load side connected advantages, due to the fact that it uses all the parasitic inductances (from T_1 and from the line). Besides, for the line side connected converter, the use of an input filter is recommended implying in a little decoupling between the inverter and the rectifier, making the conditioners output voltage control easier.

E. Converters Protection

The protection of line conditioners with series compensation is a difficult task because it is not possible to interrupt the switches command to protect the system against faults as load short-circuits. In addition, interrupting the command is necessary to provide a path for the load current at the primary side of T_1 before disconnecting the system from the line. That is made it possible by using two bypass thyristors at the primary side of T_1.

Small value capacitors are also needed on the bus to provide decoupling from the wire parasitic inductances and to avoid over voltages on the switches (S_1 to S_8).

Moreover, a clamper is needed to absorb the inductor L_o stored energy while the thyristors at the primary side of T_1 change from off to on and also to avoid switch over voltages.

V. CONVERTERS CONTROL

In this section the converter control circuits and its main considerations will be studied.

A. Control Circuits

The two converters control circuits are very similar. Fig. 8 shows only the control block diagram of the line side connected conditioner. It can be noticed that the output voltage is monitored and compared with a sinusoidal reference synchronized with the line voltage. The error voltage is applied to the voltage compensator ($C_v(s)$) and the control voltage will be used for the RPWM three level modulation.

The current compensator ($C_i(s)$) has the purpose of eliminating the average current values at the primary of T_1. For the line side converter the control voltage generated by the current loop was added to the control voltage generated by the voltage loop and after that applied to the modulation circuit. This procedure can originate an instable system and so, later, for the load side converter the current control voltage was added to the sinusoidal reference as it is shown in Fig. 9 block diagram. The dynamic response of the current compensator ($C_i(s)$) must be chosen carefully to not interfere in the voltage control loop operation.

The multiplication between the error voltage (ε_{ca}) and the input voltage signal $sign(v_i)$ to avoid the voltage compensator ($C_v(s)$) must change from one quadrant to another every cycle of the input voltage (Fig. 6). After the multiplication a continuous control voltage (v_{cc}) is obtained and multiplied again by the signal $sign(v_i)$ to obtain the comparison voltage for the RPWM modulation [3].

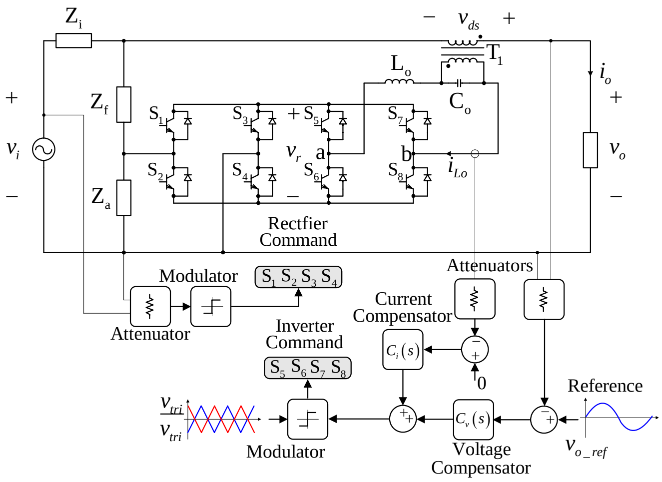

Fig. 8. Converters control circuits.

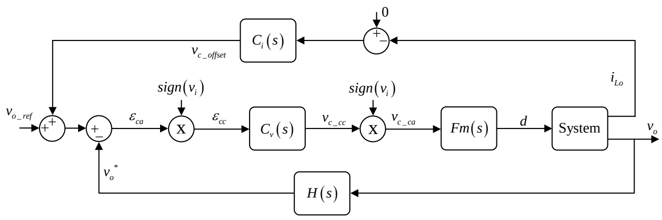

Fig. 9. Block diagrams of the load side connected converters control.

B. Converters Transfer Functions

To determine the transfer functions for the output voltage vs. duty cycle and output voltage vs. input voltage it is necessary to study the converter control and to design the voltage controller. Fig. 8 shows the complete closed loop control circuit, for the line connected converter. In this figure, $Z_i(s)$ is the line impedance and $Z_f(s)$ and $Z_a(s)$ are the series and parallel impedances of the input filter, respectively. To model the converters, 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 switching 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 inverters are Buck type converters, operating with three-level modulation, they can be modeled as a dc-dc circuit, with the maximum ac mains voltage, using Vorpérian's PWM switch model. Eliminating $Z_i(s)$, $Z_f(s)$ and $Z_a(s)$ in Fig. 8, expressions (14) and (15) can be obtained.

