

Educational Tool for the Implementation of Electric Drives Control System with Real Time Data Exchange*

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The practical implementation of a control system for an industrial electric drive involves a wide variety of well-integrated fields such as control electronics, power electronics and electric machines and drives. The learning tool presented here allows students to work with all these different fields. Furthermore, once the control system is running, this tool also provides the student with a fine-tuning system that aids understanding of the processes involved. The tuning is quite a complex task, since the whole system needs to be running in order to test the effects of successive adjustments. Traditional tuning is tedious because it is necessary to introduce the changes offline, execute the program, stop it and collect the information to be analyzed. Since the system is based on an industrial DSP, it allows an in-depth analysis of all the different phases needed to carry out the practical implementation of the drive control program on it. The low cost of this industrial DSP facilitates its use on several work benches for educational purposes. The learning system also implements a Real Time Data Exchange feature, which allows for real-time monitoring of the desired variables, such as currents, voltages and intermediate control variables.

Keywords: electrical engineering education; electric machines; drive control

INTRODUCTION

CURRICULA on the control of electric drives include the study of complex control algorithms that are often abstract and difficult to understand, as well as many aspects of control electronics. To help the students to understand them better, it is necessary to carry out laboratory sessions with real electrical machines and control systems. The control requirements call for the algorithms to be implemented using high-capacity microprocessors, so that they can be processed in short cycle times, thus improving the system's overall behavior. These microprocessors are usually Digital Signal Processors (DSP) because their hardware is designed to maximize the mathematical performance and data throughput.

Commercial systems for the development of control software use multiprocessor techniques of the master-slave type, where the processor board is plugged into a personal computer [1–3]. These systems have a very high processing capability, which makes it possible to use high-level programming languages with very short cycle times. Nevertheless, they do not reflect the limitations of a real control system, since they do not work with an industrial controller board; they turn out to be extremely costly and do not allow students to familiarize themselves with the electronics asso-

ciated with the DSP, such as sensor interfaces (input/output port configuration), signal generators, interruptions and aspects such as the execution order of the different tasks in the main program cycle, etc. [4, 5].

Commercial development systems allow the hands-on experiments in the lab to focus on the drive control strategies, but the system presented here also lets the professor teach control electronics, including the programming of the DSP and its peripherals, which is a more realistic task and exposes the student to the way in which these control systems are actually implemented in industry.

The main objectives of the work presented in this paper are as follows.

- The first is to develop a learning tool for laboratory sessions on the control of electric drives, using a DSP originally designed for this type of industrial application. In this way, in contrast to other systems oriented to the top layer of the control system (i.e., the algorithm) [3], the students become familiar with the real problems of a control system, such as the limitations on computing time, cycle time, arithmetic precision depending on data type (fixed or floating point), configuration of control electronics, memory availability, etc. [6].
- The second objective is to facilitate the tuning and debugging of the control algorithms once they have been implemented in the DSP. This is

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a complex task, since the whole system must be running in order to test the effect of successive adjustments. As a consequence, the program cannot be run step by step, no breakpoints can be inserted, etc., since it is continuously attending to the control tasks. The traditional tuning procedure [7] consists of carrying out a test and storing the resulting data in the microprocessor memory. Once the test is over, this information is recovered by the personal computer, where it can be visualized or processed to obtain conclusions to readjust the system. This operation must be repeated cyclically (cyclic debugging) [8]. Students find this a slow and monotonous process, which can lead them to lose sight of the control strategy itself. However, the system proposed in this paper takes advantage of the new specific hardware based on the JTAG interface [9] for the Real Time Data Exchange (RTDX) between the computer and the DSP. The RTDX software transfers data to/from the host in the background while the target application is running, which allows the system to transfer data between target devices and the host without interfering with the target application. In this way students can perform real-time program analysis by making changes to the program variables, and they can also instantaneously verify the effect on the behavior of the system, by the real-time monitoring of several variables, such as torque, speed estimation, etc. Furthermore, it is possible to visualize the evolution of intermediate variables in the control algorithm (real time debugging) [8], which results in better time management and in a more rewarding and interesting activity for the student.

