DIDACTIC SYSTEM FOR DIGITAL CONTROL OF POWER ELECTRONICS APPLICATIONS

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Abstract – **This paper presents the development of an educational system for controlling power electronics systems with digital signal controllers (DSCs). This system is composed of five prototypes for the development of digital controllers. The applications were in the area of power electronics, including power converters and electrical machine drives. The kits were developed to allow verification of the models and validation of the digital controller design of the implemented circuits. The interdisciplinary nature of the educational system is highlighted in this project, where the student comes into contact with various concepts related to different subjects, such as power electronics, analog electronics, control systems, digital control, and digital signal processors.**

***Keywords* - Digital Signal Controller, Digital Control, Power Electronics Applications, Didactic System.**

I. INTRODUCTION

Control systems and power electronics are part of the core curriculum of institutes of higher education offering degrees in electrical and electronics technology and engineering. Therefore, many teaching tools have been presented in the literature to help achieve the objectives of courses related to the control of processes and power electronics [1 – 5].

The course in DSP applied to control is offered in the sixth semester by the Electronic Systems Technology degree of IF-SC and encompasses concepts from various other disciplines of the Electronics Systems' curriculum. In this course, digital signal controllers (DSCs) and their application to the control of systems and processes are presented.

Currently, besides the development of theoretical projects, the performance of the controllers is verified through digital simulation and these controllers are then implemented to control an analog plant composed of operational amplifiers.

These analog systems do not represent the actual characteristics of processes found in practice. They make limited use of the capabilities of processors and do not represent real life applications, which contribute towards a lack of interest on the part of the student.

The teaching kits available on the market in this area focus on only one application and are expensive and difficult to access since they are closed structures that do not allow the user to access and reconfigure internal variables of the process. This limits their usefulness and makes them relatively unattractive.

For these reasons, teaching kits were developed for the design of digital controllers with DSCs that represent various applications and promote an intensified use of the potential of the processors being studied.

Applications in the field of power electronics were selected since they represent typical examples of the use of these processors and they also serve as demonstrations for the course in static converters offered in the same academic semester.

For each of the applications studied, we developed the following steps: design of the converter and the definition of a complete schematic; PCB layout, construction and assembly; development of programs; experimental testing of the prototype.

Since the applications are based upon well-known structures, the mathematical models used to guide the design of the digital controllers were taken from the technical literature on the subject or from testing the developed prototypes.

II. DIDACTIC SYSTEM

Five applications of digital control to power electronics were the focus of the printed circuit board design:

- Chopper circuit for the variable speed control of a dc motor;
- Circuit for inverting the rotation direction and varying the speed of a dc motor;
- Buck converter;
- Sinusoidal PWM inverter;
- Pre-regulator circuit with PFC.

For starters, students will develop programs for controlling the structures using the TMS320LF2407A digital signal processor from Texas Instruments with the eZdspTMSLF2407 development kit from Spectrum Digital.

The DSP's main characteristics of interest to these digital control applications are:

- 25 ns instruction cycle time (40 MHz) and a performance of 40 MIPS;
- Up to 32k words x 16 bits of Flash EEPROM (4 sectors) or ROM;
- Up to 2.5k words x 16 bits of data/program RAM;
- Two event-manager (EV) modules (EVA and EVB), each including two general-purpose 16-bit timers and eight 16-bit pulse-width modulation (PWM) channels;
- Synchronized A/D conversion;
- External memory interface: 64k for the program, 64k for data, and 64k for I/O;
- Watchdog (WD) timer module;
- 10-bit analog-to-digital converter (ADC):
- 8 or 16 multiplexed input channels;
- 500 ns conversion time;

- Up to 40 individually programmable multiplexed general-purpose input/output (GPIO) pins;
- Up to five external interrupts (power drive).

Among the tasks to be undertaken by the students are the verification of the models of each system, the identification of the sensors and actuators, the development of programs for the digital control, and the testing of the systems.

The system is flexible which means that the project and controller specifications can be modified. This allows for adapting the level of difficulty to the evolution of the students' knowledge and abilities.

