REGARDING THE CONTROL OF DIRECT AC-AC CONVERTERS

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Abstract – **In this work the control of a direct AC-AC converter is discussed. The converter is a half-bridge topology using a transformer with two secondary windings and switches in a modular configuration. The control of the converter is realized in three distinct forms: orthogonal detection, traditional control (PID compensator) and determination of the duty cycle based on the input and reference voltages. Both the modeling of the converter — using instantaneous average values — and experimental results are presented, with emphasis on the comparison of the three control techniques.**

Keywords – **control, AC-AC converters, classical control, orthogonal detection, modeling of converters.**

I. INTRODUCTION

The modeling and control of DC-DC converters is widely discussed in the literature [1] and several linear and non-linear techniques are used to implement the feedback control loop of the system variables upon which control is desired. On the other hand, the control of AC-AC converters is a current research topic and for which no standard control techniques are yet established. One of the difficulties of the control of AC-AC converters lies in the complexity of the systems, leading to high order transfer functions. Moreover, both the load and input voltages vary over time, demanding great control effort. If the output voltage control loop compensator is too fast, there is good dynamic response, but due to the complexity of the system it may become unstable. This is one of the reasons why the control of the output voltage RMS value (slow compensator) is the preferred technique in commercial line conditioners.

One of the solutions to obtain a fast control response is to use the output voltage sampling technique known as orthogonal detection, proposed in [2 and 3]. This technique can be easily implemented in the digital domain using dedicated microprocessors or microcontrollers. It has the disadvantage of not allowing the voltage waveform to be corrected, since a continuous voltage, proportional to the output voltage peak value, is obtained.

In classical control, the variable that is to be directly controlled is fed back by means of a sensor, and is compared to a reference signal. The error signal is then compensated using proportional, integral and derivative compensators, or a combination of those. Good results are achieved, either in terms of dynamic response and the quality of the output voltage [4 and 5]. The careful modeling of the plant becomes necessary, and further computer simulations are performed to check the system stability against unknown system parameters, such as the line impedance at the input of the line conditioner.

Another way to control a line conditioner is to directly calculate the duty cycle based on the input voltage and the desired reference value. In this case a digital implementation is preferable since multiplication and division operations may be involved, depending on the converter used. As the control signal is calculated without measurement of the controlled variable, there are steady state errors in the output voltage. Depending on the application, this may note be so relevant, such as in AC voltage supplies with programmable output waveform.

In this work those three forms of control will be studied and compared, highlighting the advantages and disadvantages of each, as well as the difficulties of implementing each technique. Experimental results gathered from a 3 kVA prototype will also be presented.

II. MODELING OF THE CONVERTER

The converter being analyzed is presented in Fig. 1, along with the procedure for driving the converter switches. All components are considered ideal in the figure. In Fig. 2 the same converter is redrawn, taking into account the non-idealities of the transformer, and with the switches laid in a half-bridge arrangement. At last, in Fig. 3, the small-signal model of the converter is shown, where the switches have been replaced by the Vorpérian PWM switch model [6].

The expression for the static gain, disregarding the non-idealities of the converter, is presented in (1).

$$\frac{V_o}{V_i} = \frac{D\left(n_a + n_b\right) + n_a\, n_b - n_a}{n_a\, n_b} \tag{1}$$

The variables and transfer functions in Fig. 3 are defined by:

$$v_i = \left(V_i + \widehat{v_i}\right),\ v_o = \left(V_o + \widehat{v_o}\right),\ n_a = V_i / V_a,\ n_b = V_i / V_b \tag{2}$$

$$Z_1\left(s\right) = \frac{s \cdot L_1 + R_1}{s^2 \cdot L_1 \cdot C_1 + s \cdot R_1 \cdot C_1 + 1} \tag{3}$$

$$Z_2\left(s\right) = \frac{s \cdot L_2 + R_2}{s^2 \cdot L_2 \cdot C_2 + s \cdot R_2 \cdot C_2 + 1} \tag{4}$$

