New Direct Ac-Ac Converters Using Switching Modules Solving the Commutation Problem

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Abstract – **The focus of this paper is the study of direct ac-ac converters, beginning by buck, half-bridge, full-bridge and push-pull converters. From the basic converters we apply a simple methodology to make possible the use of switches in commercial configurations. After that, eight line conditioners were proposed supplying them on the line side or on the load side and the static gain transformer turns ratios were presented. It can be highlighted that some of the studied topologies are known in the literature and others are new. For one of the presented topologies, the design of a 3 kVA line conditioner is developed and experimental results are shown, certifying the correct operation of the drive strategy used.**

I. INTRODUCTION

Nowadays line conditioners are equipments used in various environments in order to regulate the voltage provided by the grid and in some cases to reduce the harmonic content of the output voltage.

It is well known that the main difficulty of employing alternating current converters using fast switches and PWM has always been the switching, which remained without a solution for many years. Observing Fig. 2 it can be seen that in order to switch from S_1/S_3 to S_2/S_4 there are two alternatives: the superposition of the drive signals or the use of dead-time. In the first case, a short-circuit in the voltage source is provoked, while in the second case the current through inductor L_o is interrupted, resulting in overvoltages across the switches [14].

One solution for the switching problem is the use of indirect converters [1], which inconveniently use a larger number of switches than direct converters.

A switching proposal for ac-ac converters was presented in [2] and improved in [3-7], eliminating the need for clamping circuits. In this switching strategy it is necessary to synchronize the drive signals with the converter's input voltage signal.

In [8] a switching cell was proposed for direct ac-ac converters, studied later in [9]. These converters are robust, with few controlled switches and solve the switching problem. However, there is a problem with average current through the inductors and switches cannot be used in commercial configurations.

The arrangement of the switches in commercial configurations for ac-ac converters were proposed in [4-7, 10]. These arrangements allow the use of commercial modules, an attractive feature especially at high power.

The main idea of this work is to employ the switching strategies of [3-7] in several topologies, among which some are well known and others are new, always using switches arranged in a way that permits the usage of commercial modules [4-7, 10].

In [11] several converters topologies were proposed, however, the main focus was neither on switching nor on the commercial arrangement of the switches. In this manner, among the topologies presented in this paper, one was chosen to implement a 3 kVA line conditioner, controlled by the orthogonal detection principle [12, 13].

II. ORIGIN AND COMMUTATION OF THE PROPOSED TOPOLOGIES

To show the origin of the topologies that are going to be presented, an ac-ac buck converter in a standard configuration will be shown, as depicted in Fig. 2. Note that this converter is bidirectional in both voltage and current by using commercial switches. However, the usage of commercial modules is not possible. Altering the position of switch S_3, a configuration which allows the usage of commercial modules is obtained, as shown in Fig. 3.

The switching is performed as shown in Fig. 1; note that during the positive semi-cycle of the grid voltage, switches S_3 and S_4 conduct and switches S_1 and S_2 are driven by PWM. During the negative semi-cycle of the grid voltage, switches S_1 and S_2 conduct and switches S_3 and S_4 are modulated at high-frequency.

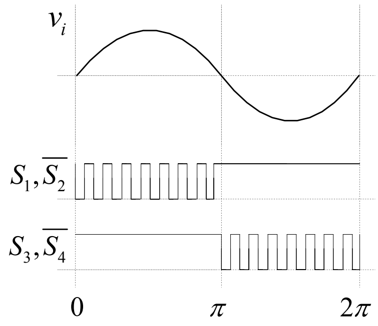
III. PROPOSED TOPOLOGIES

Using the same procedure adopted in Fig. 2, that is, rearranging the switches in a way to obtain configurations that allow the usage of commercial modules, several ac-ac converter topologies can be obtained.

With these topologies several voltage compensating ac voltage conditioners can be implemented, which have the advantage of processing just the difference between the desired output voltage and the input voltage, consequently, processing just part of the load's power, guaranteeing a high performance.

