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Design of PM Motor Drive Course and DSP Based Robot Traction System Laboratory

Driss Yousfi†, Saïd Belkouch*, Abdellah Ait Ouahman*, Damien Grenier**, Bruno Dehez***, and Eric Richard‡

†* Dept. of Electrical Eng., Cadi Ayyad University-ENSA, Marrakech, Morocco
** Ecole Normale Supérieure de Cachan, Université Européenne de Bretagne, France
*** Center for Research in Mechatronics, Universite Catholique de Louvain-la-Neuve, Belgium
‡ Institut Supérieur de l'Electronique et du Numérique, Toulon, France

Abstract

This paper presents a part of North Africa/Europe collaboration results in education to develop project-oriented courses in power electronics and motor drive field. The course aims to teach Permanent Magnet motor drives close to a real world project of significant size and depth so as to be motivational, namely mobile robot project. Particular skills, student will acquire, are those relative to the detailed design and implementation of PM motor controllers in DSP based rapid prototyping environment. Simulation work is completed using graphical modeling tools in Simulink/Plecs, while real-time implementation is achieved by means of eZdspF2812 board and Simulink/TI C2000 Embedded Target tools. This flexible development environment fit the robot traction system very well and provides exactly the functionality necessary for an efficient PM motor drives teaching as demonstrated by a set of simulation and experiments.

Key Words: PM motor drives, course, laboratory, project, simulation/implementation, rapid prototyping, TI C2000, sensorless control.

I. Introduction

Traditionally, the power electronics and motor drives subject, for undergraduate programs, included a number of self-contained and independent laboratories. The objectives were focused on observing in practice the theory presented in lectures. Laboratories were not efficient as a learning method and students found this an unmotivating academic experience.

These problems have been continuously examined by several experts in the field to develop a better learning environment [1]-[4],[7]-[13]. Restructuring of the classical power electronics course has been recently proposed in [2],[3] to stimulate students for the energy conversion field. Furthermore, many publications have appeared in the literature about new computer-aided teaching tools [4]-[6], new laboratory setups [7]-[10] and project-oriented courses [11]-[13] to aid in comprehension of topics.

It is true that project based learning method greatly increases students understanding and helps them to develop several important abilities such as cooperation, self-directed learning, project management, etc. However, a single large project spanning all lecture content without preliminary laboratories presents several disadvantages [12],[14]. The links between lecture content become hard to achieve and to maintain. Students can become overwhelmed with the magnitude of the task, and might be required to give more effort on project management skills that are not the main focus of the project. Further, every student is aware of the overall picture of the project only, except for the subsystem he should handle. Finally, project assessment becomes a large task at the end of semester.

Our educational intervention, designed to address the aforementioned problems, was to base the practical component of the power electronics and motor drives subject around mobile robot project. Then, a combination of several long laboratories and the project, linked together by a common robot platform, is planned during the academic year. A revised curriculum was elaborated to focus on the robot project and arranged in accordance with its objectives.

Three international partners have collaborated on this intervention i.e. Cadi Ayyad University-Morocco (UCAM), The Universit? Catholique de Louvain-Belgium (UCL) and ISEN Engineering College-France.

Firstly, the robot prototypes were developed based on ST7 microcontroller circuit. The traction systems were built using Permanent Magnet 'PM' Motors. For control purpose, the algorithm codes was implemented in assembly language and

Manuscript received May 31, 2010; revised Sep. 28, 2010
† Corresponding Author: dr_yousfi@yahoo.com
Tel: +212 524 434 746, Fax:+212 524 434 740, Cadi Ayyad Univ.
* Dept. of Electrical Eng., Cadi Ayyad University-ENSA, Morocco
** Ecole Normale Supérieure de Cachan, Université Européenne de Bretagne, France
*** Center for Research in Mechatronics, Universite Catholique de Louvain-la-Neuve, Belgium
‡ Institut Supérieur de l'Electronique et du Numérique, France

had to increase or decrease the motor speed in leaps, and open-loop, using four duty cycle levels only. Unfortunately, the control circuit limitation and the conventional organization of motor drive courses have opposed the curriculum evolution.

This paper describes the process and advantage of replacing ST7 system by eZdspF2812 board associated with a rapid prototyping system for all laboratories coupled with the PM motor drive subject. It presents also a summary of the redesigned course.

PM motors drives i.e. PM DC, Brushless DC (BLDC) and Permanent Magnet Synchronous Motor (PMSM) drives share several points; particularly models and controller designs. Arranged together in one course, they form very smooth, progressive and time-saving teaching of motor drives.

In the previous version of the robot, students developed the control algorithm and simulated it in Matlab/Simulink. When the functionality of the algorithm was proven, the algorithm was manually implemented in Assembly or C to target the specific processor. For each modification the code had to be updated and debugged which was very time-consuming.

At present, Computer Aided Control System Design (CACSD) tools are used to generate real-time code automatically. The general idea is to simplify the programming process by making it more graphical and thus more intuitive with CACSD environment. Consequently, any student familiar with building models in Simulink may test and upload easily real-time programs.

Recently, more and more companies begin to provide rapid prototyping system based on CACSD software and commercially available hardware.

To our knowledge, TI C2000 Embedded Target, working in Simulink environment with eZdspF2812 development board, is the best for real-time control of energy conversion systems.

Until now, several papers using similar rapid prototyping solutions have been published. But in general, these papers describe specific and small size applications such as: active power filter [15], Power Factor Boost Rectifier [16], battery charging system [17], DC motor control [18] and DC/DC buck chopper [19].

This paper presents a set of laboratories for the first semester based on eZdspF2812 rapid prototyping system which is also used for the robot project in the second semester. In all experiments, controllers are designed and tested in Simulink/Plecs environment prior to their implementation using TI C2000 library. This saves tremendous amount of time and helps to speed up the learning and the implementation of real-time applications, besides reducing the hardware cost.

II. General Layout of the Course

The course is conducted in 15 weeks of the first semester with four hours of faculty/student contact per week. Since it is part of project-oriented course, the former eight weeks are devoted to regular classes, in which the motor drive fundamentals and simulations, in addition to DSP software development, are presented.

During lectures the motor and drive fundamentals are covered. Several simulation sessions are planned for each drive as course proceeds. In these sessions, students design controllers and investigate the drive responses in different situations, in regard to some specifications.

Moreover, control system design using, Simulink / TI C2000 DSP Embedded Target / Code Composer Studio Link development environment, is also covered.

The rest of the semester, seven weeks, is devoted to the implementation of PM motor control techniques using Simulink/TI C2000 and eZdspF2812 prototyping system.

A. Laboratory Design

To ensure the laboratory component is as effective as possible, considerable thoughts were given to their design and implementation.

Long laboratories around the mobile robot are adopted to address many of the problems mentioned in the previous section i.e. the laboratory should be motivating and the learning should occur during several unstressed sessions, with opportunities for reflection and allowing deeper learning. In addition, assessing a significant amount of work, rather than a superficial examination of a small task each session, allows a more accurate final picture of student success.

Three two-week laboratories were planned (TABLE I), and each consists of four two–hour sessions. Students work in groups of two. The lecturer and tutor should minimize their interference in the laboratory progress and questions are answered only if asked.

The three laboratories were based on the power electronics and motor drives involved in the robot. They are supported by two tutorials dealing with rapid prototyping system introduction and sensors for motor drives. Each tutorial lasts tow session of two-hours. The content of these parts is as follows:

Tutorial l: Introduction to the rapid prototyping system

- Steps from the model to the implementation: Simulink, Real Time Workshop, Embedded Target for TI C2000 DSP and Code composer Studio.
- Design, simulation, implementation and verification of control systems on eZdspF2812 target.