As the students master more concepts and develop more experience, they will work on control systems with more features and more stringent performance requirements. The sequence of presentation for the systems to be controlled is:

A. Chopper circuit for the variable speed control of a dc motor:

This system consists of a converter that allows the average voltage applied to a permanent magnet dc-motor to be varied [6], operates with a commutation frequency of 1.5 kHz, and uses MOSFET technology for its power switches.

The PWM signal created by the DSP is used to drive the MOSFET switch. The variable to be monitored is the motor speed, which is estimated by reading the pulse of an encoder with twelve slots by means of an optical coupler. Figure 1 presents the pulses used for sensing the speed at a frequency of 880 Hz.

Programs were developed to test the board containing the speed control of the dc motor. Timer 1 was configured to generate the PWM signal at a frequency of 1.5 kHz. The capture module was configured to detect transitions in the pulses generated by the encoder, was synchronized with timer 2 to count to 64,000, and presented a prescale of 16.

To calculate the speed of the dc motor, a routine was developed (interruption of timer 1) to operate as a function of the measurement of time between captures (interruption of the capture module). The results of the speed calculation were stored in a buffer for displaying the variables of interest.

Duty cycle step changes were applied at five-second intervals in order to determine the transient behavior of the speed of the motor.

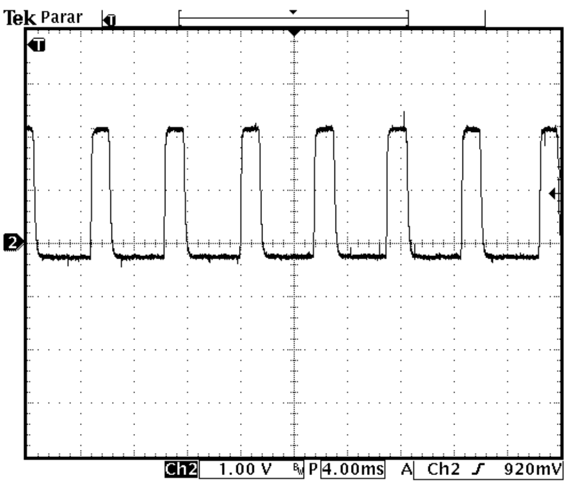

Fig. 1. Pulses for a frequency of 880 Hz.

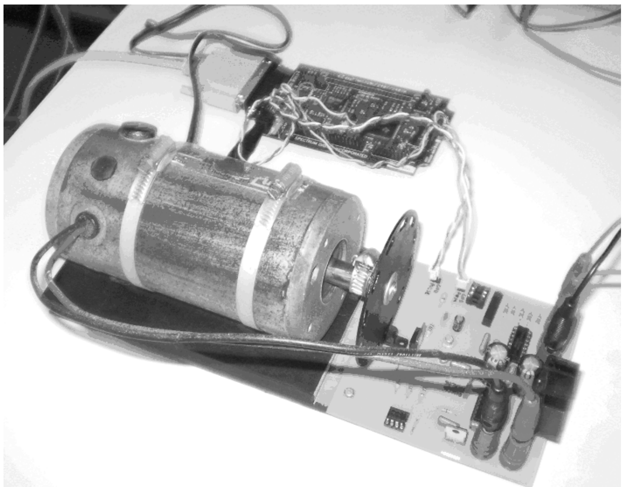
Fig. 2. Speed control system for the dc motor.

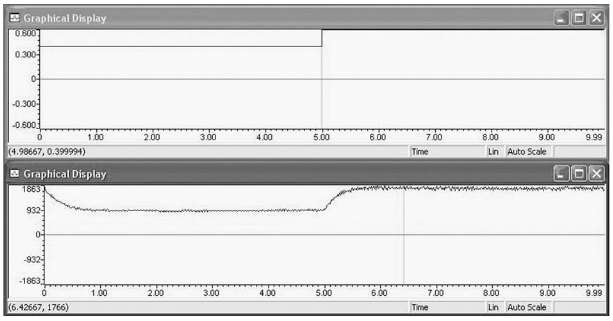

Fig. 3. Response of the system to a step change in the duty cycle.