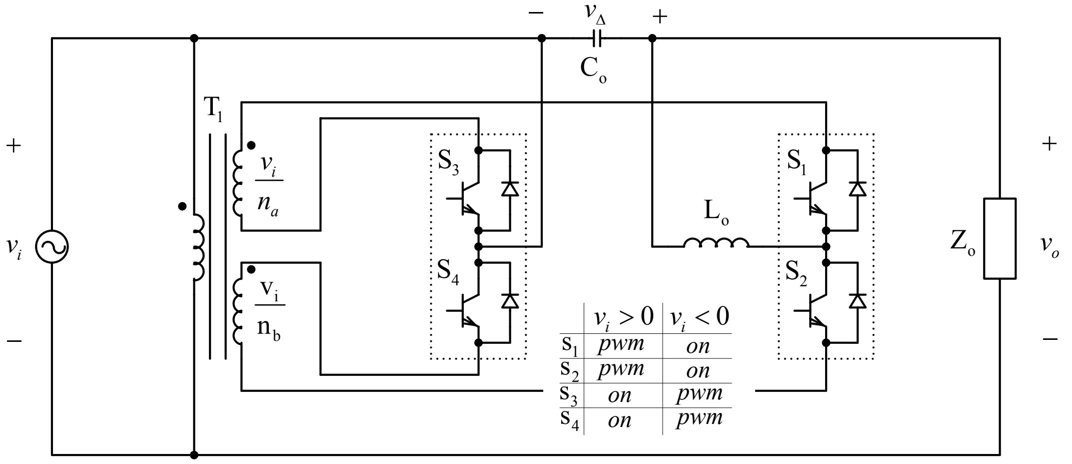

Fig. 1 – Half-bridge AC-AC converter.

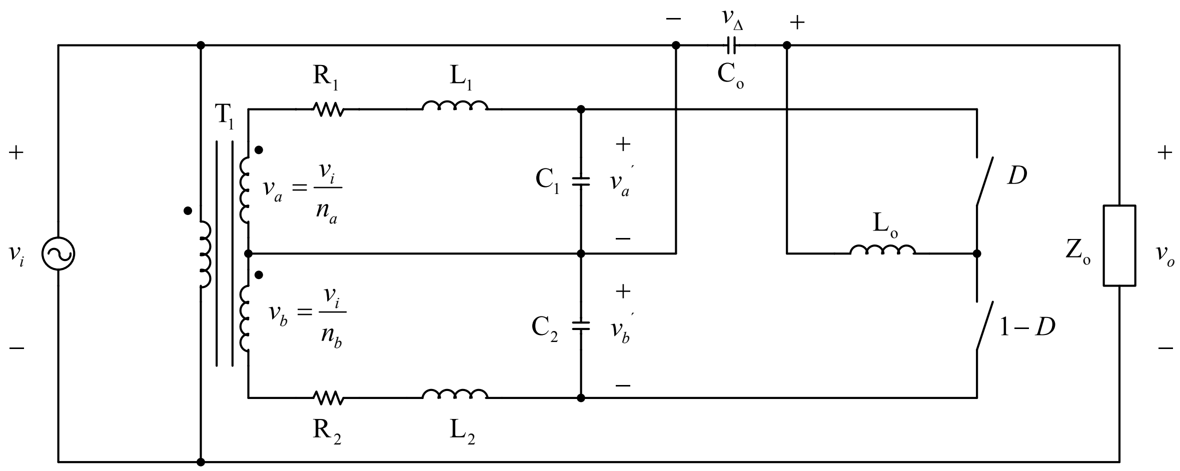

Fig. 2 – Half-bridge AC-AC converter including the non-idealities of the transformer.

