COMPARISON OF DIGITAL CONTROLLERS FOR A FULL-BRIDGE INVERTER USING A FPGA AND A MICROCONTROLLER

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***Abstract* – This paper present a comparative study of four digital controllers applied to a bipolar 1KVA full-bridge inverter, controlled by a PIC18F852 microcontroller and an EMP7064SLC44-10 ALTERA FPGA. The paper shows the design of the controllers using two different techniques (modified Ziegle Nichols e pole placement) and the experimental results attained in the prototype assembled in the Energy Processing and Control Group laboratory (GPEC) of the University of Ceará.**

***Keywords* – Inverter, Digital Control, FPGA, Microcontrollers.**

I. INTRODUCTION

Observing the modernization of the electronic equipments in the lasts years. It is observed a large increment in the techniques and methods of control in studies for converters in diverse areas, i.e. uninterrupted energy systems - UPS, hospital equipment, sources of telecommunications among others.

Due to the arrival of the new technologies, like powerful and faster processors, as the DSPs, microcontrollers, PLDs and FPGAs it comes being spread out the digital control of converters CC-CC, CC-AC and AC-CC as possible solution to reduce costs, reducing PCI circuits and will make possible, systems updates without modifying the actual hardware.

The main focus of this paper is to show a comparative study of four digital controllers for the control of full-bridge inverter using a PIC18F452 microcontroller, as solving element of the projected control equations and a FPGA as modulating and control signal manager of the inverter.

The experimental results contemplate the inverter output voltage waveforms, application of a load step in the system for verify its dynamic behavior and the graphs with the THD for each projected controller, showing that CEI/IEC 61000-3-2 international standard was reached [1].

II. PLANT DISCRETIZATION AND PROJECT PARAMETERS

All projected controllers have as discretized plant model, according to [2]. Equation (1) shows the plant model in z-plane.

$$G_P(Z) = \frac{0,2395.Z^2 + 0,4791.Z + 0,2395}{Z^2 - 0,5843.Z + 0,5057} \qquad (1)$$

The power circuit of the inverter is depicted in Fig. 1.

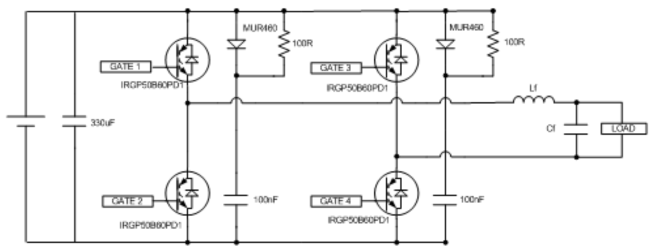

Fig. 1. Power circuit of the designed inverter.

The according to (1), the discretized plant is of second order. Thus were projected four different controllers, amongst them derivations of PI and PID controllers.

The inverter control had as purpose the implementation of feedback loop for regulation of the output voltage, using a low cost microcontroller and with an efficient A/D converter, already existent in its structure as voltage samples component. A hall-effect voltage sensor receives the voltage samples from the output of the inverter (about 110V) and converts this voltage into a smaller voltage (1.9V) to serve as reference voltage of the converter.

The output voltage proceeding from the inverter is rectified after the sampling, from the standpoint of the microcontroller cannot read negative voltages. In possession of the sampled voltage, it is compared with a sinewave reference also rectified, internally in the microcontroller for generation of the error signal. This error signal is the basis for the calculation of the implemented controllers.

The function of the microcontroller is to read the rectified voltage sampled of the output inverter's, to compare this value with a sine-wave reference also rectified implemented by software and thus to generate an error signal that will serve as basis for the controllers calculation and its ports, as is shown in Fig. 2. The FPGA function is to serve as modulator, that is, it generates the triangular wave in the switching frequency (30 KHz) and compares the response value calculated for the PIC with the triangular and thus it generates the PWMs pulses, that is connected with the gates of the switches inverter's. The FPGA also manages the correct sequence of switching, therefore mitigating the computational effort demanded by the microcontroller.