Tutorial 2: Sensors for motor drives

- Current sensing and signal conditioning to fit the ADC voltage range of eZdsp.
- Incremental encoder and use of QEP inputs to measure the motor speed.
- Hall effect sensors and use of CAP inputs to detect Hall signal edges.

Lab. 1: PM DC motor control

- DC motor parameters identification.
- DC-DC Converter control implementation and open-loop operation of the motor.
- Motor speed control based on speed step response identification.
- Cascade current/speed control.

Lab. 2: BLDC motor control

- Brushless motor parameters identification.
- Speed estimation using the motor Hall effect sensors.
- Control logic implementation.

TABLE I
CHRONOLOGICAL OUTLINE OF THE COURSE/LABORATORY

Weeks	Topics
W 1-2	Lecture and Simulation: PM DC motor control
W 3-4	Lecture and Simulation: BLDC motor control
W 5-7	Lecture and Simulation: PMSM control
W 8	Tutorial 1: Rapid prototyping system introduction
W 9	Tutorial 2: Sensors for motor drives
W 10-11	Lab. 1: PM DC motor control
W 12-13	Lab. 2: BLDC motor control
W 14-15	Lab. 3: Sensorless PMSM Field Oriented Control

- Power electronics commutator implementation and open-loop operation of the motor.
- Cascade current/speed control.

Lab. 3: PMSM Field Oriented Control

- Current Vector Control implementation for RL load.
- Position estimation using the motor Hall effect sensors.
- Sensorless Field Oriented Control of PMSM.

The laboratory tasks are increasingly complex, and match the progression of material presented in the lectures.

Chronological outline of the course/laboratory is presented in TABLE I.

During the next semester, students work on the project that is the complete design of robots with PM motorization using one of the three presented PM motor drives to deal with competition rules and constraints.

Besides power electronics and motor drives, there are also other aspects addressed in this project i.e. optical and magnetic sensors, instrumentation and robot motion control. The description of this project is outside the scope of the paper.

B. Sensorless Motor Drive Introduction

Over the past several years, various advanced sensorless controls of Permanent Magnet Synchronous Motors have been developed for industrial drives due to their high power density and high performance. It is highly desirable to eliminate mechanical sensors in order to reduce costs, save mounting space, and improve mechanical robustness and system reliability, which is crucial for many applications.

Recently, PMSM sensorless drives have been increasingly applied into home appliances [20], automotive [21], aerospace actuators [22], medical robotics [23] and many other field.

Introduction of sensorless control of electric machines in education has then become a real necessity. However, when reviewing papers published on this field it is evident that there has not been so many published, especially for undergraduate level. This is most likely due to that sensorless techniques are mainly investigated as research topic and not so much in education.

The present laboratory suggests investigating a simple speed and position estimation method based on Hall effect sensors. Similar methods are, already, applied to sensorless control of in-wheel motors for Electric Vehicle traction or to other applications [25],[26].

To derive the mechanical measurement, this technique makes use of Hall effect signals and mathematical prerequisite only. It could be easily implemented using the rapid prototyping environment.

III. LECTURES OUTLINE AND MATERIAL

For stimulating interest in the topic, PM motor drives involvement in industrial applications is exposed [2]. Then, details of PM motor modeling and drive structures are presented. Fig. 1 illustrates general drive structure.

The key idea through this course is to demonstrate that the control of Brushless motors can be reduced to a DC motor control subject.

Essentially, the problematic is associated with the torque quality, the speed control accuracy and the drive efficiency.

Thus, the material presented in the lectures focuses on:

A. PM DC Motor Drive

The advantages associated with the inherently stable and relatively simple to control DC machine are indisputable.

Closed-loop speed control of PM DC motor:

The controller design is very simple. However, the current is not controlled.

Cascade current/speed control of PM DC motor:

As shown in Fig. 2, two control loops are used i.e. the current (or torque) and the speed loops. The controllers are designed using linear control theory. This diagram forms the basis of all PM Motor control schemes of this course.

B. BLDC Motor Drive and Trapezoidal Commutation

BLDC motors can be controlled exactly in the same way as a DC motor without presenting brushes drawback.

Current commutation in BLDC motor:

As the back-emf of the motor is trapezoidal, the fed current should be also trapezoidal.

Hall effect sensors are required for the current commutation. They define 6 sectors for phases feeding.

From the relationship between the phase current and the back-emf shapes, the control logic linking the power switch states to Hall effect signals can be elaborated.

Control of BLDC motor:

At any time there are only two power switches conducting current and connecting the source to phases.

The model of the BLDC motor is a simple duplicate of the DC motor model of Fig. 2. Consequently, the controller design procedure is exactly the same.

C. PMSM Drive and Sinusoidal Commutation

In this part, it's pedagogically very effective to point out that the PMSM can be seen as a BLDC motor with extremely precise control of the rotor angle. Sinusoidal commutation is used in this case and higher resolution position sensor such as optical encoder is necessary.

PMSM Control in a-b-c reference:

To produce smooth torque; the fed current waveform should match the sinusoidal back-emf shape of the machine. This is easier to demonstrate in a-b-c reference.

Two particular control strategies are then considered:

Strategy 1: Maximum torque at given current magnitude. The stator current is in phase with the back-emf. The motivation is to reduce Ri^2 losses in the motor.

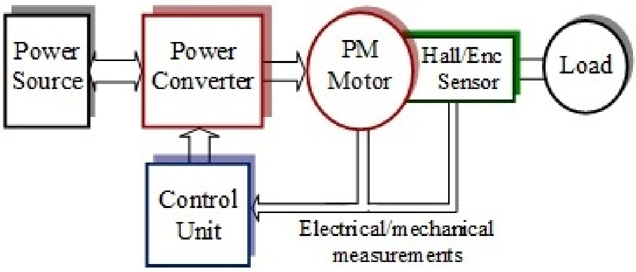


Fig. 1. Block diagram of PM motor drive system.

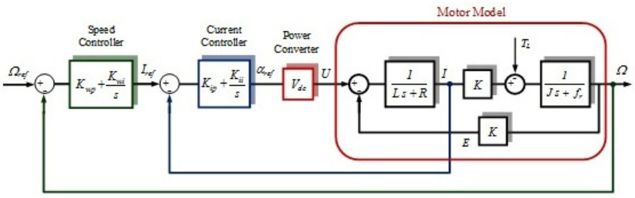


Fig. 2. Block diagram of the DC motor model with current and speed Loops.

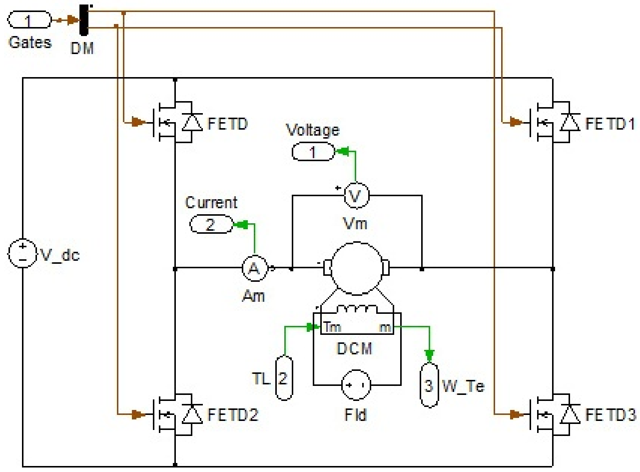


Fig. 3. Plecs circuit including DC motor and MOSFET Full-Bridge DC-DC converter.