The static gain will be expressed as a function of the switches' duty-cycle and the turns ratios, for the structures that use transformers.

In Fig. 4 the full-bridge ac-ac converter is shown, while Fig. 6 and 7 depict the line conditioners based on the converter shown in Fig. 4.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

Fig. 1 – Switching of the converter switches of Fig. 3.

Figures 8 and 12 illustrate converters based on the half-bridge converter, shown in Fig. 5. Note that the transformer has two secondary windings and not just a tap, generally used in the conventional converters [9]. This modification is performed so that switches in a modular configuration can be used.

Topologies based on the push-pull converter are shown in Figs. 9 to 11. In Fig. 9 the ac-ac push-pull converter is shown and Figs. 10 and 11 illustrate the conditioners obtained from this converter.

In Fig. 12 the designed converter diagram is shown. It can be noticed in this figure the command circuitry for providing the switches gate signals.

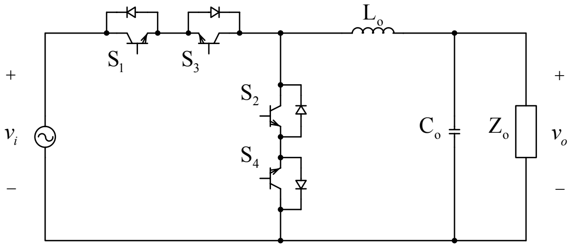


Fig. 2 – Standard ac-ac buck converter.

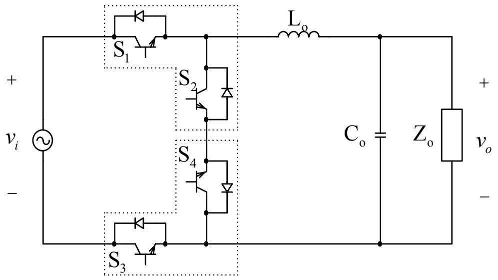
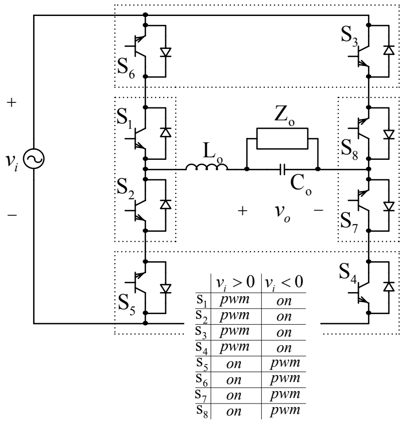


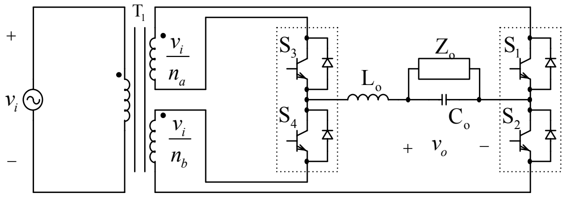
Fig. 3 – Ac-ac buck converter modified for the use of commercial switch modules.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*pwm*	*on*
S_4	*pwm*	*on*
S_5	*on*	*pwm*
S_6	*on*	*pwm*
S_7	*on*	*pwm*
S_8	*on*	*pwm*

← $\left.\frac{V_o}{V_i} = 2D-1\right|_{\text{2 levels}}$ ← $\left.\frac{V_o}{V_i} = D\right|_{\text{3 levels}}$