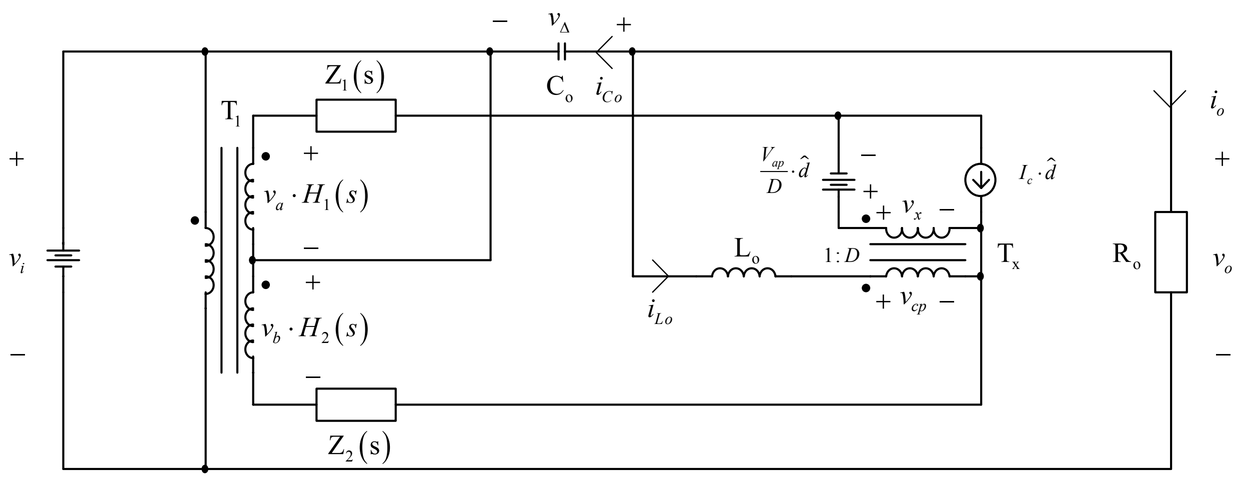

Fig. 3 – Small-signal model of the half-bridge AC-AC converter.

$$H_1(s) = \frac{1}{s^2 \cdot L_1 \cdot C_1 + s \cdot R_1 \cdot C_1 + 1} \quad (5)$$

$$H_2(s) = \frac{1}{s^2 \cdot L_2 \cdot C_2 + s \cdot R_2 \cdot C_2 + 1} \quad (6)$$

$$I_c = \frac{V_o}{R_o} \quad (7)$$

$$V_x = V_i \cdot \left(\frac{1}{n_a} + \frac{1}{n_b} \right) - \frac{V_o}{R_o} \cdot \left(R_1 \cdot D - R_2 \cdot (1 - D) \right) \quad (8)$$

$$\frac{V_o}{V_i} = \frac{n_a \cdot n_b + D\cdot(n_a+n_b)}{n_a\cdot n_b}\cdot \frac{R_o}{D^2\cdot(R_1+R_2)+R_2\cdot(1-D)-D+R_o} \tag{9}$$

$$G(s)=\frac{\widehat{v_o}}{\widehat{d}} = \frac{R_o\cdot\left[V_x - I_c\cdot\left(D\cdot Z_1(s)-(1-D)\cdot Z_2(s)\right)\right]}{s^2\cdot L_o\cdot C_o\cdot R_o + s\cdot L_o + R_o + (s\cdot C_o\cdot R_o+1)\cdot\left(D^2\cdot Z_1(s)-(1-D)^2\cdot Z_2(s)\right)} \tag{10}$$

$$F(s)=\frac{\widehat{v_o}}{\widehat{v_i}} = \frac{R_o}{n_a\cdot n_b}\cdot\frac{n_a\cdot n_b\cdot\left[s^2\cdot L_o\cdot C_o + s\cdot C_o\cdot\left(D^2\cdot Z_1+(D-1)^2\cdot Z_2\right)+1\right]+D\cdot\left(n_a\cdot H_2(s)+n_b\cdot H_1(s)\right)-na\cdot H_2(s)}{s^2\cdot L_o\cdot C_o\cdot R_o + s\cdot L_o + R_o + (s\cdot C_o\cdot R_o+1)\cdot\left(D^2\cdot Z_1(s)-(1-D)^2\cdot Z_2(s)\right)} \tag{11}$$

The realistic static gain is expressed in (9). In (10) the output voltage to control voltage transfer function (*G(s)*) is presented, and so is the output voltage to input voltage transfer function (*F(s)*) in (11).