Strategy 2: Unit power factor. The stator current and voltage are in phase. The motivation is to minimize the power electronics converter design.

PMSM Field Oriented Control in d-q reference:

d-q reference control is introduced using Park transformation. Attention is focused on the strategy 1. To force the strategy goals, two PI controllers are used: the first control d-current to be zero and the second control q-current to produce the required torque. A speed controller is inserted in the q-axis. Adequate compensation and decoupling results in a model identical to a DC motor.

The following sections give details on the simulation and implementation of PM motor drives.

IV. Simulation Models and Results

The programs used to complete the simulations are Simlink and Plecs, sub programs of Matlab. Simulink is adopted for simulation since it's a control systems oriented environment [4] and it supports the used Texas Instrument kit.

Plecs is a toolbox for simulation of power electronics and machine systems within Simulink environment. This software is preferred for this course because it provides a comprehensive block library and allows very simple and realistic simulations of electrical circuits.

During the next section, simulation models, power circuits as well as some relevant results will be presented.

The objective of the control schemes will be to get zero steady-state error and good closed-loop dynamic.

The PM motors used in this paper have the parameters given in TABLE II. The BLDC motor parameters are used to simulate both Brushless DC motor and PMSM.

A. PM DC Motor Drive Simulation

The Plecs circuit includes a PM DC Motor supplied by MOSFET Full-Bridge DC/DC Converter (Fig. 3). The control circuit is built by using Simulink blocks. Especially, 'Repeating Sequence' block is used to generate carrier based PWM for voltage modulation.

This laboratory starts by a preliminary simulation of an open-loop motor operation. In this experience, the points to highlight, particularly, are the disadvantages of this operation mode:

- Free speed response that depends on motor and mechanical system parameters.
- Speed variation with voltage and load disturbances.
- Staring and transient destructive peak current.

Closed-loop speed control of PM DC motor:

The control system here consists of only one PI speed feedback. A properly designed feedback controller makes the system faster and insensitive to the parameter and load changes. However, the peak current arising at the startup is still dangerous and this problem cannot be avoided here appropriately. This scheme simulation is not presented here.

Cascade speed/current control of PM DC motor:

To resolve the three defects of an open-loop operation at the same time, it's necessary to incorporate the speed and the current control as shown in Fig. 4. The drive performance becomes very satisfactory (Fig. 5). Note that current limitation can be used here to stop the motor drawing more than its rated current.

B. BLDC Motor Drive Simulation

The Plecs circuit includes a bipolar BLDC Motor supplied by three-phase Full Bridge inverter. After building the power circuit, students have to accomplish the following tasks:

1) Reconstitution of Hall effect signals using the available rotor angle (Hall signals Generator).
2) Composition of control logic block including PWM.

The complete Simulink model is presented in Fig. 6.

Open-loop operation of BLDC motor:

In a first basic simulation, the motor speed is changed using the DC link voltage without any modulation. This experience reveals the perfect similarity between DC and BLDC Motors.

TABLE II
PARAMETERS OF THE MOTORS

	DC Motor	Brushless Motor
Nominal power, W	20	20
Nominal voltage, V	24	24
No load speed, rpm	9550	9500
Max. cont. current, A	1.2	0.69
Max. cont. torque, mNm	26.1	14.2
Résistance, Ω	2.32	5.85
Inductance, mH	0.24	0.483
Torque const., mNm/A	23.4	23.5
Rotor Inertia, Kg·m^2	452 10^{-7}	59.3 10^{-7}

As, DC voltage control requires an auxiliary power stage, it's preferable to handle the motor voltage using modulation technique applied to the power inverter. During each of the 6 Hall sectors, the power electronics plays exactly the role of a buck converter.

Cascade current/speed control of BLDC motor:

Similarly to DC Motor case, current and speed loops are necessary to achieve good transient behavior. High current protection and robustness against disturbance are also gained. The performances of the drive are shown in Fig. 7.

C. Simulation of PMSM Filed Oriented Control

The simplest manner to introduce Field Oriented Control is by using hysteresis controllers in a-b-c reference. This controller outputs the necessary switching signals to maintain the motor currents close to the reference currents within a range that it is fixed by the controller bandwidth

Sinusoidal phase currents just need to be generated, according to the strategy 1, and the torque will be smooth and maximal. Nevertheless, hysteresis controller does not have a specific switching frequency and generates low frequency harmonics which translate to very noisy currents and fast torque oscillations. This technique is not presented in the paper.

Field Oriented Control in synchronous d-q reference is today widely implemented in industrial motor drives. For this reason the course emphasizes in greater detail this technique. Simulink model is presented in Fig. 8 in which the Plecs circuit is the same as in BLDC drive except, obviously, the motor is replaced by a PMSM.

This control scheme is based on PWM technique associated with three PI controllers for the dq-currents and speed loops. Park transformation is applied to the output phase currents and reverse transformation is used to reproduce the reference phase voltages.

Thus, the addressStreetPMSM Drive has fast dynamic response and, above all, produces smooth current and maximum torque per current unit (Fig. 9). It's then the most efficient drive.

V. EZDSP F2812 BASED LABORATORY

A. Hardware Constitution

Experimental setup is shown in Fig. 10-a. The DC motor based robot is on the right of the figure and the Brushless motor based robot on the left side.

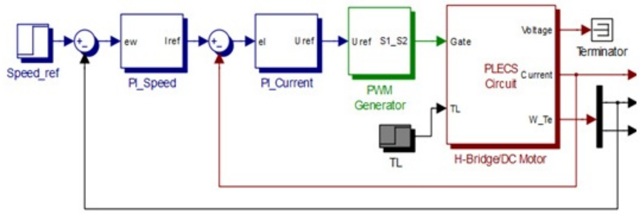


Fig. 4. Simulation model of DC motor cascade speed/current control.

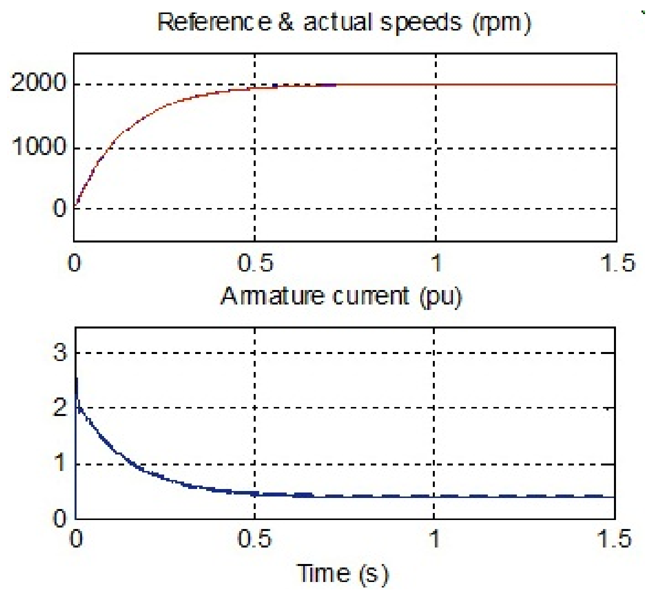


Fig. 5. Speed step response of cascade speed/ current controlled DC motor in simulation.

Each system can be divided into two sections: the control and the power circuits. Electrical isolation between these sections is achieved by optically coupled devices.