III. DIGITAL CONTROLLERS DESIGN

For the design of the controllers, two different techniques were used, modified Ziegle Nichols and pole placement. As a result we will see as if it gave to the design of an integral proportional controller (PI) and a proportional derivative integral (PID) using the modified Ziegle Nichols.

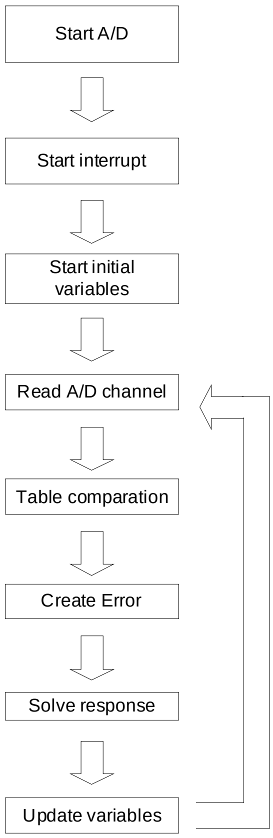

Fig. 2. PIC program flowchart.

CASE 1 - Ziegle Nichols PI controller

This method of controller parameters determination was considered by Ziegle and Nichols and has as characteristic the determination of the controller's constants P, PI and PID.

The method of modified Ziegle-Nichols has as characteristic the parameters determination of the controllers through the interpretation of the plant open loop transfer function Nyquist diagram of to be controlled.

According to the theory in [3] for the method use, it is necessary to plot the open loop transfer function Nyquist diagram system. Therefore any point in the plotted Nyquist diagram is chosen. The controller's parameters determination is made, placing the point chosen, for one another point inside of the Nyquist diagram.

The method considers to selection a point A in the Nyquist diagram complying with the following format:

$$A = r_a . e^{i(\pi + \Phi_a)} \tag{2}$$

In which r_a is the real part of the chosen point, and Φa is the angle between the real axis (ReG(jw)) and the point A.

The controller is determined, shifting the point A for a point B.

$$B = r_b . e^{i(\pi + \Phi_b)} \tag{3}$$

The controller's frequency response is obtained by:

$$r_c = \frac{r_b}{r_a} \tag{4}$$

$$\Phi_c = \Phi_b - \Phi_a \tag{5}$$

Resulting:

$$G_c(iw_0) = r_c . e^{i\Phi_c} \tag{6}$$

$G_c(iw_0)$ is the controller's frequency response. For a PI controller, observed to [3], resulting:

$$K_P = \frac{r_b . \cos(\Phi_b - \Phi_a)}{r_a} \tag{7}$$

$$T_i = \frac{1}{w . \tan(\Phi_a - \Phi_b)} \tag{8}$$

With $\Phi_a > \Phi_b$ so that T_i is positive.

For a PID controller, the proportional term K_P keeps the same in (7), however the integrator term (T_i) suffers a modification in its expression and the derivative term (T_d) is added.

$$w.T_d - \frac{1}{w.T_i} = \tan(\Phi_b - \Phi_a) \tag{9}$$

Proceeding:

$$T_d = \alpha . T_i \tag{10}$$

Where α is a constant, and according to the Ziegler-Nichols's rules are defined with $\alpha = 0,25$. So, in [3] for a PID controller, the system's constants can be calculated by:

$$T_d = 0.25 . T_i \tag{11}$$

$$T_i = \frac{1}{2.\alpha.w} . \left(\tan(\Phi_b - \Phi_a) + \sqrt{4.\alpha + \tan^2(\Phi_b - \Phi_a)} \right) \tag{12}$$

For the design of a PI controller using the modified Ziegle-Nichols method, it is first necessary to plot the plant Nyquist diagram, as is shown in Fig. 3.