The complexity of the converter transfer functions becomes apparent in expressions (10) and (11). This makes the design of the control system very difficult and highly dependent on the system parameters. The aforementioned expressions can be used to study the closed loop behavior of the converter with different controllers, and aid the design of these compensators in the frequency domain.

III. CONVERTER CONTROL

The control of the converter will be implemented in three different ways; two of them can be characterized as closed loop operation and the last one, which will be using just the input and reference voltages to calculate the duty cycle, can be regarded as open loop operation.

The control structure of the converter is shown in Fig. 4. It is noted that the output voltage is sampled and rectified, prior to being used in the control of the converter. This is true for the orthogonal detection and the traditional techniques. For the direct control of the converter the input voltage is used instead.

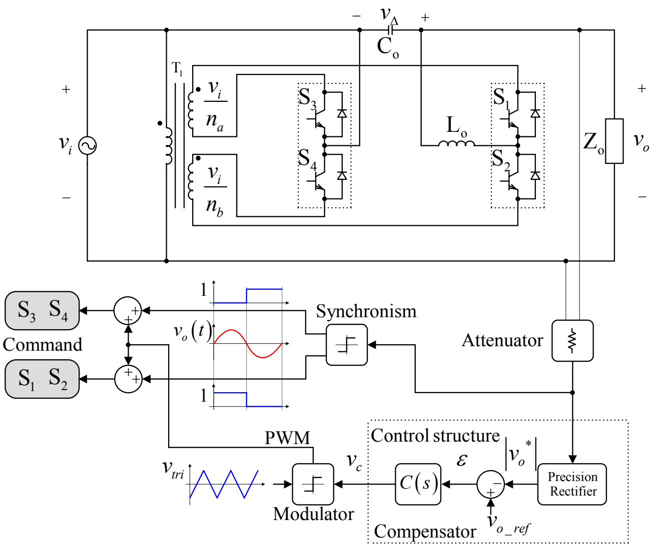

Fig. 4 – Control structure of the converter.

From the input/ouput voltage sample, and considering that the two must be in phase, a synchronization signal is obtained to generate the driving logic for the switches, as shown in Fig. 1 and in Fig. 4. It is noted that during half of the line voltage period the switches of the same leg (S_1 and S_2 or S_3 and S_4) remain in conduction, while the other two receive Pulse Width Modulation (PWM) driving signals.

The following is a study of the three control techniques and how they were implemented. Experimental results for each one of them will also be presented.

A. Control using orthogonal detection

The basic principle of the orthogonal detection is quite simple, using trigonometric relations to obtain a continuous voltage value proportional to the input voltage RMS value [2 and 3]. The expressions (12) to (18) show how this detection is implemented.

If the measured voltage is sinusoidal then the output of the orthogonal detector will be proportional to the RMS value of the measured voltage. If the measured voltage isn't exactly sinusoidal, the output value will not be the true RMS value of this voltage. This problem is shown in Fig. 6 where the difference in the output values can be seen, despite the same RMS value of the voltages being applied at the input of the orthogonal detector.

$$v_o(t) = v_{o\_pk}\cdot\sin(\omega t) \tag{12}$$

$$v_{o\,1}^{*}(t) = h(t)\cdot v_o(t) = h(t)\cdot v_{o\_pk}\cdot\sin(\omega t) \tag{13}$$

$$v_{o\,2}^{*}(t) = v_{o\,1}^{*}(t-90^o) = h(t)\cdot v_{o\_pk}\cdot\cos(\omega t) \tag{14}$$

$$v_{o\,3}^{*}(t) = \left[h(t)\cdot v_{o\_pk}\cdot\cos(\omega t)\right]^2 \tag{15}$$

$$v_{o\,4}^{*}(t) = \left[h(t)\cdot v_{o\_pk}\cdot\sin(\omega t)\right]^2 \tag{16}$$

$$v_{o\,5}^{*}(t) = h(t)\cdot v_{o\_pk}\cdot\left[\sin^2(\omega t)+\cos^2(\omega t)\right] \tag{17}$$

$$v_{o\,6}^{*}(t) = \sqrt{h(t)\cdot v_{o\_pk}} = \propto\cdot v_{o\_rms} \tag{18}$$