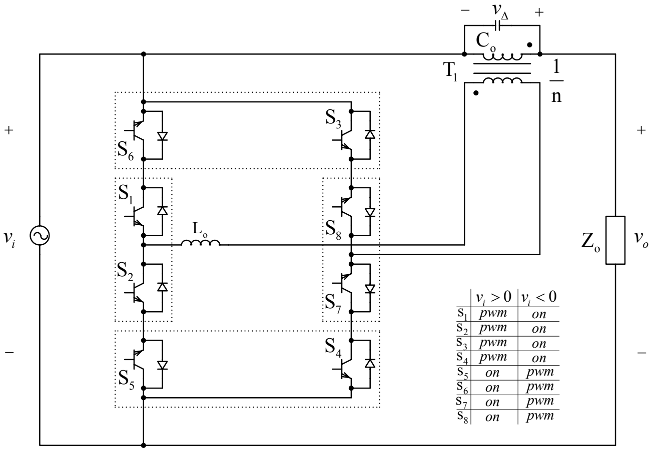
Fig. 4 – Full-bridge converter.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

$$\frac{V_o}{V_i} = \frac{D(n_a + n_b) - n_a}{n_a n_b}$$

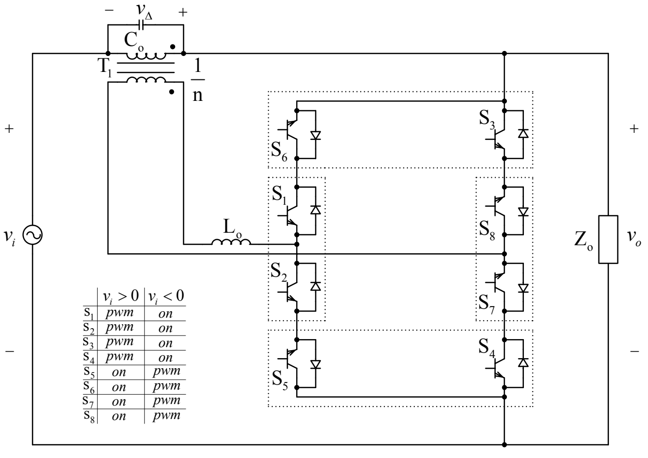
Fig. 5 – Half-bridge converter.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*pwm*	*on*
S_4	*pwm*	*on*
S_5	*on*	*pwm*
S_6	*on*	*pwm*
S_7	*on*	*pwm*
S_8	*on*	*pwm*

$\left.\frac{V_o}{V_i} = 1 + \frac{2D-1}{n}\right|_{\text{2 levels}}$ $\left.\frac{V_o}{V_i} = 1 + \frac{D}{n}\right|_{\text{3 levels}}$

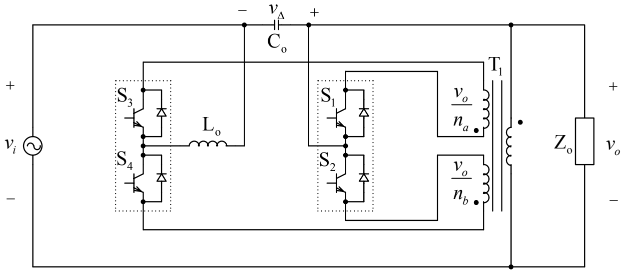
Fig. 6 – Full-bridge conditioner supplied on the line side.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*pwm*	*on*
S_4	*pwm*	*on*
S_5	*on*	*pwm*
S_6	*on*	*pwm*
S_7	*on*	*pwm*
S_8	*on*	*pwm*

$\left.\frac{V_o}{V_i} = \frac{1}{1 - \frac{2D-1}{n}}\right|_{\text{2 levels}}$ $\left.\frac{V_o}{V_i} = \frac{1}{1 - \frac{D}{n}}\right|_{\text{3 levels}}$

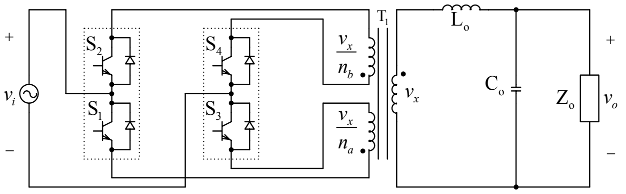
Fig. 7 – Full-bridge conditioner supplied on the load side.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