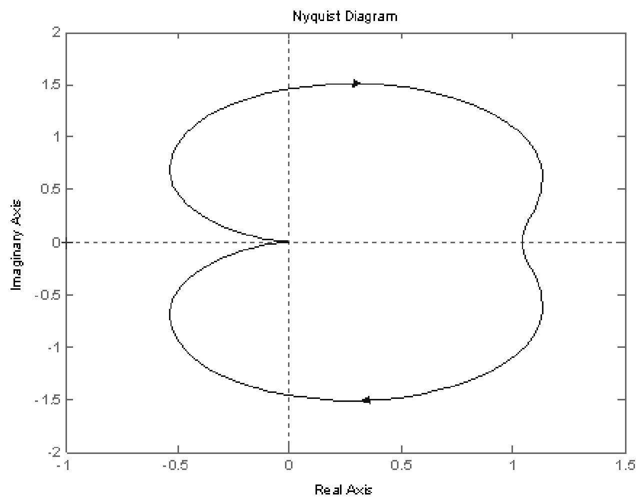

Fig. 3. Plant Nyquist diagram.

Next, we choose a point in the third quadrant of the diagram, for the selection of the point "A". The point "A" chosen in the Nyquist diagram to be taken as basis for the controller's design was the dominant pole point of the system. The dominant pole is that one, which possesses higher importance for the system's transitory response. According to control theory, for a stable system, it is necessary that the dominant poles are in the left-hand side of the real axis [4].

The system's dominant pole is represented in:

$$A = 0.7191 . e^{i(\pi + 0.7805)}$$

The chosen point "B" for the controller was:

$$B = 0.5.e^{i(\pi+1.1345)}$$

According to [5], (13) determines the PID digital control non-recursive algorithm, because to determine u(k), all the last values of e(k) have that to be stored. For the programming in digital processors, the recursive form is suitable. For this reason implies that the control calculation in one u(k) instant, depends on the previous value u(k-1) and other another terms.

$$u(k) = u(k-1) + q_0.e(k) + q_1.e(k-1) + q_2.e(k-2) \tag{13}$$

Where:

$$q_0 = K_p.\left(1 + \frac{T_d}{T_s}\right) \tag{14}$$

$$q_1 = -K_p.\left(1 + 2.\frac{T_d}{T_s} - \frac{T_s}{T_i}\right) \tag{15}$$

$$q_2 = K_p.\frac{T_d}{T_s} \tag{16}$$

For the design of the considered PI controller, from the standpoint of the points "A" and "B" already had been selected, are enough to calculate the values of the K_p and T_i variables as accordance with (14) e (15). The derivative factor is inexistent. This way it is had that the control expression has the following equation:

$$u(k) = u(k-1) + 0{,}6522e(k) - 0{,}1949e(k-1) \tag{17}$$

The step response is shown in Fig. 4.

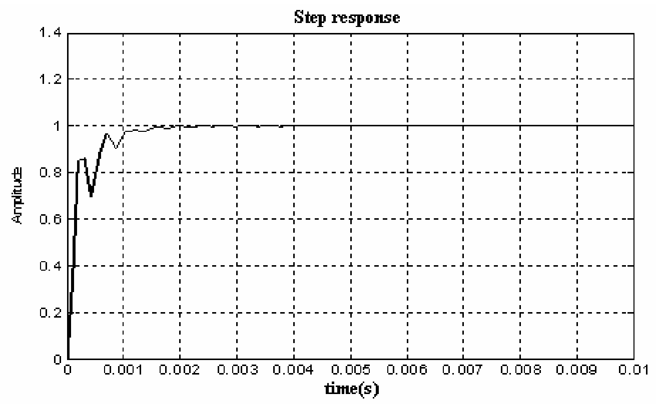

Fig. 4. Step response for a Ziegle Nichols PI controller

CASE 2 – Ziegle Nichols PID Controller

The design of PID controller using the modified Ziegle-Nichols method is similar to the one of PI controller, however, has an increase of the number of terms of the response, since that now the derivative term will be different of zero (Td≠0).

The chosen points for the PID controller design also remain the same ones of PI controller, since the dominant pole system stays the same. Using the shown previously equations, it is:

$$u(k) = u(k-1) + 0.902e(k) - 0.6618e(k-1) + 0.2346e(k-2) \tag{18}$$

The step response is depicted in Fig. 5.