The block diagram of the control structure using orthogonal detection is shown in Fig. 5. The converter output voltage is sampled (attenuated) and rectified with a precision rectifier to be then applied to an input of a PIC 18F252 microcontroller. This microcontroller implements the algorithm to determine the RMS voltage value according to the principle of the orthogonal detection. At the output of the microcontroller there is a practically continuous voltage, which will be compared to the reference voltage to generate an error signal, which in turn will be compensated by a PI controller. This compensator has a cutoff frequency of approximately 1.59 kHz, more than 12 times lower than the 20 kHz switching frequency.

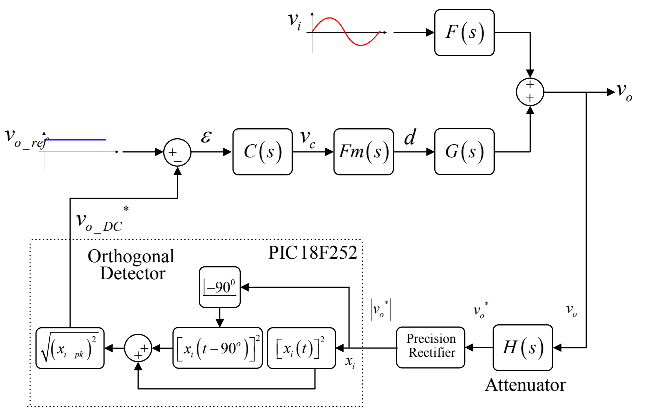

Fig. 5 – Block diagram of the control using orthogonal detection.

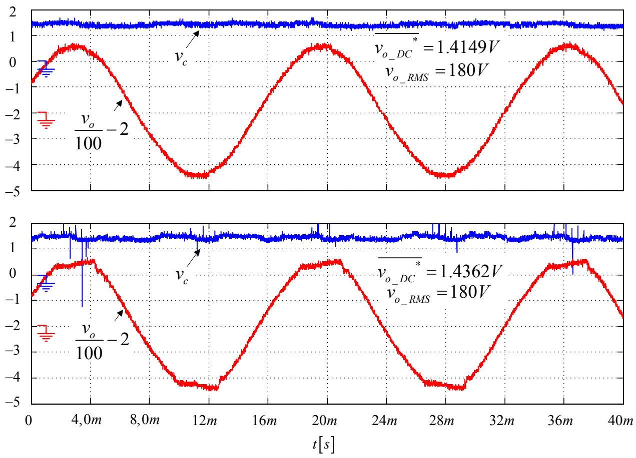

Fig. 6 – Orthogonal detector output with sinusoidal voltage and with distorted voltage.

B. Traditional control

In the traditional control the output voltage is sampled by a voltage divider and compared to a sinusoidal or rectified sinusoidal reference, as one may wish. The error signal is compensated by a PID type controller, generating the control voltage, as shown in the block diagram of Fig. 7.

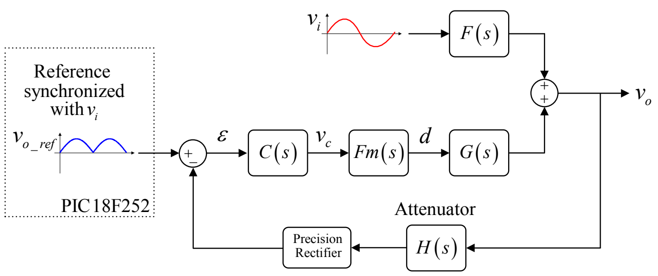

Fig. 7 – Block diagram of the control using the traditional method.