The next three sections of the paper describe the educational system in sufficient detail to allow one to reproduce it. The last section presents a case study on the use of the system at Universidad Politecnica de Madrid.

GENERAL DESCRIPTION OF THE SYSTEM

The educational system developed was implemented on four laboratory benches. Figure 1 shows a scheme of the general layout of each, and Fig. 2 shows a photograph of the complete system.

Each bench consists of the following parts.

1. Electrical machine bench

This bench is a general purpose teaching set-up developed at the Universidad Politecnica de Madrid for courses on electrical machines in power systems. It features three rotating machines coupled together on the same shaft, as shown in the lower part of Fig. 2: a 2.7 kW direct current machine, a 4 kW asynchronous machine, and a 5 kVA synchronous machine. The set-up has a

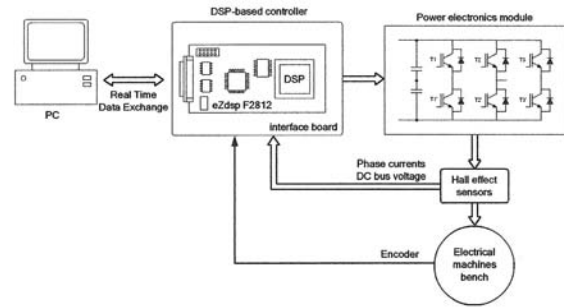


Fig. 1. General layout of the laboratory bench implementing the educational system developed.

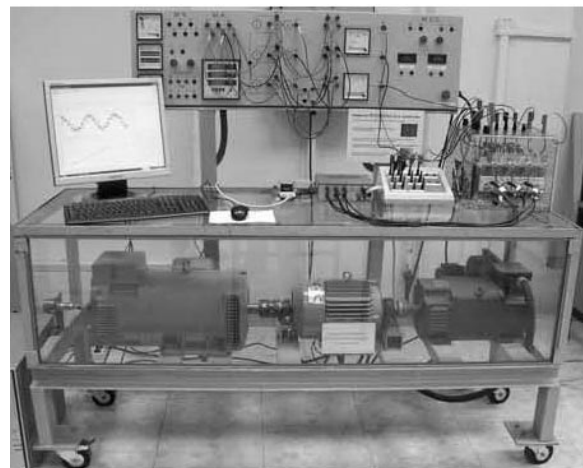


Fig. 2. Rotating electrical machines bench. From left to right: synchronous machine, asynchronous machine, and DC machine.

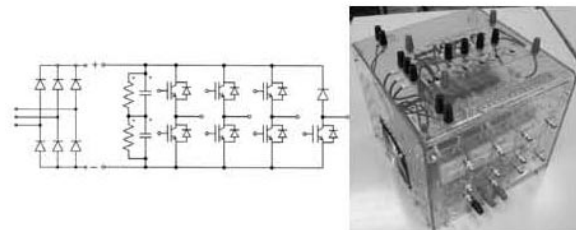


Fig. 3. Power electronics module: diagram and photograph.

torque transducer and a 2048 pulse/rev encoder for position and speed measurements, and is protected by reinforced glass for safety purposes. Connections are made through secure terminals in a front panel that also include some basic instrumentation (upper part of Fig. 2).

2. Power electronics module

The power electronics module is a configurable IGBT electronic converter from SEMIKRON [10], which can be configured to obtain different converter topologies. Figure 3 shows a diagram of the available electronic devices, together with a photograph of the module, where the methacrylate protective shield and the secure terminals can be seen.