A PID (proportional-integral-derivative) controller allows obtaining good results in closed loop operation, for a system with transfer functions given by (14) and (15).

$$G(s) = \left.\frac{\hat{v}_o}{\hat{d}}\right|_{\hat{v}_i = 0} = \frac{V_i \cdot R_o \cdot n_1}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o \cdot n_1^2} \quad (14)$$

$$F(s) = \left.\frac{\hat{v}_o}{\hat{v}_i}\right|_{\hat{d} = 0} = \frac{R_o \cdot \left(s^2 \cdot L_o \cdot C_o + n_1^2 + n_1 \cdot D\right)}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o \cdot n_1^2} \quad (15)$$

These expressions do not represent the real situation for a line conditioner connected at the line side. Taking into account $Z_i(s)$, a much more complex transfer function is found and the control becomes more difficult to implement because the zeros that appears on the right-hand side of the complex plane [1].

The same occurs for the load side connected line conditioner, and the zero on the right-hand side of the complex plane becomes evident to observe as shown by expressions (16) and (17) [3].

$$G(s) = \left.\frac{\hat{v}_o}{\hat{d}}\right|_{\hat{v}_i = 0} = \frac{\dfrac{-s \cdot L_{eq} \cdot N^2 \cdot V_o}{R_o \cdot (N-D)} + V_o \cdot (N-D)}{s^2 \cdot L_{eq} \cdot C_o \cdot N^2 + \dfrac{s \cdot L_{eq} \cdot N^2}{R_o} + (N-D)^2} \quad (16)$$

$$F(s) = \left.\frac{\hat{v}_o}{\hat{v}_i}\right|_{\hat{d} = 0} = \frac{N \cdot (N-D)}{s^2 \cdot L_{eq} \cdot C_o \cdot N^2 + \dfrac{s \cdot L_{eq} \cdot N^2}{R_o} + (N-D)^2} \quad (17)$$

The conditioner connected at the line side, without input filter, must be controlled in a manner to have a slow dynamic response in order to avoid instabilities. By using an input filter and considering $Z_f(s)$ and $Z_a(s)$ together with $Z_i(s)$ its transfer function becomes complex. However, using a traditional PID controller the system can operate with a good dynamic response and will be stable [1].

The conditioner transfer function depends strongly on the load changes, mainly for the load connected converter, but with a carefully project of a PID controller the system avoids instabilities and has a good dynamic response [3].

C. The Line Impedance Problem

The line impedance influence, in others words, the fact that $Z_i(s)$ is different from zero in Fig. 8, was discussed in details in [1]. This problem is due to a particular physic issue of the series voltage compensators and becomes more complex with converters that operate without dc bus (dc link). It happens due to the fault of decoupling between the inverter and the rectifier and so, duty cycle (*d(t)*) variations appear simultaneously as a voltage drop over $Z_i(s)$, affecting the input voltage. Therefore, the control of this kind of converters becomes more difficult.

VI. DESIGN EXAMPLE AND EXPERIMENTAL RESULTS

In this section a design example and the experimental results are presented for two 10 kVA converters, showing that the output voltage regulation is very similar for the two conditioners.

A. Converters Specifications

The prototypes built in laboratory have 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.

For the conditioner connected at the line side it is found:

- $n_1 = 3$ - 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.

The conditioner connected at the load side has as main components:

- $n_1 = 4$ - T_1's transforming ratio;
- $L_{eq} = 150[\mu H]$, $C_o = 20[\mu F]$ - output filter.

B. Operation with Non-Linear Load

Operation with non-linear loads is more difficult in comparison with operation with linear loads. However, both conditioners present good results, as shown by Fig. 10 and Fig. 11. The Total Harmonic Distortion (THD) for the load side connected conditioner is reduced from 6.5%, at the input, to 3.7%, at the output, while the line side connected conditioner reduces the THD from 5.54%, at the input, to 2.05%, at the output.

C. Input Voltage Transients

The results for fast input transients are presented in Fig. 12. In this case both converters have similarly good responses.

VII. CONCLUSION

In this article a comparison between the main characteristics of two line conditioners with serial compensation were presented. The first one has its ac-ac converter connected at the line side, while the second one has the ac-ac converter connected at the load side.

The main waveforms, operation principle, modulation and control strategies are similar for the two converters.

However, in terms of static gain, energy flow and T_1 transformation ratio the characteristics are different. The transformation ratio N_1 for the conditioner connected at the load side is bigger than for the conditioner connected at the line side, causing differences in the power processed by the ac-ac converter.

On other side, the voltage ripple over the output capacitor C_o is bigger for the conditioner connected at the load side. But its advantage is the use of all the leakage inductance from the transformer T_1 and from the line as an output filter together with the capacitor C_o.

The transfer function *G(s)* of the control system is also very different for the two converters. Even considering the load side connected conditioner as ideal, in other words, considering that the line impedance $Z_l(s)$ is zero, the transfer function *G(s)* has a zero on the right-hand side of the complex plane. In this ideal situation the line side conditioner has a transfer function similar to Buck and Forward converters. However if $Z_l(s)$ is not zero for this conditioner, its transfer function presents zeros on the right-hand side of the complex plane making the control system design difficult.