The voltage compensator design is done using the classical methodology for the Buck and Forward converters with a PID type compensator. The crossover frequency was stipulated at $f_s/8 = 2.5$ kHz. Fig. 8 presents the Bode diagram of the absolute value of the open loop transfer function for the closed loop system. This is for the ideal system, that is, without the transformer non-idealities shown in Fig. 2. The Bode diagram of the phase angle is shown in Fig. 9.

The choice of the crossover frequency is important to avoid instabilities in the closed loop operation of the converter, and so a good phase margin must be guaranteed in the ideal system.

To generate the rectified sinusoidal reference a microcontroller was used in order to ease the synchronization procedure that must be performed between the input and output voltages of the converter. Another advantage of digitally implementing the reference signal is the possibility of adjusting its frequency according to small variations in the line frequency.

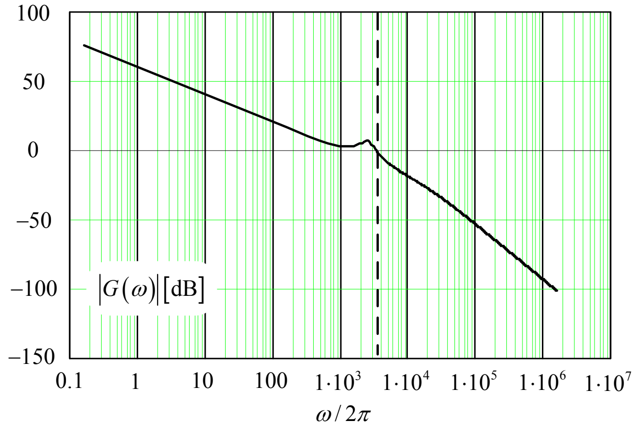

Fig. 8 – Bode diagram of the absolute value of the open loop transfer function for the closed loop system.

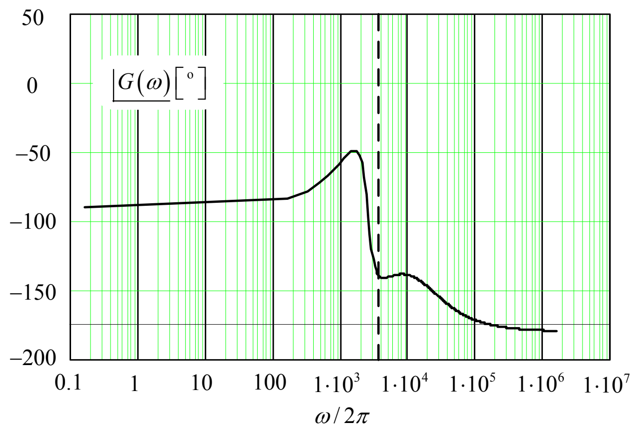

Fig. 9 – Bode diagram of the phase angle of the open loop transfer function for the closed loop system.

C. Direct control without memory

The direct control without memory consists in using the expression for the static gain of the converter (1) and calculating the duty cycle (D) as a function of the input voltage and the desired reference. This form of control exhibits steady state error, since the controlled variable (output voltage) is not sampled and used to generate the control action.

Fig. 10 shows the block diagram of the direct control without memory. It can be observed that the input voltage is sampled and rectified with precision, before being applied to the microcontroller that will calculate the duty cycle according to an internal reference. From expression (1) it can be noted that multiplications and divisions must be performed, which leads to considerable numerical error if the microcontroller operates with small word lengths (number of bits).

This technique possesses an intrinsic steady state error. Moreover, the expression for the static gain of the ideal converter (1) had been implemented, rather than that of the realistic converter (9), making the performance of the system even worse.

Due to numerical problems it was necessary to put a filter at the control voltage output, with cutoff frequency at approximately 100 Hz. This has greatly limited the dynamic response of the converter.

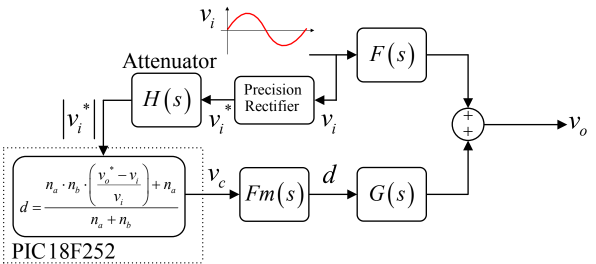

Fig. 10 – Block diagram of the direct control without memory.