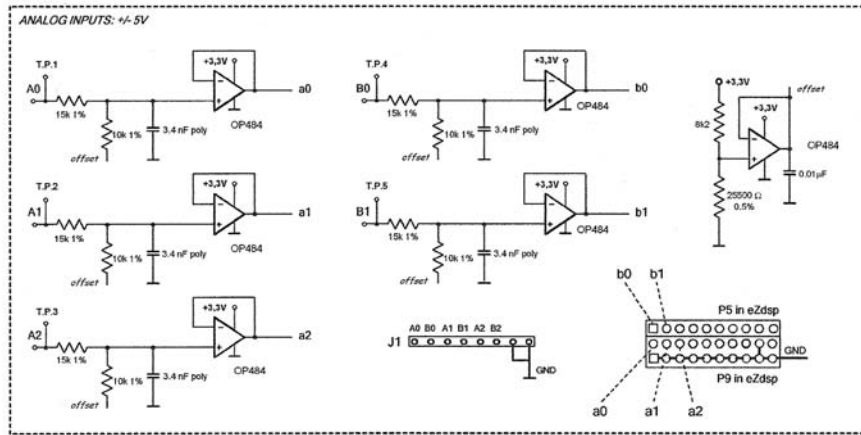


Fig. 4. Interface board: diagram of the analog input interface.

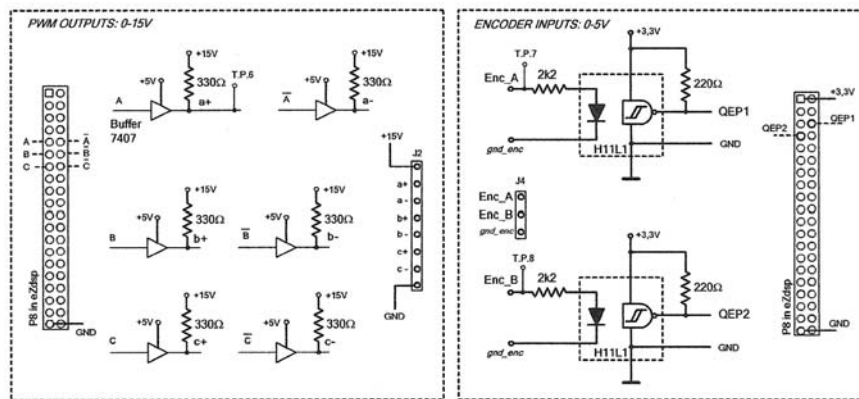


Fig. 5. Interface board: diagrams of the PWM output interface (left) and the encoder input interface (right).

3. DSP-based controller with RTDX

The core of the system is a Texas Instruments TMS320F2812 DSP [11], a Digital Signal Processor that implements the new Real Time Data Exchange (RTDX) feature. The Spectrum Digital's eZdsp F2812 module [12] is used as the hardware environment for the controller. It has been adapted for the control of electric drives by means of an interface board specifically developed for this purpose. The hardware is described in detail in the next section.

4. Personal computer

A personal computer is used for the software implementation of the control algorithms, the RTDX communication, and the developed graphical interface. It is equipped with Windows XP, Code Composer Studio [13, 14], and MATLAB [15, 16]. The software architecture is detailed below.

5. Miscellaneous equipment

The complete system includes some auxiliary components, such as Hall effect transducers for three currents and three voltages (models LA25 and LV25-P from LEM), a 0–15 V DC power supply and digital multimeters.

HARDWARE ARCHITECTURE

The eZdsp module is the starting point for the hardware architecture of the DSP-based controller. It contains all the necessary electronics for the operation of the DSP and its communication with the PC (including an emulator), but it needs additional electronics to adapt it to the task of controlling electric drives. The module has expansion connectors which, by means of external circuitry, allow the DSP to be connected to the peripherals needed to control the electrical drive. Figures 4, 5 and 6 show diagrams of the main parts of the interface board that have been designed for such a purpose in sufficient detail to allow one to reproduce it. The board circuitry is simple and flexible, and may be adapted to various types of sensors and power converters.