Figure 2 presents a photograph of the complete system (DSP, control circuit, and motor) and the transient behavior of the speed of the motor is shown in Fig. 3. These results are presented in the programming environment of the DSC for a duty cycle step change from 0.4 to 0.6.

A speed variation of 943 to 1,667 rpm with a time constant of 0.27 seconds was verified, as shown in Fig. 3. The transfer function was determined from the measured data and was then used to design the controller according to (1).

$$\frac{\tilde{N}(s)}{\tilde{d}(s)} = \frac{K_M}{T \cdot s + 1} = \frac{0{,}1543}{0{,}27 \cdot s + 1} \quad (1)$$

B. Circuit for inverting the rotation direction and varying the speed of a dc motor

The circuit for inverting the rotation direction and varying the speed of a dc motor was based upon a full-bridge converter (H-bridge) using the L298 integrated circuit [7].

The control variables are the inputs that define the rotation direction of the motor. A PWM signal is applied to the enable pin of the integrated circuit to vary the speed of the motor. Similar to the previous application, the speed and rotation direction of the motor are determined by reading two encoder pulses.

The program developed to drive the motor used a similar configuration as in the previous case, with two I/O pins defined to determine the rotation direction of the motor.

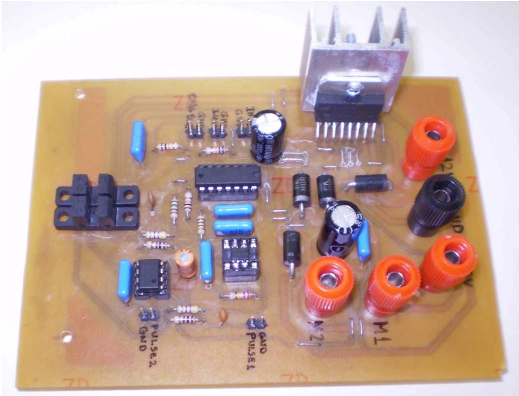

Fig. 4. PCB of the circuit for inverting the rotation direction and varying the speed of a dc motor.

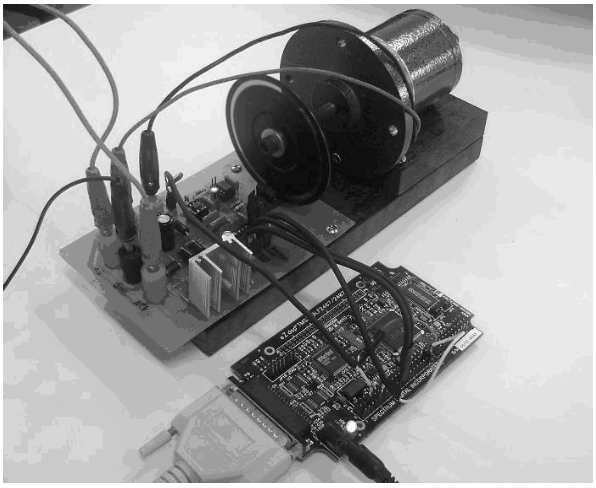

Fig. 5. System for inverting the rotation direction and varying the speed of a dc motor

Figure 4 presents a photograph of the printed circuit board used to invert the rotation direction and vary the speed of the dc motor.

A photograph of the entire system connected to the DSP kit is shown in Fig. 5.

The mathematical model for analyzing the transient speed response and designing the digital controllers was obtained in the same manner as in the previous case.

A speed variation from 1,350 to 2,100 rpm over a time constant of 0.4 s was verified. From these results, the transfer function was determined and was then used to design the controller, according to (2).

$$\frac{\tilde{N}(s)}{\tilde{d}(s)}=\frac{K_M}{T\cdot s+1}=\frac{0.1612}{0.4\cdot s+1} \qquad (2)$$

C. Step-down dc-dc converter (buck converter)

The buck converter has the function of supplying an output voltage that is lower in magnitude than its fixed input voltage. Figure 6 shows the conventional buck topology [8].

The step-down dc-dc converter was designed to operate with load variations in order to study its dynamic response. The control variable is the PWM drive signal of the MOSFET. The main variable to be controlled is the output voltage of the converter.