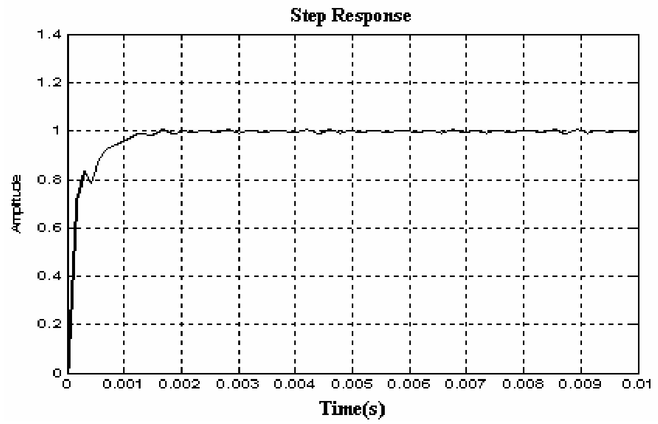

Fig. 5. Step response for a Ziegle Nichols PID controller

CASE 3 – Pole Placement PI Controller

The pole placement method is similar to the root locus method in which we set the dominant pole system in desired positions. In this project we place all the poles in strategical places.

The design of controllers using the pole placement method utilizes a logic control that stable a system, in principle unstable. At least, it is possible shifting the poles of the right-hand side transfer matrix in the real axis, to the left-hand side, finally stabilizing the system [4].

Analyzed the plant open loop pole placement, it has one zero in the point -0,717 and a pair of conjugate poles in the points 0,202±0,589i. These points are critical for the controllers design.

In practice, for a better system response, it was observed that a slower and less oscillatory response, results in a better performance of the inverter. This way, changing the system gain and adjusting the step response with no overshoot and no steady-error, it was obtained a PI controller transfer function with the following step response in Fig. 6.

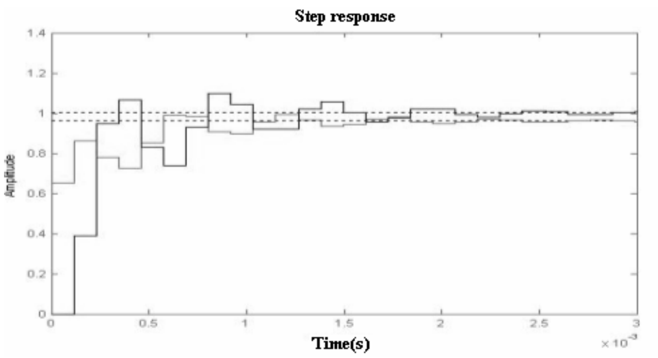

Fig. 6. Step response for a pole placement PI controller

Attained the step response of the process, it is possible to see the transfer function of the designed PI controller in the MATLAB program, resulting in a z-plane function given by (19).

$$G_C(z) = \frac{U(z)}{e(z)} = \frac{0.65z - 0.19}{z - 1} \tag{19}$$

Where, Gc(Z) is the discretized controller transfer function, U(Z) is the controller output and e(Z) is the system error both in z-plane. It was converted the controller transfer function from discrete to space state equations, it results in (20).

$$U(k) = U(k-1) + 0.65e(k) - 0.19e(k-1) \qquad (20)$$

CASE 4 – Pole Placement PID Controller

In this type of controller, the proportional gain reduces the steady-state error, the integral gain eliminates the steady-state error and the derivative gain reduces both the overshoot and the settling time. That leads to a better speed response when compared with P and PI [4].

PIDs controllers are used for second order systems, which time gain, are sufficiently distinct. In view of that the inverter transfer function is of second order, this kind of controller fits perfectly to this application.

PID Controller has in its basic structure, one pole and two zeros. For the development of this project one pole (P1) was placed in the origin (point 1 of the real axis), one zero (Z1) next to the LC filter cutoff frequency. (Point 0.3515) and another zero (Z2) placed in the half of the cutoff frequency.