Figure 4 shows the diagram of the interface circuit for the analog input signals to the Analog to Digital Converters (ADC). It has been designed with unipolar operational amplifiers that allow for the DC input to be supplied by the eZdsp module (it can supply 3.3 V and 5 V DC), so that an external symmetrical source is not necessary, whereas its rail-to-rail characteristic allows for the entire range of input and output feeding

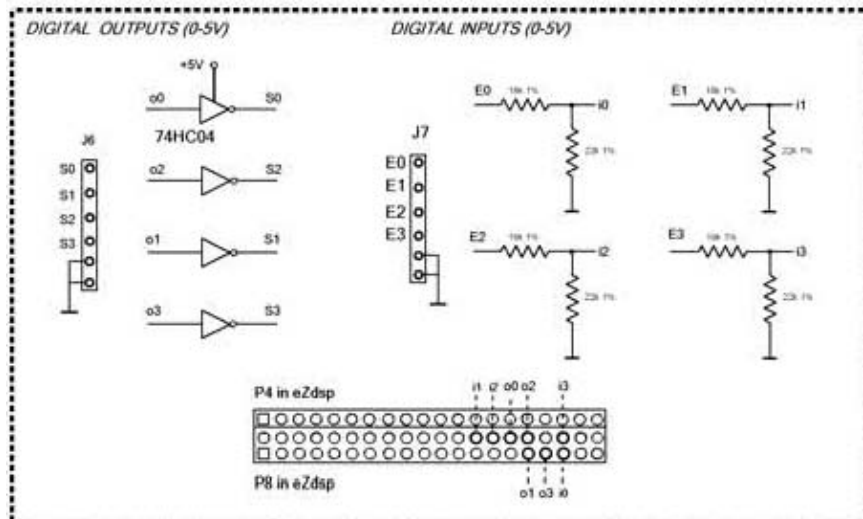


Fig. 6. Interface board: diagram of the interface for digital outputs and inputs.

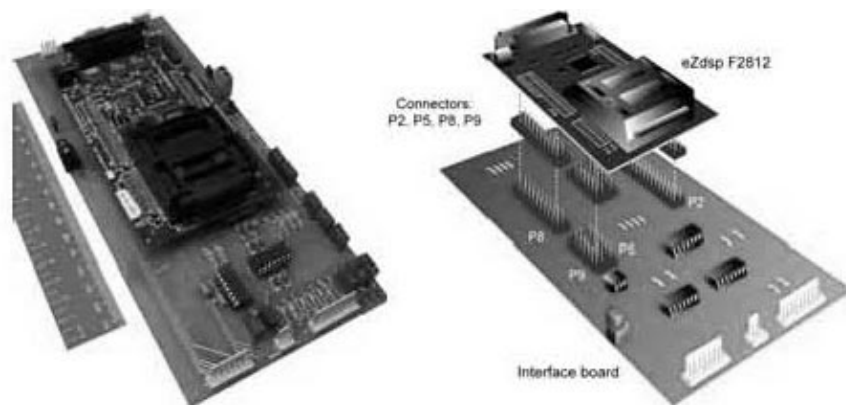


Fig. 7. DSP-based controller developed: photograph of the prototype (left) and schematic representation of the connection between the eZdsp module and the interface board (right).

voltages. It uses a simple Butterworth filter for the inputs [17–19], which is sufficient for industrial applications [20, 21]. Its cut-off frequency has been tuned to 1 kHz and it admits a ± 5 V analog input range. Digital filtering in the control program is used to achieve additional noise reduction [17].

Figure 5 (left) shows the interface for the PWM outputs. Depending on the chosen supply level (5 V or 15 V), voltage output levels appropriate for different models of inverter drivers can be obtained by means of pull-up resistors. The diagram in Fig. 5 (right) corresponds to the interface for opto-coupled inputs from encoders. The two channels allow for a determination to be made of the machine's speed and direction of rotation.

It is worth noting that several test points have been included on the interface board (T.P.1 to T.P.8 in Figs 4 and 5), so that an oscilloscope can be easily used to visualize the current and voltage measurements from the sensors, the signals from the encoders, and the generated PWM output signals.

Figure 6 shows the adaptation for digital outputs and inputs [17].

Figure 7 shows a photograph of the entire DSP-based controller (left), along with a schematic representation of the connection between the eZdsp module and the developed interface board (right). The P2, P5, P8, and P9 connector layouts are outlined on both the eZdsp module and the interface board. Although not shown in Fig. 7, in the eZdsp module, jumper JP4 is connected in the 3.3 V position and JP5 in the 5 V position.