In both systems, control circuit is essentially composed of an eZdspF2812 DSP board and MOSFET drivers which correct the power and voltage levels for proper transistors operation. Hall effect current sensors are also included with their conditioning electronics. The sampling frequencies of the current and speed loops are respectively *10 kHz* and *1 kHz*.

The power circuit of the DC motor platform involves a Full-Bridge DC/DC converter (Fig. 10(b)).

For the second platform, bipolar Brushless geared motor and 3-phase Full-Bridge inverter are used (Fig. 10(b)). This brushless motor is equipped with only three Hall effect sensors. The motor parameters are those of the TABLE II.

B. Simulink Real-Time Models and DSP Implementation

The control algorithms are implemented using TI C2000 package in Simulink and eZdsp F2812 board. This DSP system allows fast fixed-point processing at *150 MHz* and can be adapted to all motor drives laboratories thanks to its motor control peripherals i.e. *2* event managers, *16 12-Bit* ADC channels with fast conversion rate (*80 ns*) and up to *56* general purpose I/O (GPIO) [18].

Embedded Target tool also includes tow special libraries namely the IQmath and DMC (Digital Motor Control). The functions in these libraries, which are implemented by the

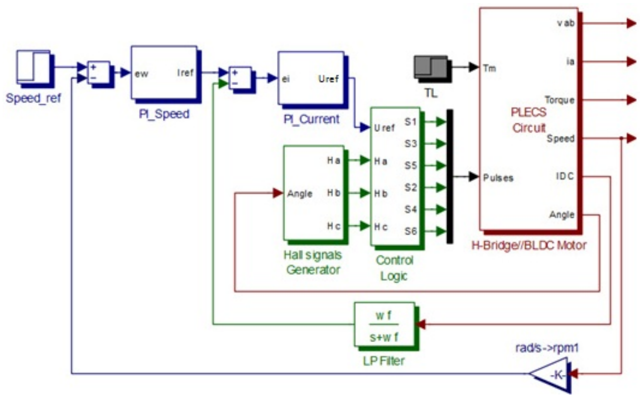


Fig. 6. Simulation model of BLDC motor cascade speed/current control.

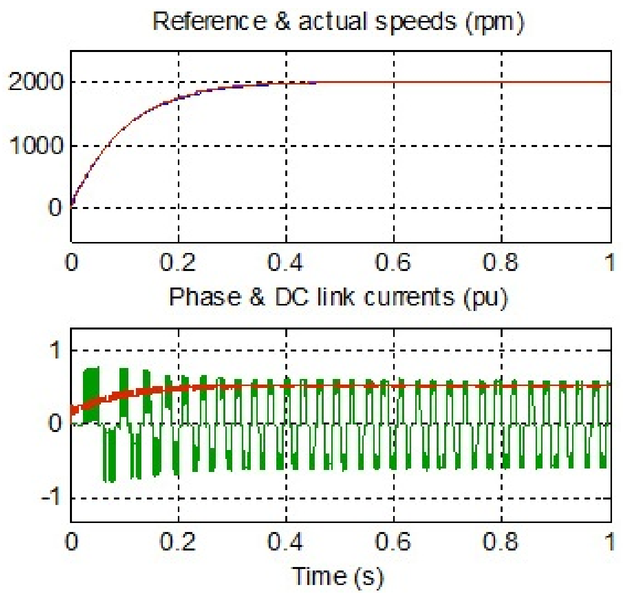


Fig. 7. Speed step response of cascade speed/ current controlled BLDC motor in simulation.

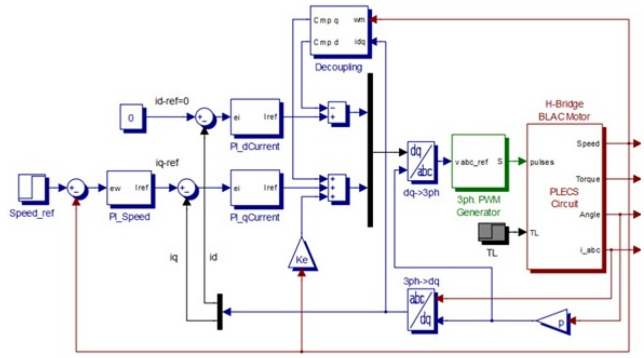


Fig. 8. Simulation model of PMSM Field Oriented Control.

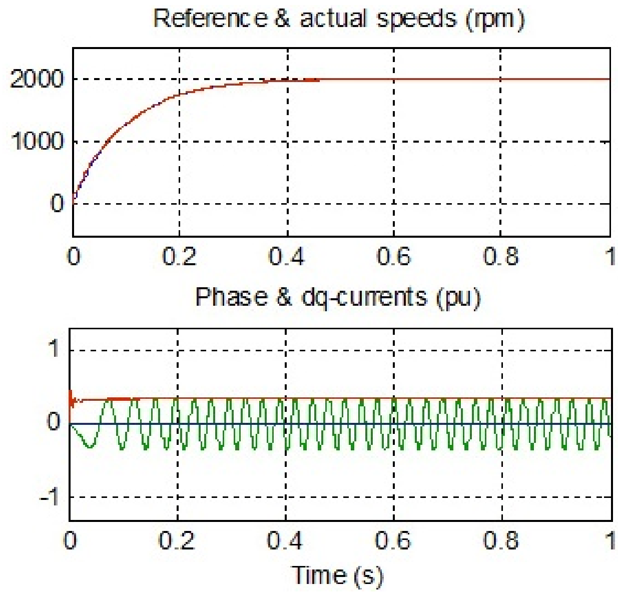


Fig. 9. Speed step response of PMSM with Field Oriented Control in simulation.

blocks, are for example Clark and Park Transformations, PID Controller, Space Vector Generator and fixed point mathematical operations. These are the main blocs from TI C2000 used in these laboratories. A Target Preference block, F2812 eZdsp, has to be added to the model.

Once the desired Simulink model has been constructed and simulated, the code for the DSP can be generated by Real Time Workshop. The code may be instrumented with Real Time Data eXchange modules (RTDX) to stream data to and from the target. Online parameter tuning is also possible via Code Composer Studio.

The experimental results presented in this section have been specifically chosen to demonstrate some of the typical operations of the studied drives. The results provide a confirmation of the validity of the simulation results in both steady-state and transient operations.

C. PM DC Motor Control

Simulink model of the speed control structure is presented in Fig. 14. PWM timer is used to modulate the duty cycle and thus the voltage applied to the motor. On the other hand, the speed of the motor is measured using an optical encoder, and it's accessible via the QEP block.

This measure is applied at the feedback input port of a PID Controller block from a Digital Motor Control Library (DMC). At the reference input port of the controller is applied the target speed using a RTDX block.

Obviously, the controller can be computed using the motor model. But in order to diversify the controller design techniques, an experimental method is investigated.