It can be evidenced that for a PID controller, the oscillation observed in the previously described controllers disappears due to the derivative portion, which acts as an event viewfinder, thus preventing others oscillations.

$$G_C(z) = \frac{0.79z^2 - 0.42z + 0.05}{z-1} \qquad (21)$$

Converting the equation (21) into the space state format, it results in:

$$U(k) = U(k-1) + 0.79e(k) - 0.42e(k-1) + 0.05e(k-2) \qquad (22)$$

The step response is shown in Fig. 7.

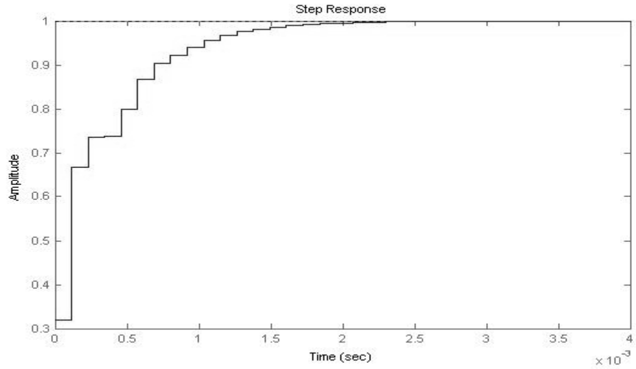

Fig. 7. Step response for a pole placement PID controller

IV. EXPERIMENTAL RESULTS

The experimental results acquired regard to good work of the inverter with different types of digital controllers. During the experimental results, it will be presented to the output voltage waveforms, output current waveform, total harmonic distortion and load transient response of 40% down in the inverter.

The Fig. 8, 9 and 10 shows to the output voltage waveform and the output current waveform for the PI controller using the modified Ziegle Nichols, as well as the load transient response of 40% down and the THD.

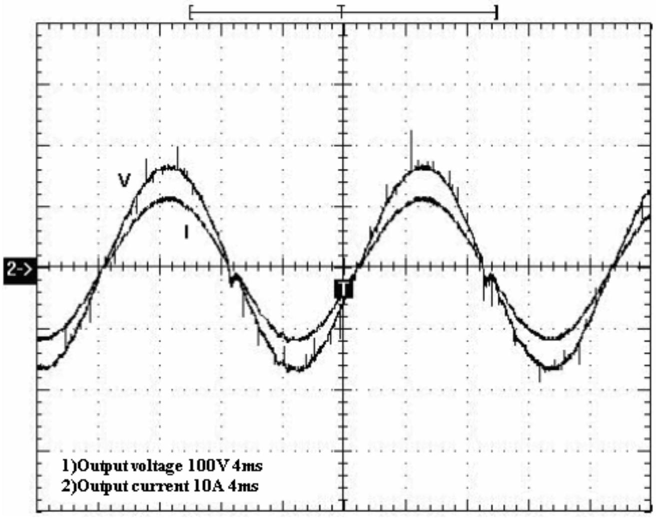

Fig. 8. Output voltage and output current: V) 100V/div; I) 10A/div; 4ms/div.

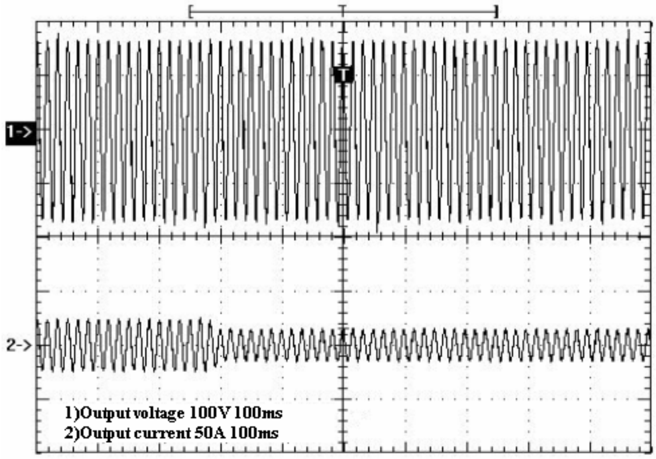

Fig. 9. Load transient response of 40% down: 1) 100V/div; 2) 50A/div; 100ms/div.