Experimental results are similar for the two converters. However, the fact that the load side connected conditioner has not an input filter implies a high frequency ripple on the input current, which will provoke a voltage ripple on the input side of the converter. This can be reduced by using an inductor with an inductance higher than the line parasitic inductance.

Both converters have high efficiency, above 97% for power between 1 to 10 kVA.

REFERENCES

[1] C. A. Petry, J. C. Fagundes, I. Barbi. *Study of an AC-AC Indirect Converter Used as a Line Conditioner*. ISIE'2005 - 2005 IEEE International Symposium on Industrial Electronics, June 20-23 2005, Dubrovnik, Croatia.

[2] B. H. Kwon, G. Y, Jeong, S. H. Han, D. H. Lee. *Novel line conditioner with voltage up/down capability*. IEEE Transactions on Industrial Electronics, Vol. 49, n. 5, Oct. 2002, p. 1110-1119.

[3] T. B. Soeiro, C. A. Petry, A. J. Perin. *Estudo de um Condicionador de Tensão com Compensação Série, Utilizando um Conversor Indireto CA-CA com Alimentação à Jusante*. XVI Congresso Brasileiro de Automática (CBA 2006), outubro 03-06, Salvador, Bahia.

[4] C. A. Petry, J. C. Fagundes, I. Barbi. *New Direct Ac-Ac Converters Solving the Commutation Problem*. ISIE'2006 - 2006 IEEE International Symposium on Industrial Electronics, July 09-13 2006, Montréal, Canada.

[5] B.–H. Kwon, B.–D. Min, J.-H Kim. *Novel topologies of AC choppers*. IEEE Proceedings Electric Power Applications, p. 323-330, July 1996.

[6] J.-H. Kim, B.-D. Min, et al. *A PWM Buck-Boost AC Chopper Solving the Commutation Problem*. IEEE Transactions on Industrial Electronics, Vol. 45, n. 5, p. 832-835, October 1998.

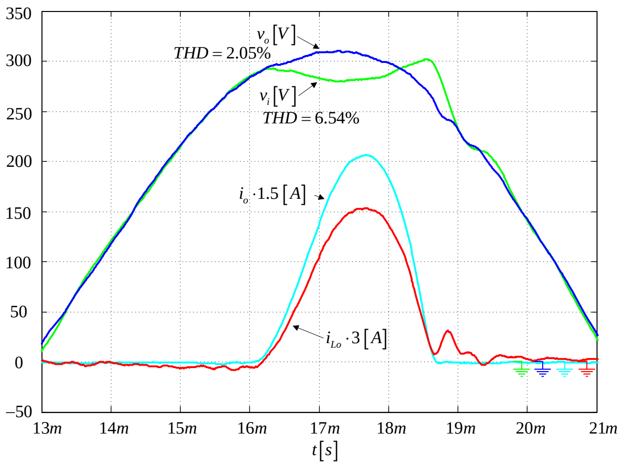

Fig. 10. Operation with a non-linear load, line connected conditioner.

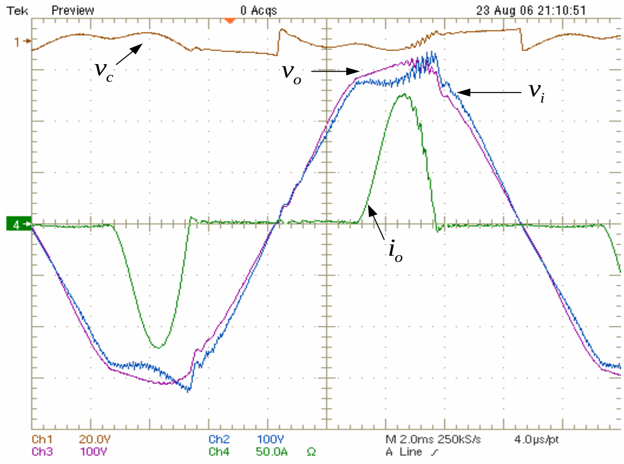

Fig. 11. Operation with a non-linear load, load connected conditioner.

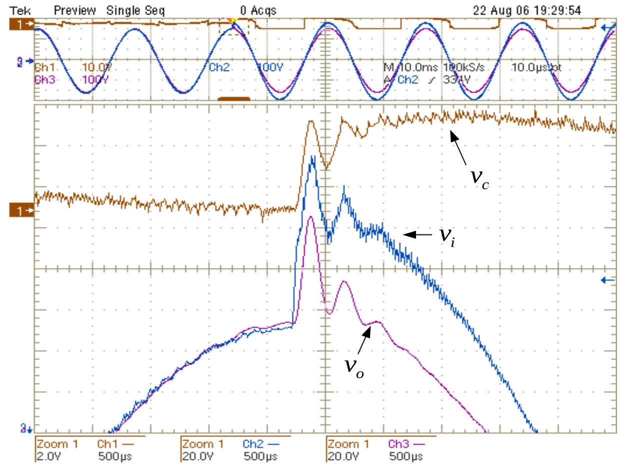

Fig. 12. Input voltage transient (+20%) for the load connected conditioner.