$$\frac{V_o}{V_i} = \frac{n_a n_b}{n_a n_b + n_a - D(n_a + n_b)}$$

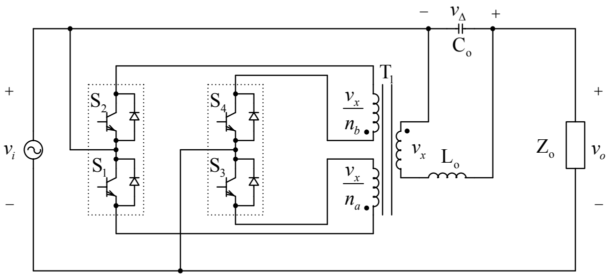
Fig. 8 – Half-bridge conditioner supplied on the load side.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

$$\frac{V_o}{V_i} = \frac{D(n_a + n_b) - n_a}{n_a n_b}$$

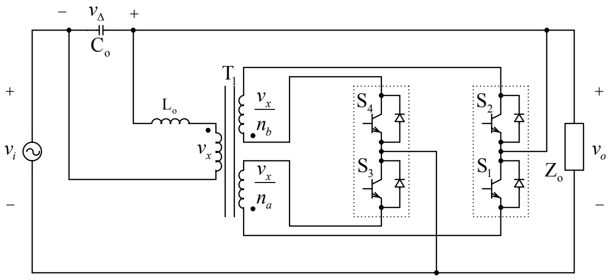
Fig. 9 – Push-pull converter.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

$$\frac{V_o}{V_i} = \frac{D(n_a + n_b) - n_a + n_a n_b}{n_a n_b}$$

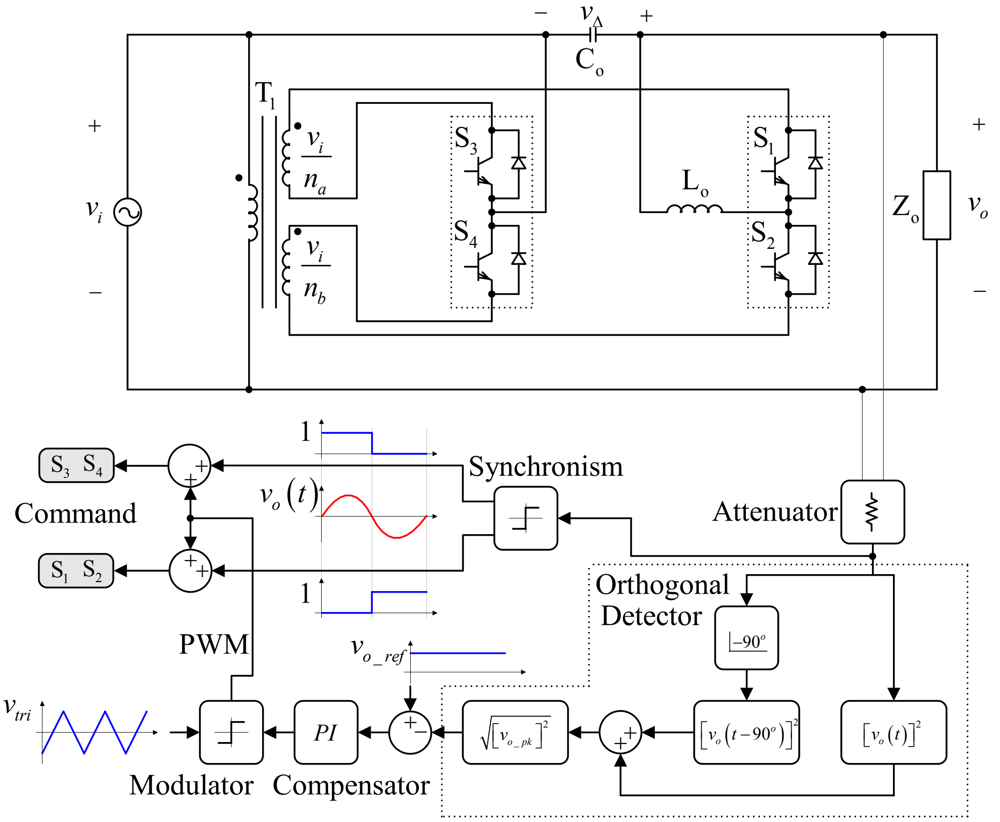
Fig. 10 – Push-pull conditioner supplied on the line side.