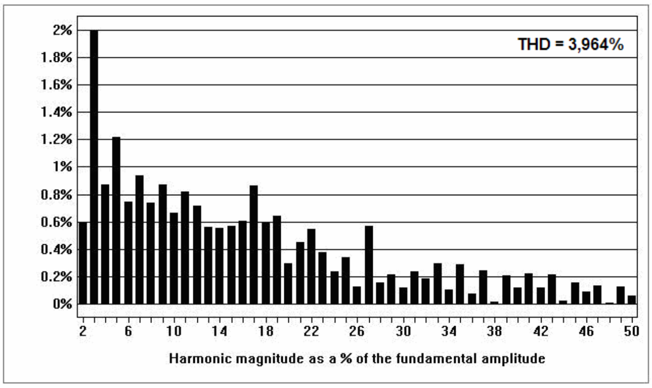

Fig. 10. Harmonic magnitude as a % of the fundamental amplitude for the Ziegle Nichols PI controller.

In applications as single-phase energy sources, for output power up to 3.4 KW, the international standard CEI/IEC 61000-3-2 establishes that the total THD of the inverter's output RMS voltage does not to exceed 5% of the low frequency fundamental amplitude, and that most important harmonic does not have exceed 3% [1].

The Fig. 11, 12 and 13 shows the waveforms of the PID controller using the modified Ziegle Nichols.

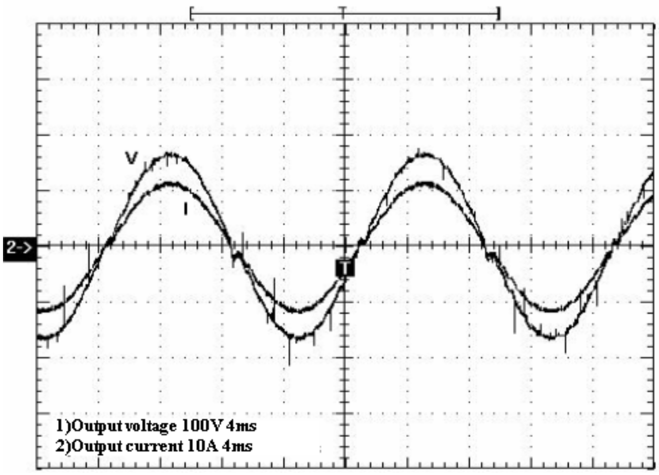

Fig. 11. Output voltage and output current: V) 100V/div; I) 10A/div; 4ms/div.

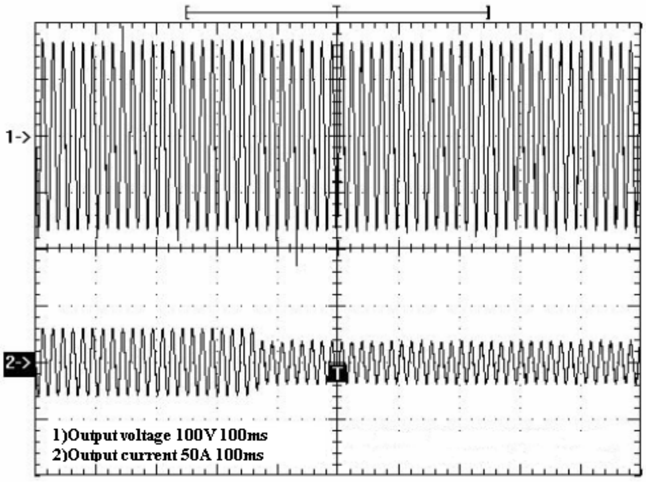

Fig. 12. Load transient response of 40% down: 1) 100V/div; 2) 50A/div; 100ms/div.