Motor model identification and speed control:

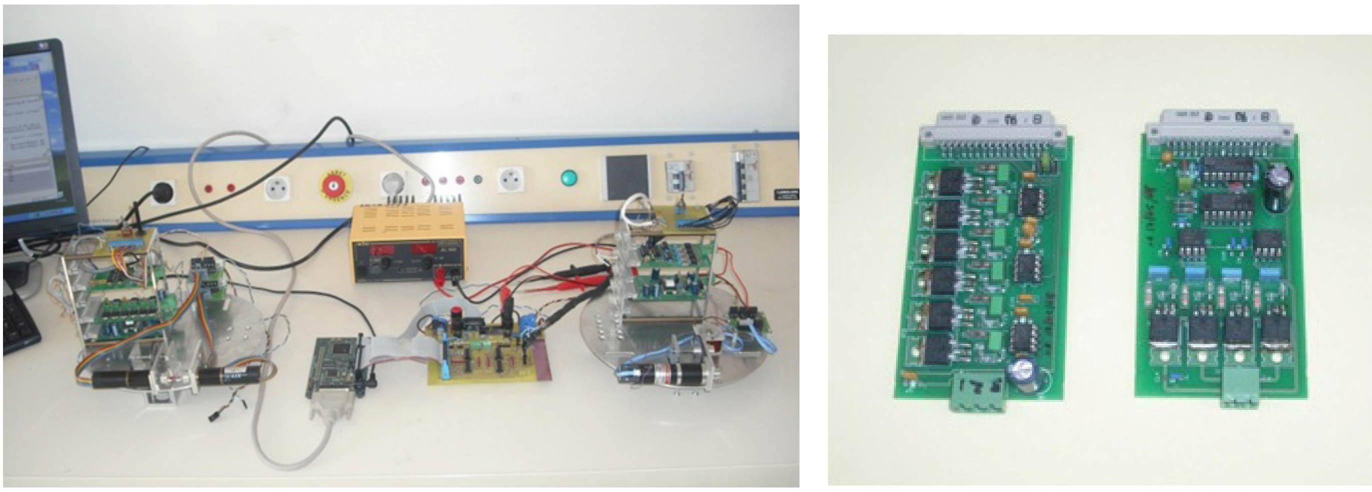
The time constant of an open-loop voltage step change is identified by means of the Matlab Curve Fitting Tool 'cftool' with an exponential model:

$$\Omega(t) = a\times\exp(b\times t) + c\times\exp(d\times t). \qquad (1)$$

The time constant of the model is related to the coefficient d as:

$$\tau_s = {}^{1}/_{d}, \quad d = -4.28 \;\Rightarrow\; \tau_s = 0.234s. \qquad (2)$$

So the motor transfer function, between the voltage and the



(a) (b)

Fig. 10. (a) DC motor and BLDC motor based robot (right and left respectively).
The first platform is connected to the eZdspF2812 board via an optocoupler/conditioning board.
(b) Full-Bridge DC/DC converter and 3-phase Full-Bridge inverter (right and left respectively).

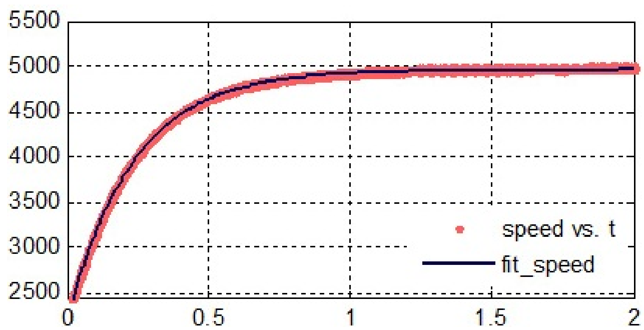


Fig. 11. Speed and its associated fit following an open-loop voltage step change.

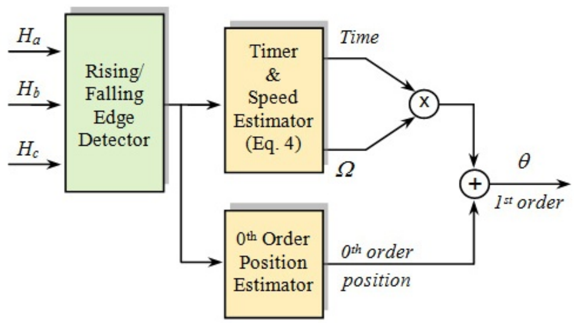


Fig. 12. Block diagram of the Hall Effect sensor based estimator.

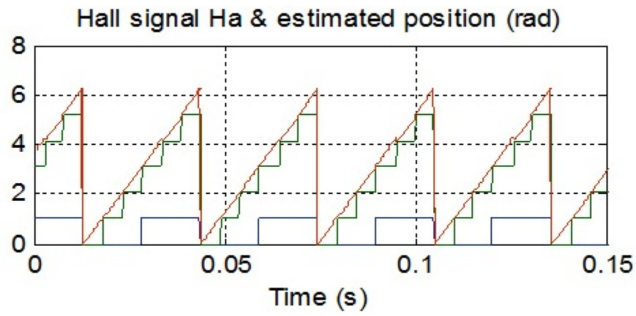


Fig. 13. Hall effect based 0^{th} and 1^{st} order position estimates.

speed, can be represented as a *1st* order system:

$$T_m(s) = \frac{G_s}{1+s\tau_m}. \tag{3}$$

The speed step coincides entirely with its associated fit as shown in Fig. 11. The gain G_s is determined using steady-state voltage and speed measurement.

The controller is then quickly calculated using the identified parameters.

Using this design approach, there is no need to determine a mathematical model of the motor.

The control performances of the Fig. 19 are obtained by tuning the controllers around those designed in simulation session. The speed follows closely a *1st* order reference model with a time constant $\tau_\Omega = 0.10s$.

Although the transient current exceeds *300%* the nominal value, this control scheme cannot remedy this problem.

Cascade current/speed control of PM DC Motor

Fig. 15 shows the current and speed closed-loops used in this drive. Note that two rate transition blocks are connected at the input and output ports of the speed controller (Fig. 16). This is a requirement for all signal paths between blocks running on different sample rates.

The capability of this complete control scheme is demonstrated in Fig. 20.

In Fig. 21, current limitation is enforced to stop the motor drawing more than its transient permissible current, which is $125\%\ I_{nominal}$. Visibly, this limitation is responsible for current nonlinearity and further increase in the response delay.

D. Cascade Current/Speed Control of BLDC Motor

The Brushless motors used in the robots exhibit sinusoidal back-emf characteristics. They can be used either with sinusoidal or trapezoidal commutations.

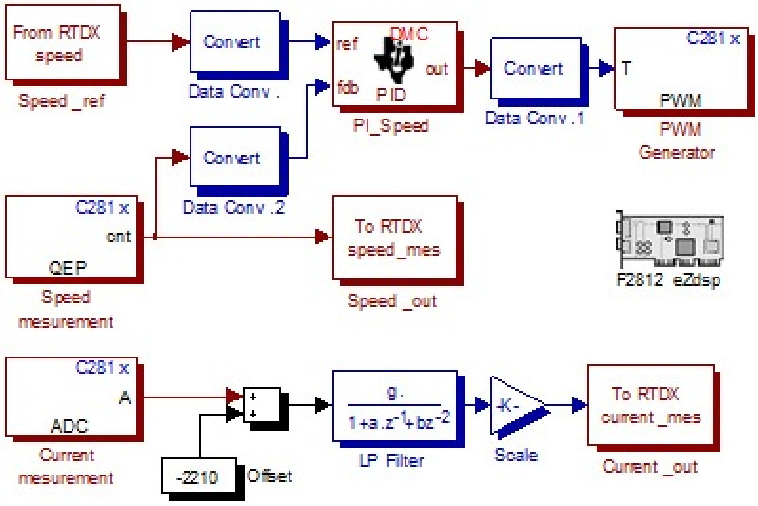


Fig. 14. Simulink RT model of DC motor speed control.