IV. EXPERIMENTAL RESULTS AND COMPARISON OF THE TECHNIQUES

The prototype that was implemented is characterized by the following parameters:

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

For each control technique basically three different tests were conducted: +50% step change in the load, operation with non-linear load and +20% step change in the input voltage. The results of these tests are presented bellow.

A. Step change in the load

The +50% step change in the load is shown in Fig. 11. It is noted that, for all techniques, the output voltage is practically insensitive to load variation, presenting a small oscillation at the moment the load is changed.

The performance of the three techniques is very similar for this kind of test.

B. Operation with non-linear load

The output voltage, load current and control voltage waveforms are presented in Fig. 12. None of the three techniques is able to provide a sinusoidal voltage with low harmonic content at the output.

The traditional control could do it, as long as it had been designed to have greater bandwidth. In this case, however, some instability problems could arise due to the non-idealities of the converter. The main problem is the interaction between the voltage on capacitors C_1 and C_2 of Fig. 2 and the control voltage, because of the negative impedance characteristic presented by the converter. Steep variations in the control voltage provoke variations in the converter input current, affecting the voltage on capacitors C_1 and C_2, leading to oscillations and possibly system instability. Fortunately, the series resistances R_1 e R_2 of the transformer offer damping to the system, attenuating the voltage oscillations on capacitors C_1 and C_2.

The methods of orthogonal detection and determination of the duty cycle don't allow distortions in the output voltage to be corrected.

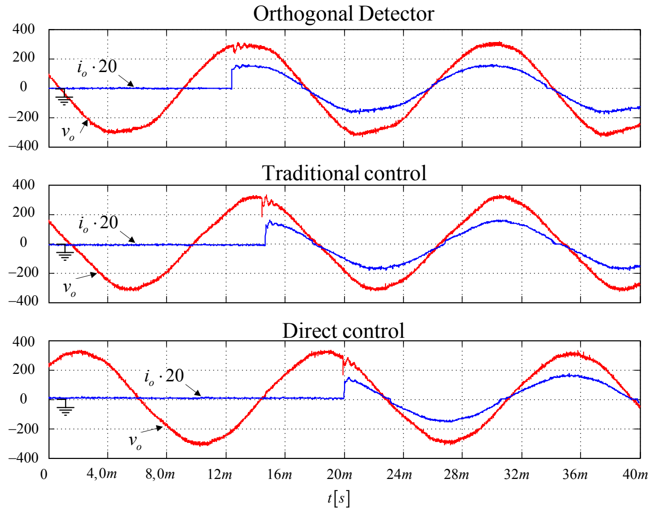

Fig. 11 – Test results for +50% step change in the load.

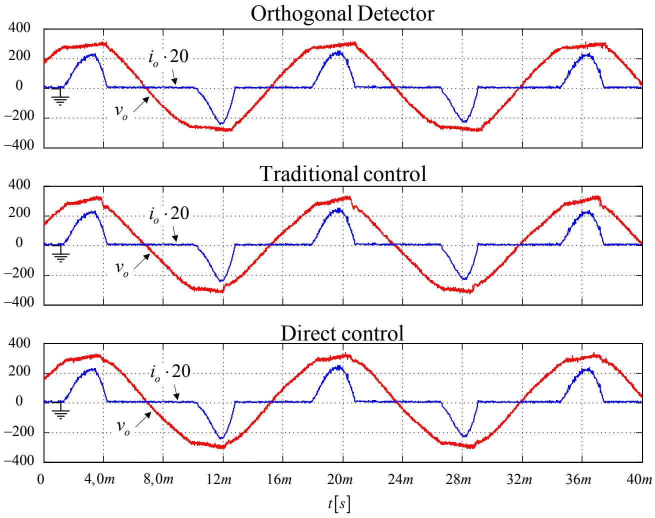

Fig. 12 – Operation of the converter with non-linear load.