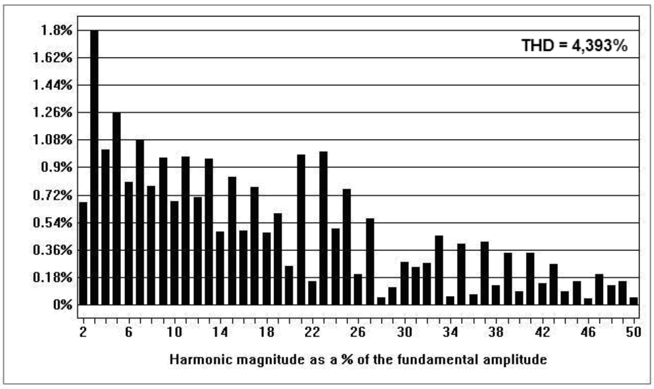

Fig. 13. Harmonic magnitude as a % of the fundamental amplitude for the Ziegle Nichols PID controller.

The Fig. 14, 15 and 16 shows the waveforms of the PI controller using the pole placement.

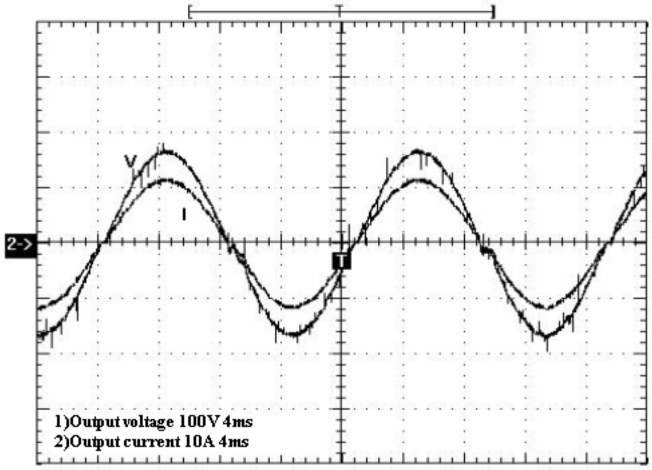

Fig. 14. Output voltage and output current: V) 100V/div; I) 10A/div; 4ms/div.

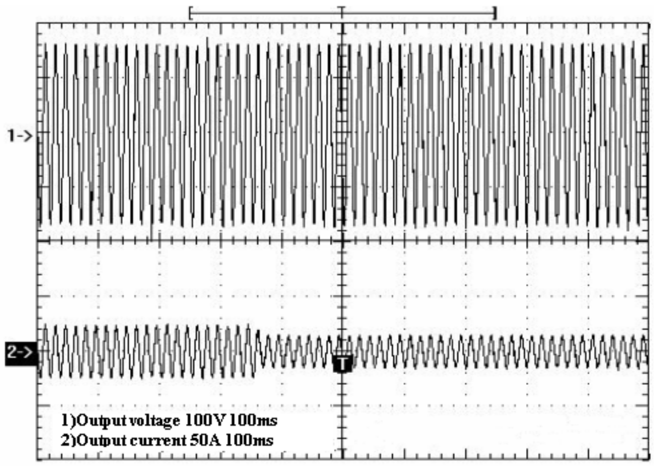

Fig. 15. Load transient response of 40% down: 1) 100V/div; 2) 50A/div; 100ms/div.

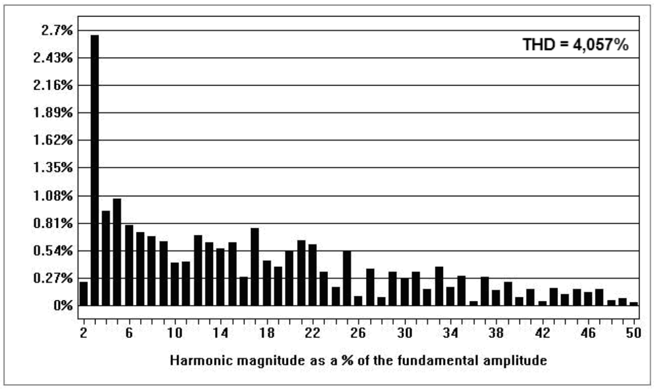

Fig. 16. Harmonic magnitude as a % of the fundamental amplitude for the pole placement PI controller.