SOFTWARE ARCHITECTURE

The educational system for the control of electric drives can be exploited on two different learning levels: basic and advanced. At the basic level, the student uses a previously programmed control system from a specifically developed graphical interface. At the advanced level, the students implement and test their own control algorithms, and they can configure the electronics associated

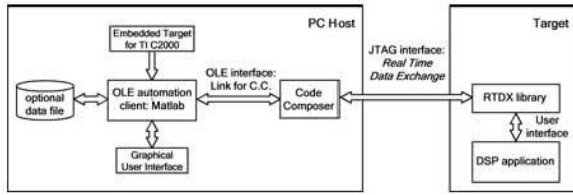


Fig. 8. Software architecture.

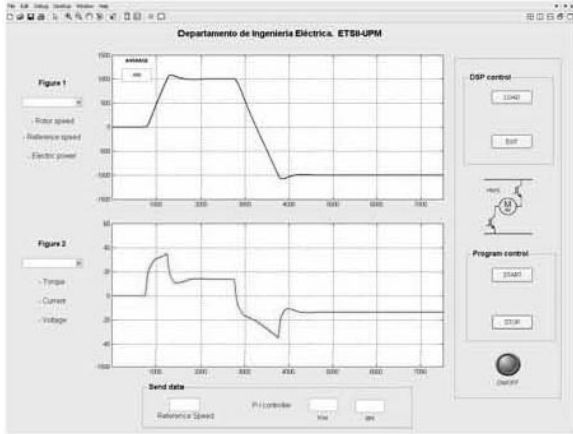


Fig. 9. Graphical interface of the educational system for DC-drive control.

with the DSP, implement the memory allocation, test the execution time of the different pieces of code, etc. To accomplish these goals, several software tools have been used. In this work, they have been arranged according to the software architecture shown in Fig 8, where MATLAB has been chosen as the OLE automation client.

At the basic learning level, the student must deal with a computer graphical interface that has been specifically developed to operate the system. As an illustration, Fig. 9 shows the computer screen for the case of DC-drive control.

The graphical interface can easily be programmed with a number of tools, such as LabView, Visual C or Visual Basic. The interface shown in Fig. 9 has been developed using the MATLAB Toolbox ‘Graphical User Interface (GUI)’ [15] (lower block in the PC Host part of Fig. 8). It is an easy object-oriented language that allows for custom interfaces and features push buttons, sliders, pop-up menus, mean values, etc.

The real time data exchange (RTDX) between the DSP and the PC has been programmed with the MATLAB Toolbox Embedded IDE Link™ CC 3’ [13] (as shown on the right, in the PC Host part of Fig. 8), using a specific object-oriented language.

The control algorithms are programmed (by the instructor, in the basic learning level, or by the student, in the advanced learning level) in ANSI C language by means of the ‘Code Composer Studio’ compiler [14], or with the MATLAB toolbox ‘Target Support Package™ TC2 3’ [16] (the case shown in Fig. 8, as the upper block in the PC Host part). This tool provides an easy way to implement control algorithms with standard Simulink blocks, along with other DSP-specific blocks. To illustrate the simplicity of this programming tool, Fig. 10 shows the case of a complex algorithm, a vector-controlled three-phase drive, where the DSP-specific blocks have been highlighted. Further hardware configuration details can be achieved via ‘s-function’ programming.

CASE STUDY

As an example of an application for this educational system, in this section we discuss the way this system is used in the Department of Electrical Engineering of the Universidad Politecnica de Madrid.