	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

$$\frac{V_o}{V_i} = \frac{n_a n_b}{n_a n_b + n_a - D(n_a + n_b)}$$

Fig. 11 – Push-pull conditioner supplied on the load side.



$$\frac{V_o}{V_i} = \frac{D(n_a + n_b) + n_a n_b - n_a}{n_a n_b}$$

	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*on*	*pwm*
S_4	*on*	*pwm*

Fig. 12 – Half-bridge conditioner supplied on the line side – implemented conditioner.

TABLE 1

Figure	Converter	Static gain	Turns ratios
2	Buck	$\frac{v_o}{v_i}=D$	-
4	Full-bridge - 2 levels	$\frac{v_o}{v_i}=2\cdot D-1$	-
	Full-bridge - 3 levels	$\frac{v_o}{v_i}=D$	
6	Full-bridge conditioner supplied on the line side – 2 levels	$\frac{v_o}{v_i}=1+\frac{2\cdot D-1}{n}$	$n=\frac{1-\Delta}{\Delta}$
	Full-bridge conditioner supplied on the line side – 3 levels	$\frac{v_o}{v_i}=1+\frac{D}{n}$	
7	Full-bridge conditioner supplied on the load side – 2 levels	$\frac{v_o}{v_i}=\frac{1}{1-\frac{2\cdot D-1}{n}}$	$n=\frac{1}{\Delta}$
	Full-bridge conditioner supplied on the load side – 3 levels	$\frac{v_o}{v_i}=\frac{1}{1-\frac{D}{n}}$	
5	Half-bridge	$\frac{v_o}{v_i}=\frac{D\cdot\left(n_a+n_b\right)-n_a}{n_a\cdot n_b}$	-
12	Half-bridge conditioner supplied on the line side	$\frac{v_o}{v_i}=\frac{D\cdot\left(n_a+n_b\right)+n_a\cdot n_b-n_a}{n_a\cdot n_b}$	$n_a=\frac{1-\Delta}{\Delta}\quad n_b=\frac{1+\Delta}{\Delta}$
8	Half-bridge conditioner supplied on the load side	$\frac{v_o}{v_i}=\frac{n_a\cdot n_b}{n_a\cdot n_b+n_a-D\cdot\left(n_a+n_b\right)}$	$n_a=n_b=\frac{1}{\Delta}$
9	Push-pull	$\frac{v_o}{v_i}=\frac{D\cdot\left(n_a+n_b\right)-n_a}{n_a\cdot n_b}$	-
10	Push-pull conditioner supplied on the line side	$\frac{v_o}{v_i}=\frac{D\cdot\left(n_a+n_b\right)-n_a+n_a\cdot n_b}{n_a\cdot n_b}$	$n_a=\frac{1-\Delta}{\Delta}\quad n_b=\frac{1+\Delta}{\Delta}$
11	Push-pull conditioner supplied on the load side	$\frac{v_o}{v_i}=\frac{n_a\cdot n_b}{n_a\cdot n_b+n_a-D\cdot\left(n_a+n_b\right)}$	$n_a=n_b=\frac{1}{\Delta}$

Table 1 summarizes the proposed topologies and the static gain expressions for all the converters and the turns ratios for the structures that use transformers.

IV. IMPLEMENTED CONDITIONER AND EXPERIMENTAL RESULTS

A. Converter Design

The line conditioner which will be implemented in the laboratory with the objective of certifying the operation of the proposed topologies is the converter shown in Fig. 12. This is a half-bridge converter which uses a transformer with two secondary windings and four controlled switches. L_o and C_o compose the converter's output filter. Voltage compensation, with proper amplitude and phase, is applied in series with the input voltage so that the output voltage has the correct amplitude.