C. Step change in the input voltage

Fig. 13 shows the results obtained with a +20% step change. The time necessary for correcting the output voltage, in the case of direct control, was much longer than that of the other two techniques.

In the classical control, the recovery time was approximately 3 ms.

In the control using orthogonal detection, the correction occurs in two stages, due to the way the algorithm was implemented in the microcontroller. The first correction is done in approximately 3 ms and the total correction takes 6 ms.

The direct control without memory required approximately 13 ms to correct the output voltage, thanks to the control voltage filtering used on account of the numerical problems in the implementation of expression (1).

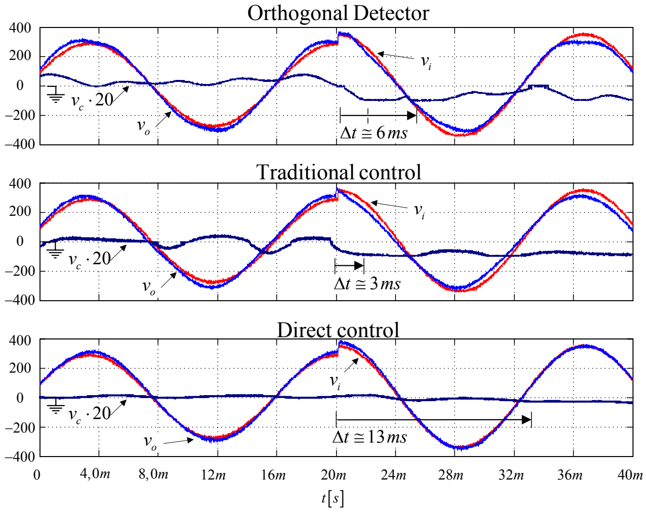

Fig. 13 – Test results for +20% step change in the input voltage.

D. Comparison of the techniques

Table 1 shows a brief comparison of the three methods for the control of the line conditioner that were studied. Several items were verified: the possibility of an analog implementation, if the design is simple or complex, if it has numerical problems and if it is capable of providing an output voltage with low harmonic content.

The traditional control method is cost-effective, but requires a great deal of effort to design the controller. The other two techniques are easy to be digitally implemented, but have problems with the numerical precision of the microcontrollers or microprocessors used.

The direct control of the output voltage was the technique that presented the worst performance, considering its large steady state error and the requirement of devices with high processing power.

The converter that was studied may have an average value problem in the output voltage, mainly when the traditional control technique is used. In this case, if the reference signal has an average value, so will the compensating voltage (v_Δ), posing problems for certain types of load.

Table 1 - Comparison of the three control techniques studied.

Control technique	**Analog**	**Simple design**	**Numerical problems**	**v_o THD**
Orthogonal detection	no	yes	yes	no control
Traditional	yes	no	no	controllable
Direct control	difficult	yes	yes	no control

V. CONCLUSIONS

Three distinct techniques were presented in this work for the control of AC-AC converters, more specifically the direct converters of the half-bridge type. Those techniques can also be used in other AC-AC converters, be they direct or indirect.

The first form of control that was used was orthogonal detection. It has the advantage of being fast and easily implemented in microcontrollers. In the second technique a conventional PID compensator is used, but it must be carefully designed due to the complexity of the plant being controlled. The last form of control that was studied determines the duty cycle according to the input voltage and the desired reference.

Depending on the application and the cost of the converter being controlled, one technique can be more advantageous than the others. At the same time, if the plant is not entirely modeled, a simpler but more robust form of control, such as the orthogonal detection, may be more appropriate than the classical control with a PID compensator.

The techniques can be used in conjunction or isolated. The direct control can be employed as a feedforward loop, operating together with the feedback loop using orthogonal detection.

Classical control was the technique that exhibited the best performance and has the ability to provide an output voltage with low harmonic content. Despite demanding great care in the design of the controller, it is implemented easily and at low cost. On the other hand, the other two techniques demand parts with high signal processing power in order to obtain a level of performance comparable to the traditional control.

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