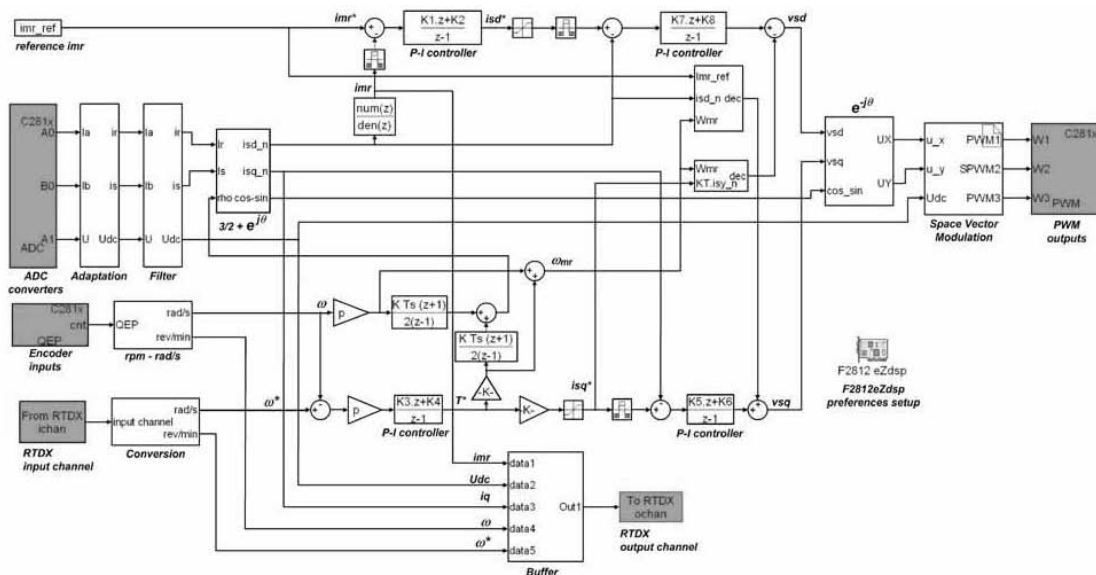


Fig. 10. Control algorithm of a vector controlled three-phase drive implemented with the ‘Target Support Package™ TC2 3’.

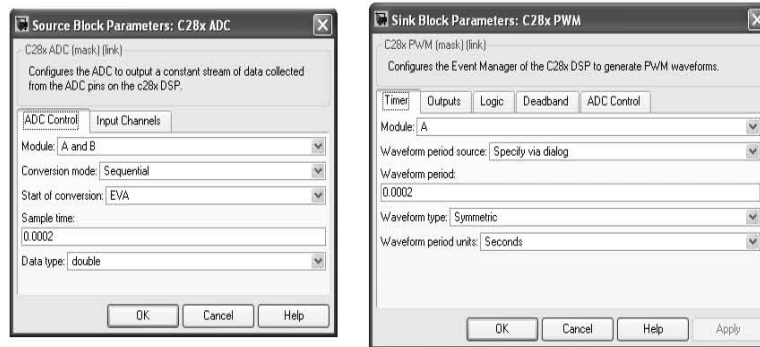


Fig. 11. Configuration of the ADC and the Event Manager in MATLAB.

To work efficiently in the laboratory with the control of electric drives requires one to have, in advance, a broad description of the different systems involved, such as the power converter, the DSP, sensors, etc. In order to optimize the time spent in class and increase the number of laboratory classes, a complete laboratory guide has been prepared for each session, and every student must pass a short test on its contents before attending it. This guide describes not only the system that the students will be dealing with, but also the laboratory tests and practical experiments that they have to complete.

1. Development of laboratory sessions

In the electrical machines laboratory within the Department of Electrical Engineering, there are complete work benches available with three machines mounted on the same shaft (see Fig. 2). Each bench's electronic converter may be configured differently: either as a bipolar chopper feeding a DC motor, or as an inverter feeding an AC motor (synchronous or asynchronous). All this, together with the additional equipment consisting of sensors (Hall effect, encoder, torque measurement, etc), power supplies and the DSP installed in each bench, allows for a wide variety of laboratory tests to be performed in the field of electric drive control.

In this complete laboratory educational system, it is therefore possible to implement not only typical tests with the three types of machines (DC, AC synchronous and asynchronous), both as motors or generators, but also specific tests on the control of electric drives that include these types of motors: open- and closed-loop speed control for DC motors, both separately and shunt excited; direct and indirect vector control of a squirrel cage induction motor with voltage source inverter (VSI), and vector control of a slipping synchronous motor.