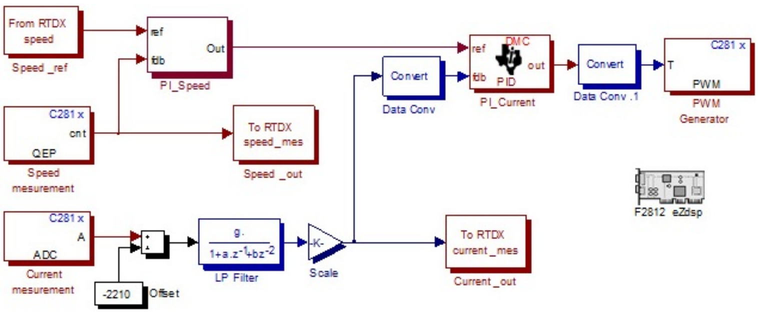


Fig. 15. Simulink RT model of DC motor cascade speed/current control.

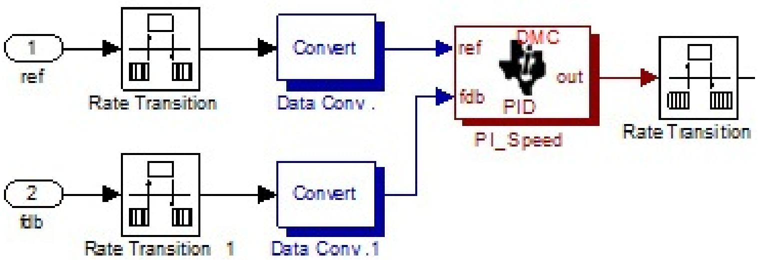


Fig. 16. PI_Speed subsystem.

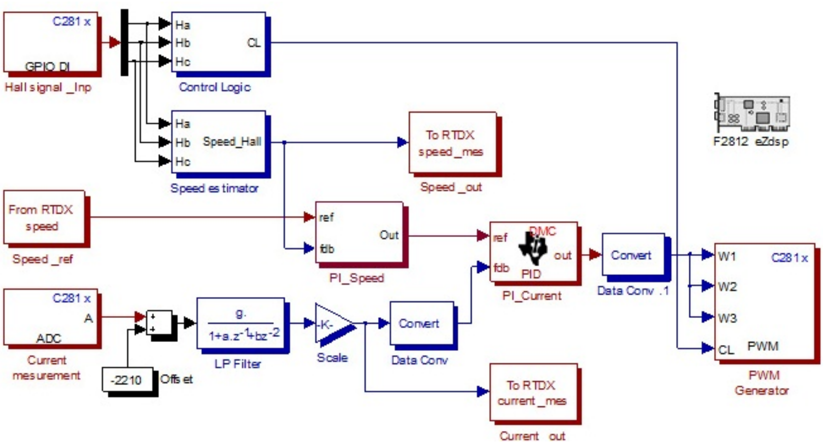


Fig. 17. Simulink RT model of BLDC motor cascade speed/current control.

The encoders are usually mounted on the end of a gearbox. However, in the used BLDC motors only Hall sensors are provided. In consequence, sensorless speed estimation method is necessary to complete the outer loop.

Without encoder, the speed can be measured using Hall signal interrupt [24]. The angle between two consecutive Hall signal edges is *60* degrees by construction. Using a Timer peripheral, the time T_{hall} between two consecutive Hall edges are measured and speed can be computed as:

$$\Omega = \frac{\pi/3}{T_{hall}} rad.s^{-1}. \tag{4}$$

This algorithm is implemented within the 'Speed estimator' block of the Fig. 17 model, adding an LP-filter.

In addition to the speed estimator and controller, the control system of the BLDC motor involves a current controller and commutation logic that use Hall sensor feedback (Fig. 17). The measured current in this experiment is the DC link one.

The results presented in Fig. 22 depict respectively: DC link and phase currents in the motor open-loop operation. The measure window shows a duty cycle transition from *1*, which means no PWM is applied, to *0.5* with reduced voltage. The particular six-step phase current and trapezoidal voltage waveform, characteristic for BLDC motor commutation, are clearly shown in this figure.

Other experimental results related to speed acceleration from *2000 rpm* to *4000 rpm* are presented in Fig. 23. The speed reference tracking is perfect without any overshoot.

As the motor is geared, the actuator inertia is weak and the motor drive doesn't draw large current during transient operations. Consequently no current limitation is necessary in this case.

E. Sensorless PMSM Field Oriented Control

As can be seen in Fig. 18, Field Oriented Control consists of two nested loops. The first loop controls the stator currents in the d-q reference frame and thus the torque, while the second loop controls the motor speed.

For this control scheme, the measured input signals are the rotor position and two of the stator phase currents.

Typical examples of position sensors that can be used are resolvers, incremental encoders or absolute encoders.

In the absence of optical encoder, suitable strategies must be developed to determine the rotor position. Here again, digital signal processing of Hall sensor outputs is an alternative solution to estimate the rotor position [24]. The Hall Effect sensors detect when the rotor magnetic axis enters a new 60° sector.

The electric angular position is generally given by:

$$\theta(t) = \int_{t_k}^{t} \Omega(t)\, dt + \theta_k \tag{5}$$

t_k is the instant when the magnetic axis enters sector k (k*=1, 2,…, 6*).

θ_k is the initial angle of sector k. It is equivalent to a zeroth-order position estimation obtained by taking into account only the 0^{th} order term of an approximated Taylor series expansion.

The electric angular position can be obtained by numerical integration of (5), under the constraint that the resulting angle value has to be within the sector k limits.

The angular position is, thus, calculated as

$$\theta(t) = \theta_k + \Omega_k(t - t_k), \quad \theta_k \leq \theta(t) \leq \theta_k + \pi/3. \tag{6}$$

Ω_k is here the angular speed when the magnetic axis enters sector k ; it's obtained from the speed estimator block presented in the previous section.

The Fig. 12 shows the block diagram of the position and speed estimation technique and Fig. 13 illustrates the 0^{th} order (stairs line) and the *1*st order (straight line) position estimates which are synchronous to Hall signal H_a edge.

The overall sensorless Field Oriented Control scheme, with speed and position estimator, is shown in Fig. 18.

By driving the motor with sinusoidal current commutation, less frequency harmonics are presents in the current waveform as shown is Fig. 24; thus an immediate reduction in power losses occurs. As a result, larger torque is produced for the same RMS current. Sinusoidally driven motors also gain reduced torque ripple.

Moreover, these experimental results testify that the first strategy objectives with the Field Oriented Control are reached. Notice the d-current, which is kept null in order to make good use of the current in producing torque.

The last Fig. 25 confirms the ability of the Hall effect based estimator to replace encoder in sensorless control during dynamic operation of the drive. The motor operates correctly and the actual speed flows accurately the simulated speed.

VI. Students Feedback

During the last year, we have used this course and rapid prototyping tool to teach a group of 22 undergraduates PM Motor drives and their real-time DSP implementation concept.

We noticed that three groups from 11 were able, within the given time, to complete the laboratory tasks and to explore more challenging topics like those linked to regenerative control of PM DC motor or PMSM Field-Weakening control. Though framed, these long laboratories can generate favorable environment for initiative and creativity.

The students start the second semester project, after the completion of the presented course, when they have gained adequate theoretical knowledge from lectures and experimental skills from the laboratories designed around the robot platform.

Some students affirm that, in the early stages of this course, they had already felt involved in the robot project.

From the students response also, they can easily handle the rapid prototyping system for the construction of different drive structures, data acquisition and scaling as well as for controller implementation.