Finally, The Fig. 17, 18 and 19 shows the output voltage and current waveforms, as well as the load transient response of 40% down and the THD for a PID using pole placement.

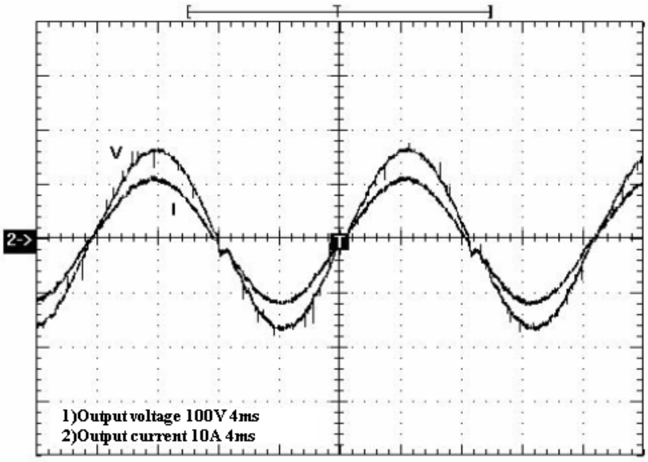

Fig. 17. Output voltage and output current: V) 100V/div; I) 10A/div; 4ms/div.

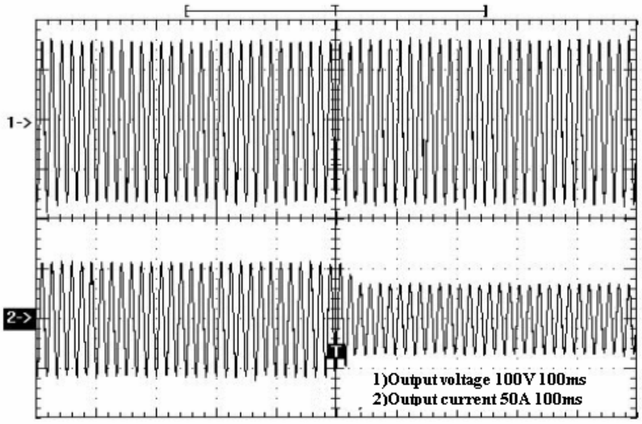

Fig. 18. Load transient response of 40% down: 1) 100V/div; 2) 50A/div; 100ms/div.

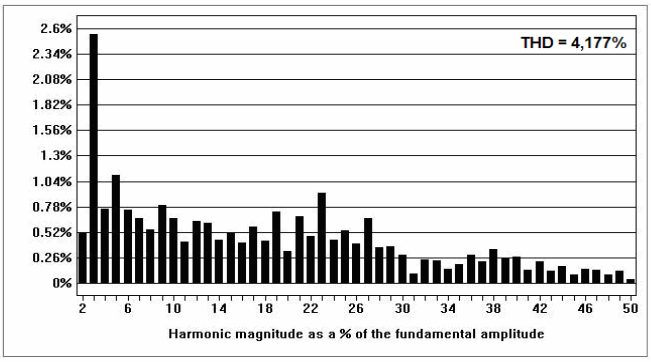

Fig. 19. Harmonic magnitude as a % of the fundamental amplitude for the pole placement PID controller.

In the table I, shows the results of the designed controllers, all of them reached the international standard CEI/IEC 61000-3-2 for inverters.

TABLE I

Controller	**Output Voltage THD**	**Standard THD CEI/IEC 61000-3-2**	**Reach the standard**
PI by Ziegle Nichols	3,964%	5%	YES
PID by Ziegle Nichols	4,393%	5%	YES
PI by pole placement	4,057%	5%	YES
PID by pole placement	4,177%	5%	YES

V. CONCLUSION

A comparative study of four digital controllers for a full-bridge inverter using two different techniques was shown. The use of a low cost microcontroller as equation calculator and a FPGA as modulator and control signal manager obtained a good result for the developed prototype. Between the designed controllers, all of them reached the international standard CEI/IEC 61000-3-2, however, the best response attained, was the PI controller using modified Ziegle Nichols with THD less than 4%.

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