From all the possible laboratory tests mentioned above, some specific laboratory sessions on drive control were chosen to develop the control interfaces that are presented in this paper.

Using these interfaces, the student can readily visualize the time evolution of the chosen system

variables (voltages, currents, flux, torque, speed, etc.), and modify certain control parameters in the system (regulator parameter tuning, references, etc.) in order to observe their effect in real time.

Control interfaces have been developed for the following laboratory sessions: control of a direct current motor, control of a squirrel cage induction motor and control of a synchronous motor. By way of example, we will later describe the laboratory session and the related interface developed for the speed control of a DC drive.

In the Universidad Politecnica de Madrid, the procedure carried out in the laboratory sessions includes an initial explanation about the particular topic that is going to be tested: control of a DC motor, induction motor, etc. This explanation also covers the most suitable converter type, the chosen regulation system (open- or closed-loop control, field oriented control, etc.), as well as the variables to be measured. Depending on the student's specialty, it may include aspects relating to the electronics associated with the DSP. For example, they must configure the PWM type (symmetric or asymmetric, double updated, etc.), the sample time, the ADC number and conversion sequence, the CPU interruptions, the encoder reading, the watchdog timer, etc., as illustrated in Fig. 11.

Finally, the student performs tests corresponding to those made in the laboratory session using the software explained above. Each laboratory session comprises different tests that are intended to help the student visualize in real time the effects on the system caused by the changes previously introduced (reference values, load torque, etc.). Once the curves and results of each laboratory session are recorded, the student must complete a report explaining the session objectives, the tests done, and the conclusions obtained from this task.

2. Application example

As an example, the procedure to follow in the session 'Control of a DC drive' (see Fig. 12) is presented below.

Before the laboratory session begins, the corresponding machine must be connected to the power converter, which must be set up with the proper

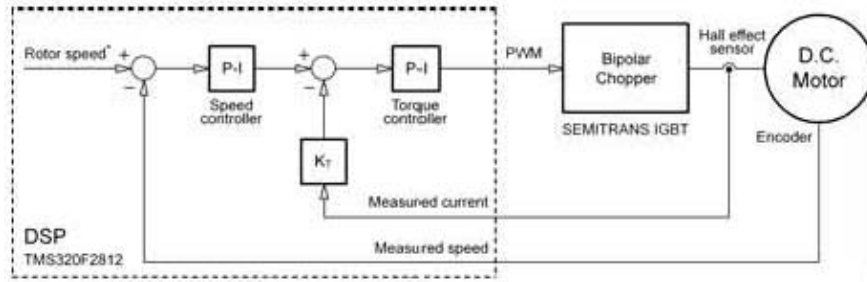


Fig. 12. Control system used in the laboratory session 'Control of a DC drive.'