Furthermore, they can actually connect real platform to the eZdspF2812 board and see how the drives behave in real-time.

The introduction, of Hall effect based sensorless technique has upgraded the laboratory to a new motor drive technology. Nevertheless, the technique could be quickly implemented so that students are kept focusing on the main topic i.e. motor drives.

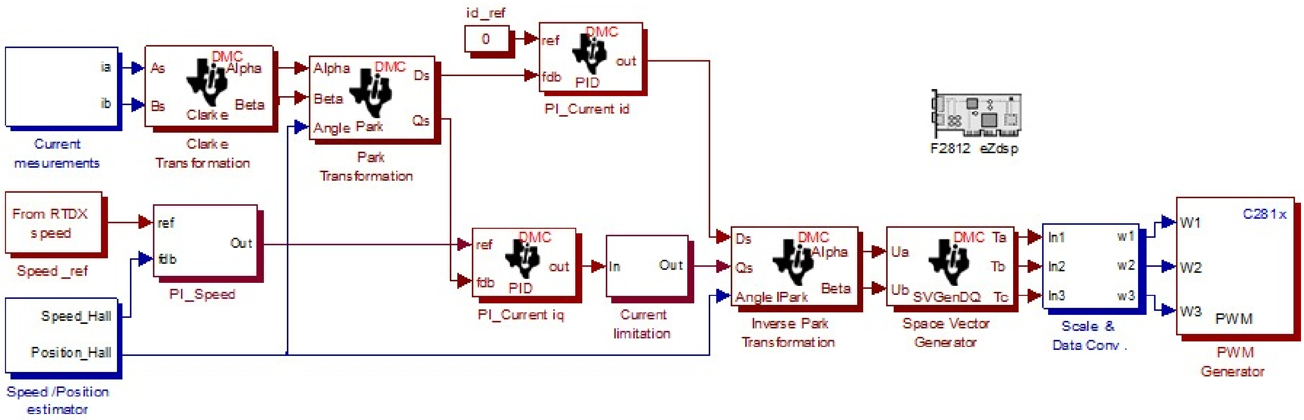


Fig. 18. Simulink RT model of PMSM Field Oriented Control.

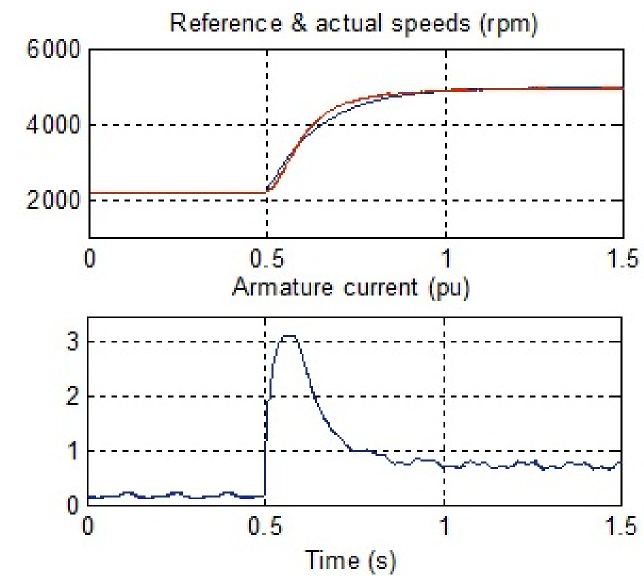


Fig. 19. Experimental speed step response of speed controlled DC motor.

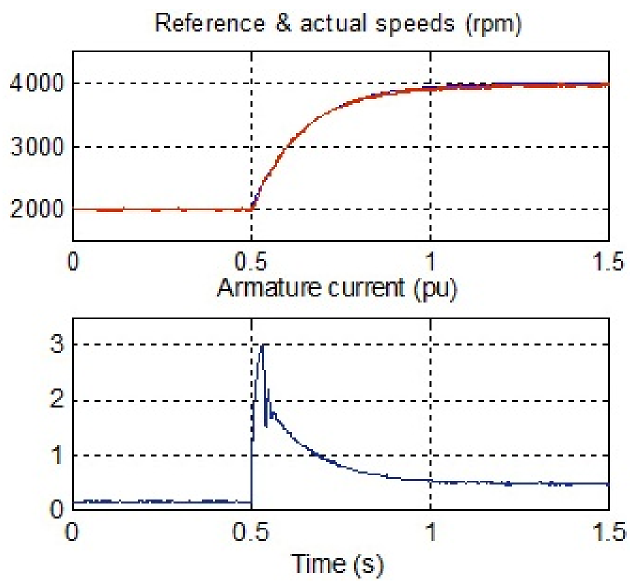


Fig. 20. Experimental speed step response of cascade speed/ current controlled DC motor without current limitation.

Finally, our experience has shown that this course and teaching platform has clearly heightened student interest in the learning of power electronics and motor drives.

VII. Conclusion

This paper objective is redesigning the structure and content of PM motor drives course along with developing new laboratory experiments to align the technical content of the course with mobile robot project.

Simulink/Plecs software together with TI C2000 DSP Embedded Target in eZdspF2812 have constituted an appropriate rapid prototyping environment for all combined simulation/implementation of the drives presented in this course.

In order to demonstrate the effectiveness of this approach, the paper presents several laboratory results showing valuable correspondence between simulation results and their experimental verification.

The major advantages of the low cost DSP prototyping tool, in the laboratory context, are the following:

- It provides enough control peripherals not only for the robot traction system, but also for the final robot motion control project.
- The graphical programming approach removes the need to write long software by hand and allows the student to focus instead on learning motor drive functionalities.
- Practically the same simulation models used in Simulink are used in the hardware implementation.
- An easy-to-use interface i.e. CCS and RTDX, which allow real-time parameter adjustment and data capture.

The ease of algorithm implementation in the rapid prototyping environment allowed also the introduction of sensorless control techniques to enrich the course.

To sum up, the presented course, hardware and software platform proves to be very adequate to PM motor drives and associated power electronics teaching as well as to mobile robot project preparation. It is a low cost solution too for growing number of undergraduate students enrolling in this engineering field.

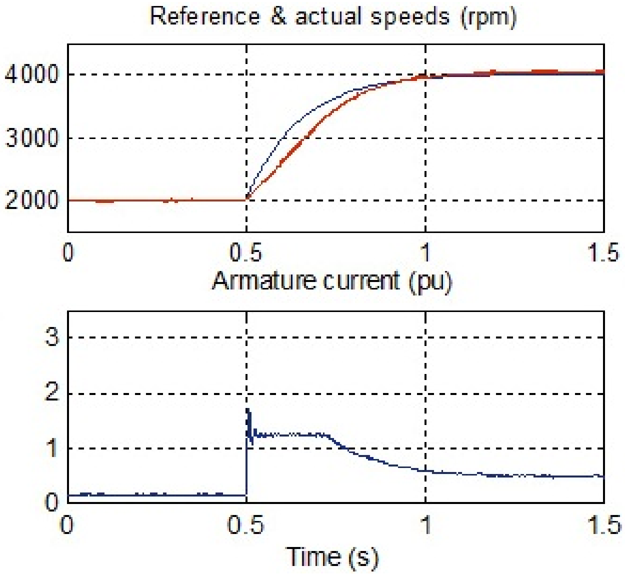


Fig. 21. Experimental speed step response of cascade speed/ current controlled DC motor with current limitation.