The duty-cycle (D) is defined as the ratio between the conducting interval of switches S_1 and S_2 and the total period ($T_s=1/f_s$), considering the positive semi-cycle of the grid voltage. During the negative semi-cycle, the duty-cycle is the ratio between the conducting intervals of switches S_3 and S_4 and the total time, given by the switching frequency (f_s).

The expression for the static gain is again described in (1). The turns ratios (n_a and n_b) of transformer T_1 are given as a function of the voltage variation permitted at the input (Δ) and shown in (2). In (3) the expression for the ripple current of inductor L_o is shown and (4) describes the ripple voltage of capacitor C_o.

$$\frac{V_o}{V_i}\left(\Delta,D\right)=\frac{\Delta\cdot\left(1-2\cdot D\right)-1}{\left(1+\Delta\right)\cdot\left(1-\Delta\right)} \tag{1}$$

$$n_a=\frac{1-\Delta}{\Delta}\qquad n_b=\frac{1+\Delta}{\Delta} \tag{2}$$

$$\Delta i_{Lo}=\frac{V_o}{f_s\cdot L_o}\,\frac{-2\cdot D\cdot\left(D-1\right)\cdot\Delta}{1-\Delta+2\cdot D\cdot\Delta} \tag{3}$$

$$\Delta v_{Co}=\frac{4}{\pi^3\cdot f_s\cdot C_o}\Delta i_{Lo} \tag{4}$$

Using the above mentioned expressions, a conditioner with the following parameters was designed:

- $v_i = 220 \pm 20\%\ V$, $v_o = 220V$, $S_o = 3kVA$
- $f_s = 20kHz$, $n_a = 3.2$, $n_b = 4.8$, $v_{tri\_pkp} = 12.6V$
- $\mathrm{L_o}$=400µH, $\mathrm{S_1}$ to $\mathrm{S_4}$=IRG4PSC71UD, $\mathrm{C_o}$=10µF

Fig. 12 illustrates the simplified circuit of the implemented conditioner. In this figure, note that the output voltage is sampled in order to generate the synchronism signals in order to properly obtain the drive signals of the switches, according to the input/output voltage's polarity. The control technique using orthogonal detection is also shown and the voltage compensator is a classic proportional-integral [12, 13].

B. Experimental Results

In Fig. 13 the drive signals (at low frequency) of switches S_1 and S_2 are shown along with the synchronism signal. Note that during the positive semi-cycle these switches are controlled by means of PWM (as shown in details), while during the negative semi-cycle they conduct continuously. In the same manner, Fig. 14 illustrates the drive signals of S_3 and S_4.

Figure 15 shows the voltages across switches S_1 and S_3 without overvoltages, demonstrating the proper operation of the drive strategy used here. The input and output voltages are shown in Fig. 16, note that for an input of -10%, the output voltage is being stabilized at 220 V, as desired.

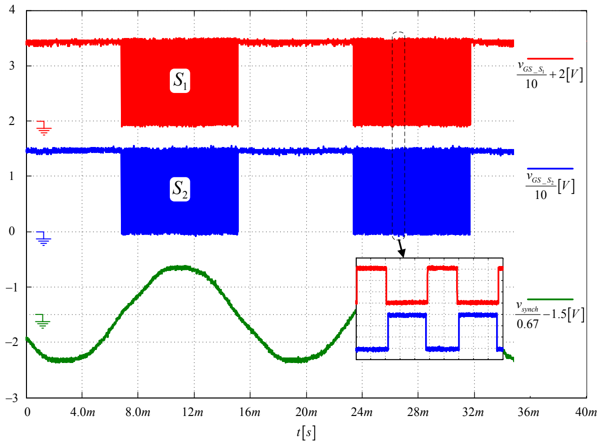


Fig. 13 – Drive signals of switches S_1 and S_2.