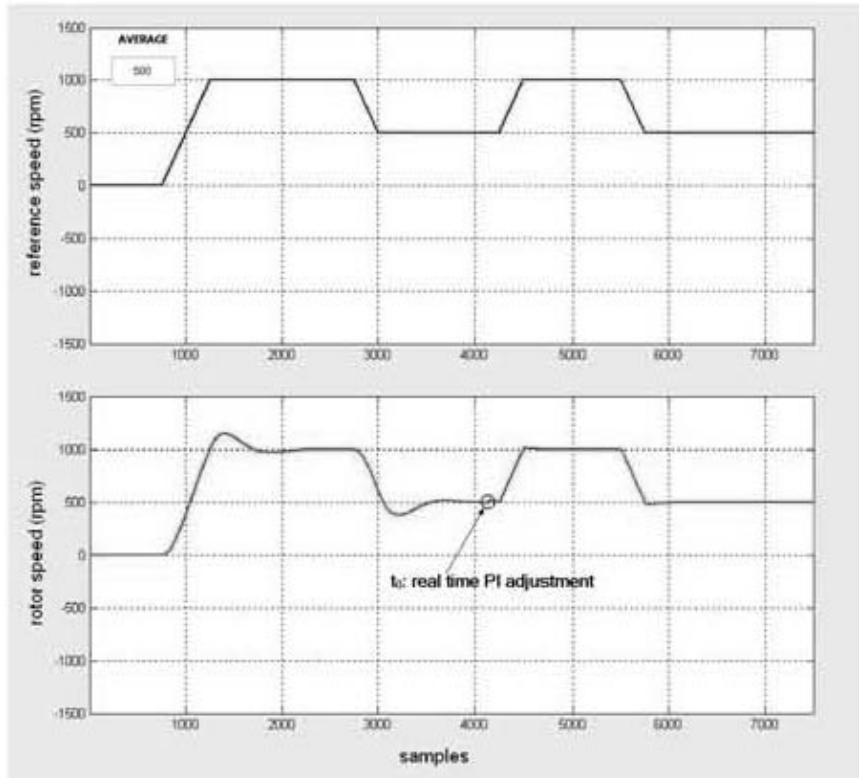


Fig. 13. Reference and measured speed before and after the PI regulator is adjusted in real time.

configuration (a four quadrant chopper with bipolar commutation, in this case). Once the theory has been explained, the student opens the graphical interface corresponding to this laboratory session (see Fig. 9). With this tool, the student will be able to do the following.

- Load the program into the DSP and exit the interface.
- Start and stop the control program execution.
- Select two variables, from six possibles, for simultaneous real-time visualization (real magnitudes or intermediate control variables).
- Change the constant values of the PI regulator, as well as the speed reference value in real time.
- Save the resulting data to an Excel file.
- Use the MATLAB calculation capability to analyze the data.

At the beginning of the session, the student uses a version of the control program in which the motor is simulated by means of its transfer function. In this way, the student can make the first adjustment of the regulator parameters. This simulation is run on the DSP and uses the same control program that will be used later with the real motor but, in this case, it is the motor transfer function that determines the motor variables such as currents, speed, torque, etc. (neither the sensors nor the inverter are used).

Before the simulation starts, the student must introduce the motor parameters (armature resistance and inductance, inertia, etc.) in order to calculate the PI speed regulator constants that are best suited to achieving a certain behavior.

Then, the student may introduce these constants in the control program so that, after loading it in

the DSP, he or she can check how they work. This last task is carried out using the graphical interface to yield real-time graphical results.

Once the control loop is considered to be properly adjusted, the student may load into the DSP the version of the control program that governs the converter and the real motor. In this way, the system's performance can be checked against the previous simulation. While the program is running the system may be performance-tuned by changing the regulator constants in real time, that is, without stopping the machine (see Fig. 12). The speed range for the reference values that the system may accept is software limited, and includes positive and negative values, which allows for a better analysis of the control system's response.

During this session, the student may visualize, at any time while the motor is running, the time evolution of the following variables: armature current, motor torque, motor speed and speed reference, applied voltage, and electric power consumed or delivered to the mains by the motor.

In the second part of the session, the load torque may be changed by using the synchronous machine that is mounted on the bench as a generator. In this way, the control system behavior may be checked when the speed is kept constant under load torque changes. Since the student can continuously visualize the motor speed and torque evolution, it will be easy to decide whether it is necessary to readjust the regulators. For example, Fig. 13 illustrates the effect of the real time adjustment of a PI regulator on the measured

speed, where t_0 is the time at which the modification takes place. Finally, the student can save the recorded variables data in an Excel format file, which can be used to prepare the evaluation report.

CONCLUSIONS

A new learning tool that allows one to make an in-depth analysis of the different phases required for the practical implementation of the control of an electric drive has been presented. With the aim of improving the learning of drive control strategies, an interface that facilitates the communication with the DSP control program has been developed. By allowing the control parameters to be changed and the results to be visualized in real time, the student can focus on the control algorithm, making the laboratory sessions more appealing and efficient. The system is developed on an industrial DSP, so in addition to the benefits of familiarizing students with actual constraints, its low cost allows it to be used on several working benches for educational purposes. As a result, the students are provided with new interactive learning tools that will enable them to deal with the complex task of controlling electrical drives through stimulating and motivating hands-on experiments.

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