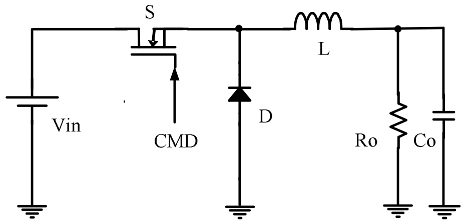

Fig. 6. Step-down dc-dc converter (buck converter).

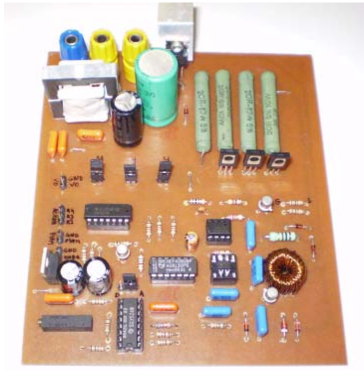

Fig. 7. PCB of the step-down dc-dc converter (buck converter).

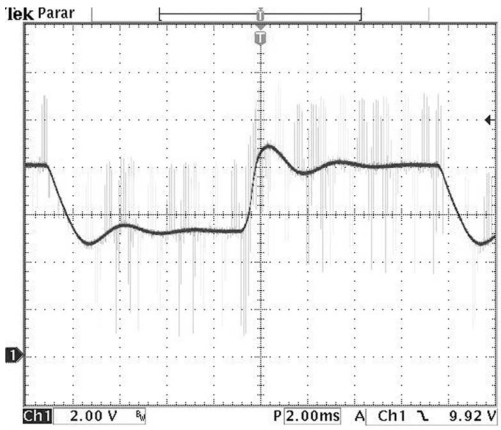

Fig. 8. Output voltage transient for a duty cycle variation from 0.2 to 0.3.

Figure 7 shows a photograph of the PCB of the step-down dc-dc converter.

To test the control board of the buck converter, timer 1 was configured to generate the PWM signal at a frequency of 30 kHz. Timer 1 also triggers the A/D conversion to sample the output voltage and the program flow is then redirected to process the measured data.

Four I/O outputs were used as control signals for load transients and system protection by inhibiting the switch command signal (inhibit).

The transfer function used to design the output voltage controller was obtained analytically in [9] and is given by (3).

$$\frac{\tilde{v}_O(s)}{\tilde{d}(s)}=\frac{\frac{K_{AV}\cdot K_{AD}}{V_T}\cdot V_{CC}\cdot\left(C\cdot R_{se}\cdot s+1\right)}{\left(L\cdot C\cdot\left(\frac{R_{se}}{R_O}+1\right)\cdot s^2+\left(\frac{L}{R_O}+R_{se}\cdot C\right)\cdot s+1\right)} \qquad (3)$$

Figure 8 shows the output voltage waveform resulting from a step change in the duty cycle from 20% to 30%. As can be seen in Fig. 8, the voltage presents a typical second order response, as predicted by (3).

D. Pre-regulator circuit with power factor correction (PFC)

This system has the objective of converting the ac voltage of the mains into a dc voltage at its output as well as correcting the power factor and improving the harmonic distortion of the input current.

Figure 9 presents the topology of the pre-regulator circuit with power factor correction [10].

The structure of Fig. 9 is composed of a single-phase full-bridge diode rectifier and a boost converter. The control variable is the PWM drive signal of the MOSFET.

The main variables to be controlled are the output voltage and the input current, which should follow a sinusoidal reference and present low total harmonic distortion.

A pre-charge circuit is used to avoid excessive current peaks through the components of the PFC converter due to the charging of the output capacitors, as can be seen in Fig. 10.

In order to obtain synchronism with the mains, an analog comparator is used which detects the beginning of every line cycle.

Figure 11 presents the sinusoidal voltage at the output of the isolation transformer and the output of the synchronism circuit (Vsinc_DSP).

Figure 12 shows a photograph of the PCB of the control of the pre-regulator circuit with PFC and the single-phase full-bridge inverter. Both structures can be simultaneously controlled by the same microprocessor.