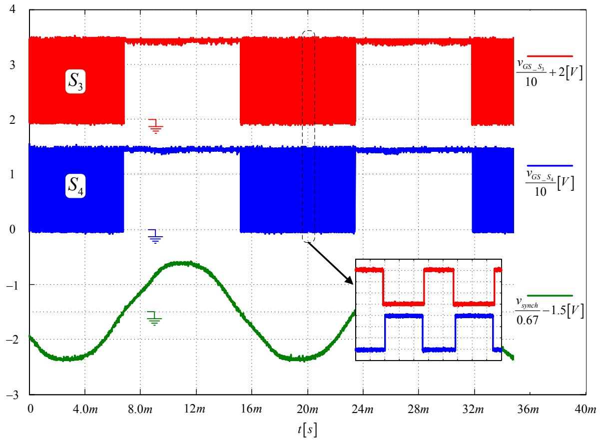


Fig. 14 – Drive signals of switches S_3 and S_4.

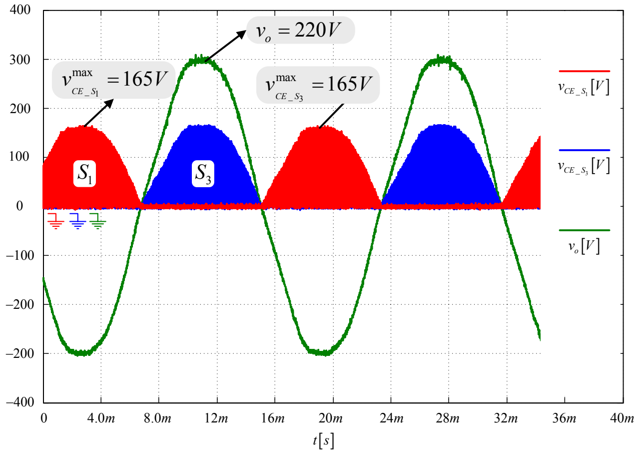


Fig. 15 – Voltages across switches S_1 and S_3.

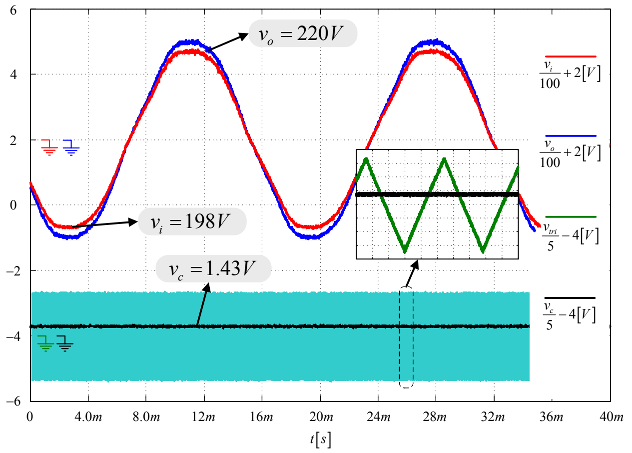


Fig. 16 – Input and output voltages - (*v_i=0.9·v_o, D=0.613*).

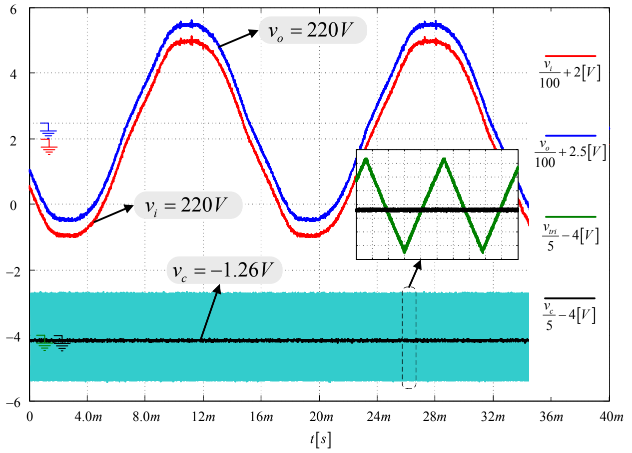


Fig. 17 – Input and output voltages - (*v_i=v_o, D=0.4*).

In Fig. 17 the input and output voltages are shown for line voltage at 220 V. In this case the duty cycle is 0.4.

Finally, figure 18 shows the input and output voltages for a line voltage at 242 V, so the duty cycle is 0.225.

Observing Figs. 16 to 18 it can be noticed that the control voltage is continuous during all the line voltage period, characteristic of direct ac-ac converters. As an example, for PWM inverters, the duty cycle varies in a sinusoidal shape, while, for indirect ac-ac converters without dc link, in a rectangular shape [1].

The prototype implemented at laboratory is shown by Fig. 18. It can be seen the power stage, drive circuits and control and command circuitry. Attempt for the two secondary windings transformer also the output filter inductor and capacitors as well as the snubber capacitors.

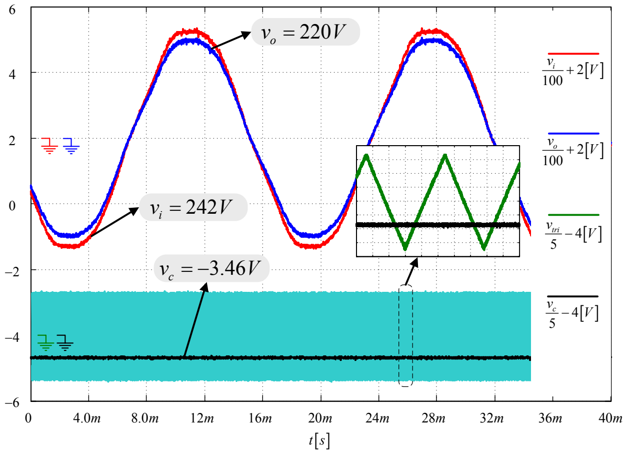


Fig. 18 – Input and output voltages - (v_i=*1.1*·v_o, *D*=*0.225*).

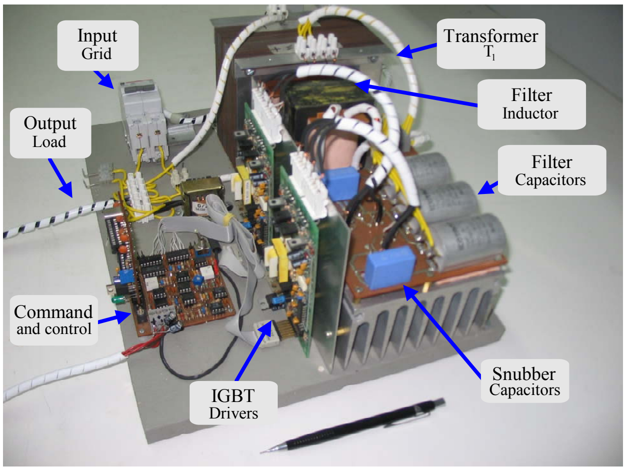


Fig. 18 – Picture of the prototype implemented at laboratory.

V. CONCLUSIONS

In this paper several topologies for direct ac-ac converters, which permit using commercial switch modules, were presented.

For all the basic converters (buck, full-bridge, half-bridge and push-pull) we applied the proposed methodology to use switch modules, obtaining then four converters which has the advantage of using commercial switch modules.

Besides, these converters where used to implement line conditioners that can be supplied on the line side or on the load side. This way, eight line conditioners were proposed. For all the converters table I summarize the static gain expressions and the turns ratios for the structures that use transformers.

From these topologies line conditioners were proposed, among which one was chosen for implementation as a laboratory prototype.

The main expressions for the half-bridge conditioner were presented as well as the origin of the proposed topologies.

The experimental results of this prototype were shown, demonstrating the proper operation of the drive strategy as well as orthogonal detection control.

The possibility of using commercial modules makes the studied topologies attractive for high power applications, either as voltage conditioners or reactive, harmonics, sags and overvoltage compensators, among others.

ACKNOWLEDGMENT

The authors would like to thank CNPq for their financial support and Luis C. Tomaselli, Telles B. Lazzarin and André L. Fuerback for their contributions in assembling the laboratory prototype.

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