For testing the PCB of the PFC converter's control, timer 1 was configured to generate the PWM signal at a frequency of 20 kHz and the trigger of the A/D converter was synchronized to the same timer to measure the current through the boost inductor and the output voltage of the converter.

One of the I/O pins was configured as the input for monitoring the synchronism signal and the other pin was configured as the output for the protection system, which disables the drive signal of the switch.

Figure 14 presents the waveforms of the input voltage and current without power factor correction. A flattening of the voltage can be observed at its peak.

The total harmonic distortion of the voltage (THDv) was 7.61%, the total harmonic distortion of the current (THDi) was 80.69%, and the power factor was 0.743.

The experimental results for the current loop operation are presented in Fig. 15. In this case, the measured input voltage total harmonic distortion was 3.55%, the input current total harmonic distortion was 5.77% and the power factor was 0.991.

The transfer function for the design of the current loop is presented in (4) and the transfer function for the design of the voltage loop is presented in (5).

In this case, the dynamics of the internal current loop is considered faster than the dynamics of the voltage loop (Fig. 13).

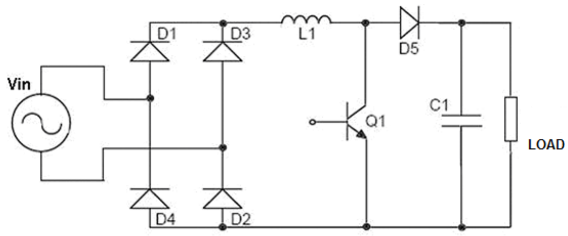

Fig. 9. Pre-regulator converter with PFC.

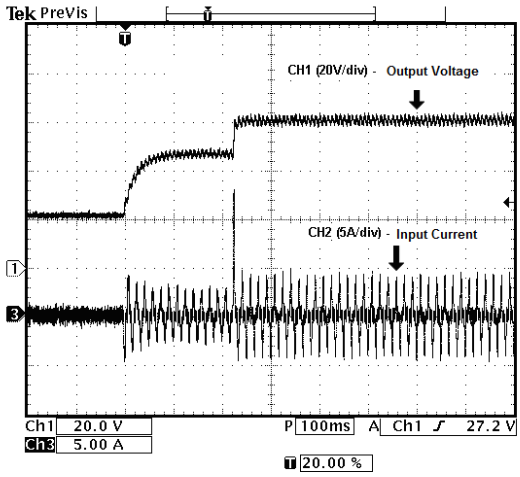

Fig. 10. Start-up signals of the PFC converter.

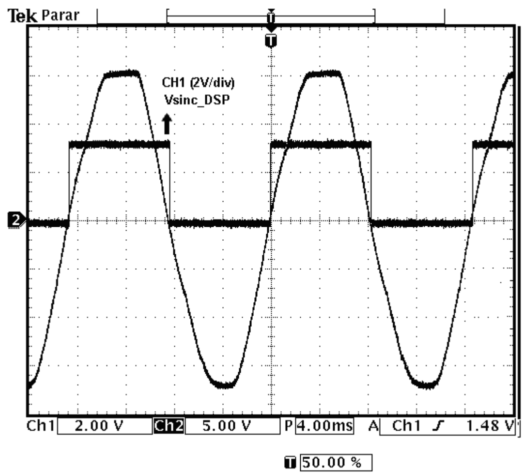

Fig. 11. Synchronism signals of the PFC converter.

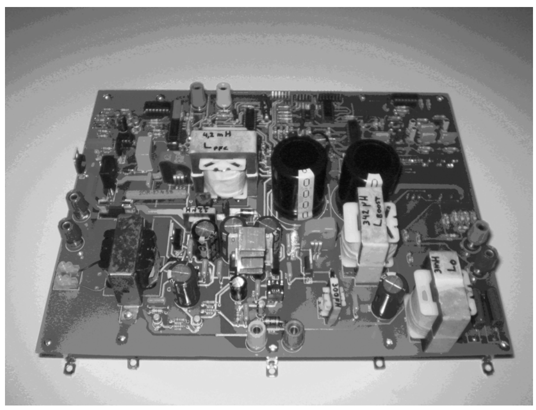

Fig. 12. PCB of the PFC converter and single-phase inverter.

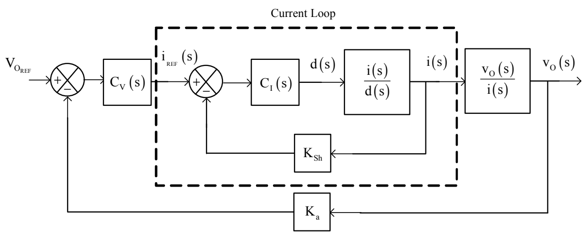

Fig. 13. Block diagram of the current and voltage loops.

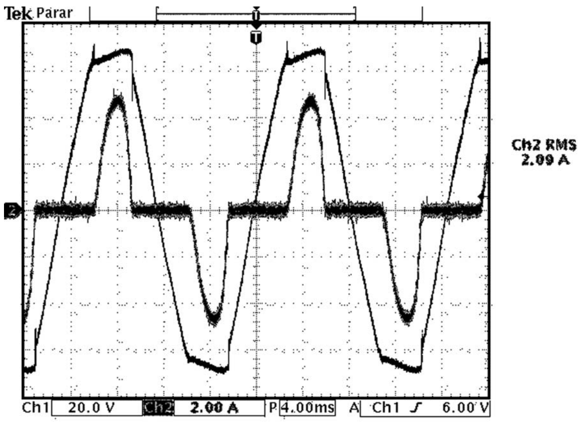

Fig. 14. Input voltage and current.

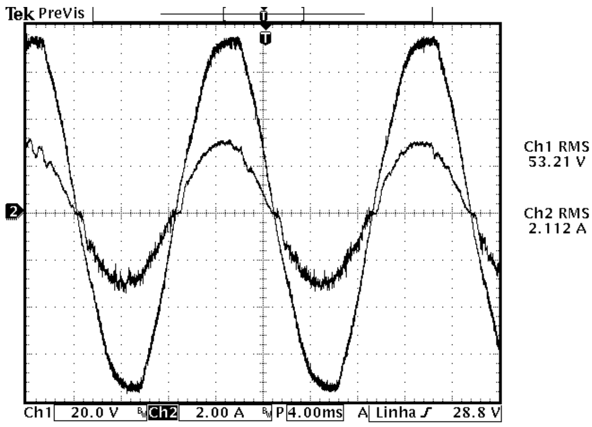

Fig. 15. Input voltage and current.

$$\frac{\tilde{i}(s)}{\tilde{d}_{PFC}(s)} = \frac{K_{AI} \cdot K_{AD}}{V_T} \frac{V_O}{L_{\_PFC} \cdot s + R_{SE}} \tag{4}$$

$$\frac{\tilde{v}_O(s)}{\tilde{i}_{ref}(s)} = \frac{K_{AV} \cdot K_{AD}}{K_{AI} \cdot K_{AD}} \cdot \frac{(1 - D_{MED}) \cdot R_{CC}}{1 + s \cdot C_O \cdot R_{CC}} \tag{5}$$

Where $D_{MED} = 2/\pi$ [10].

E. Sinusoidal PWM inverter

The single-phase full-bridge inverter is presented in Fig. 16 [11]. This system has four controlled switches (S1, S2, S3 and S4) and four free-wheeling diodes.

This circuit was assembled on the same board as the power factor correction circuit. The FSBS10HC60 [12] module was used for the inverter's switches and diodes

The control variables are the PWM signals generated by the DSP to drive the switches of inverter. The controlled variable is the output voltage of the inverter, which should follow a sinusoidal reference.

For the tests of inverter's control board, timer 1 was configured to generate symmetrical and complimentary PWM signals at a frequency of 20 kHz. These outputs are PWM3 (and PWM4) and PWM5 (and PWM6) in Fig. 17 [13]. A dead time was implemented in the drive signals of the switches sharing an inverter leg.

The timer 1 triggers the A/D converter to measure the output voltage. After the conversion, the data is processed by an interruption routine.

The protection function for the system was implemented by activating an I/O pin, which disabled the drive signals of the switches.

Figure 18 presents the output voltage of the inverter. The duty cycle of the switches has a 60 Hz sinusoidal variation.

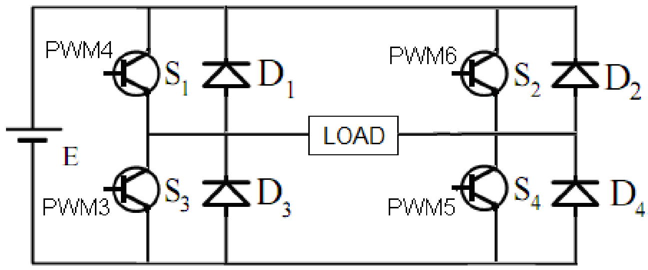

Fig. 16. Single-phase full-bridge inverter.

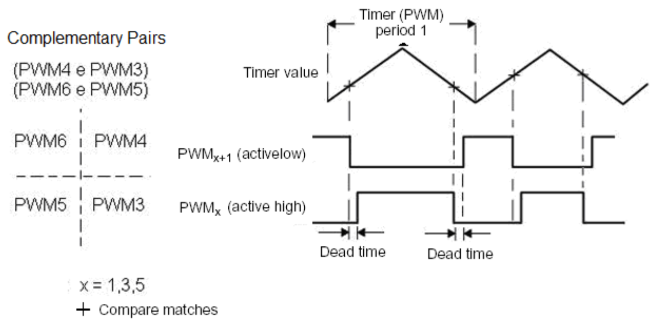

Fig. 17. Configuration of the drive signals of the inverter.

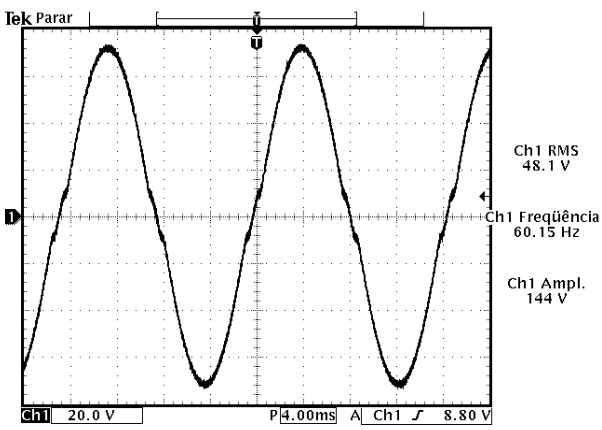

Fig. 18. Output voltage of the inverter.

Since the full-bridge inverter is derived from the buck converter, the transfer function of (3) can be used to design the output voltage controller.

III. CONCLUSION

For each application, a printed circuit board was assembled and a program was developed for testing it.

This made it possible to realize all of the functions of the sensors and actuators needed in the design of the digital controllers.

The experimental results demonstrate the functionality of structures and can serve as references for the development of test procedures for the controlled systems.

A mathematical model was proposed for each application and was used as a starting point for the design of the controllers. The test programs can serve as an example for the settings required for the operation of each prototype.

Students of previous semesters used the speed control system for the dc motor, implemented a speed measurement system, and designed and implemented controllers to improve the dynamic response of the system.

This system was well received by the students, who demonstrated its ease of use and the interconnection of the structures (DSC, control board, and dc motor).

With the development of the project, a more realistic system is being made available for students and teachers, which allows the student to apply the knowledge acquired in his/her Electronic Systems course.

The system is very flexible, *i.e.*, the design specifications and the performance requirements of controlled systems can be modified. Therefore, the degree of difficulty can be adjusted according to the evolution of the students' knowledge and abilities.

In this manner, the student will be faced with more complex and complete situations, than the highly idealized, theoretical or computer simulation examples. Furthermore, it allows the students to use innovative technologies, explore the resources of modern day processors, and understand power electronics applications.

By using different applications, it is possible to come into contact with many different concepts in the area of power electronics, such as different modulation strategies, pre-charge and synchronism circuits, protection, dead time, internal current control loops, etc.

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