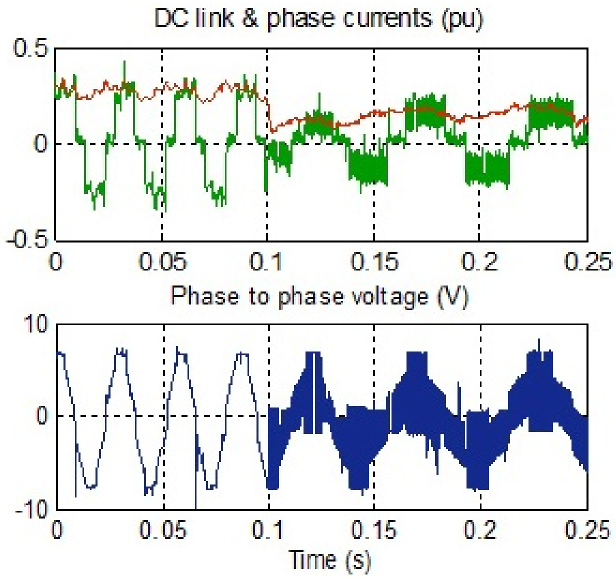


Fig. 22. Duty cycle transition from *1* to *0.5* in open-loop control of BLDC motor.

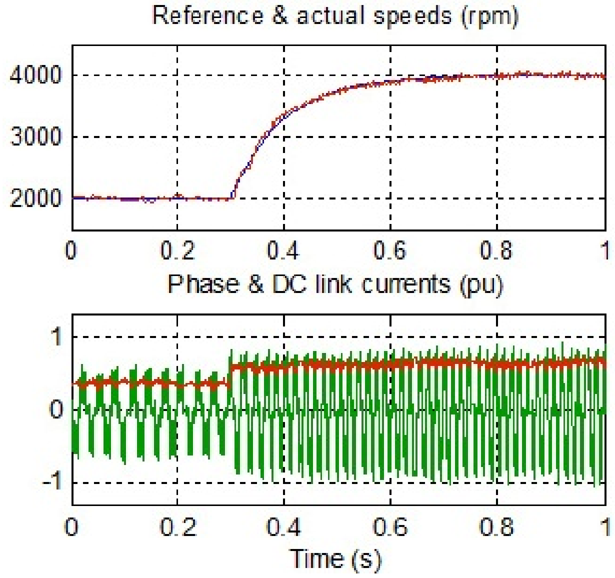


Fig. 23. Experimental speed step response of cascade speed/current controlled BLDC motor.

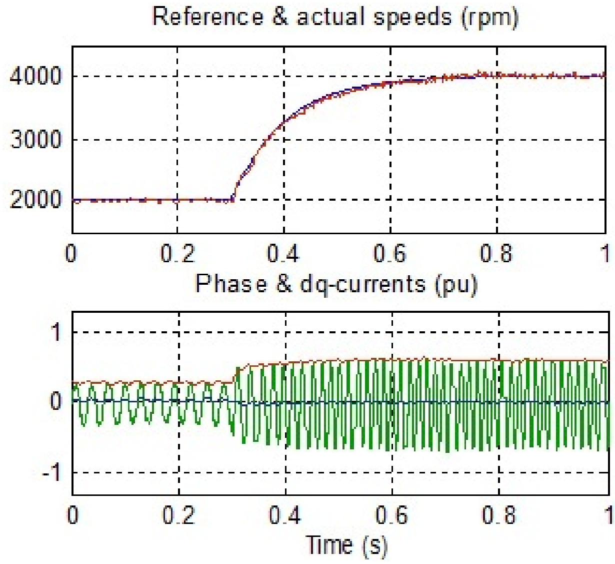


Fig. 24. Experimental speed step response of PMSM Field Oriented Control.

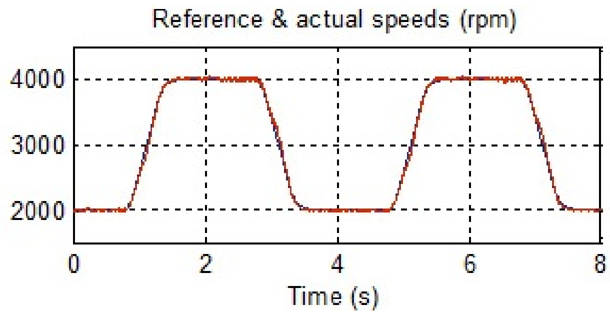


Fig. 25. Test of the dynamic performance of the estimation method and the sensorless PMSM drive.

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Driss Yousfi was born in Oujda, Morocco, in 1970. He received the B.S. and M.S. degrees in Electrical Engineering from Fes University, Morocco, respectively, in 1994 and 1996, and the Ph.D. degree in Electrical Engineering from placeOujda University, in 2001. From 1997 to 2001 he was a member of.the Electrical Engineering Laboratory at the High National School of Electrical and Mechanical Engineering, Morocco, working on the Modeling and Sensorless Control of Synchronous Motors. Since November 2001, he has been with Marrakech University-ENSA, Morocco, where he is currently professor at the Electrical Engineering Department and Staff Member of Control Systems, Power Electronics and Electric Drives "CSPEED" Group. Dr. Yousfi is a Member of the IEEE Industry Applications, IEEE Industrial Electronics, and IEEE Power Electronics Societies. His main research interests include sensorless control of Permanent Magnet Synchronous Machine, power converters and motor drives for electric traction systems, and DSP-based systems for real-time control.

Said Belkouch is Professor at Electrical Engineering Department, National School of Applied Sciences-Marrakech, Morocco from 2003. He has completed his Ph.D. in Microelectronics at University Joseph Fourier-Grenoble in placeFrance. He worked respectively as Assistant Researcher at University of Sherbrook in Canada, Research Officer at National Council of Canada, and ASICs Design Engineering at Tundra Semiconductor Corporation (now called IDT). His area of research includes embedded systems and microelectronics. He has published several research papers in Journals and Proceedings.

Abdellah AIT OUAHMAN was born in Marrakech, Morocco. He received the doctorate thesis in Signal Processing from the University of Grenoble, France, in November 1981. His research was in Signal Processing and Telecommunications. Then he received the Ph.D. degree in Physics Sciences from Cadi Ayyad University, Marrakech, Morocco, in 1992. He is now Professor and responsible of the Telecommunications and Computer Science and Networking laboratory in the Faculty of Sciences Semlalia in Marrakech. His research interests include the signal and image processing and coding, telecommunications and networking. Currently, he is a director of National School of Applied Sciences, Marrakech.

Damien Grenier was born in Rouen, France in 1965. He received the Ph.D. degree in electrical engineering from the Ecole Normale Sup?rieure de Cachan, France, in 1994. During 1994-1996, he was Post- Doctoral Researcher at the Ecole de Technologie Supérieure, Montréal QC Canada. He joined in 1996, the Université Catholique de Louvain, Louvain-la-Neuve, Belgium where he took part to several pedagogical projects support by the European Union. Since 2005, he is Professor in the Department of Mechatronics of the brittany site of the Ecole Normale Sup?rieure de Cachan.

Bruno Dehez received the degree in electromechanical engineering and the Ph.D. degree from the Universit catholique de Louvain (UCL), Louvain-la-Neuve, Belgium, in 1998 and 2004, respectively. Since 2006, he is associate professor in the Centre for Research in Mechatronics at UCL. His research interests include the design and the optimization of dedicated electrical actuators.

Eric Richard , received his engineer Diploma from ‘Ecole Nationale Supérieure des Télécommunications’, France, in 1978. Since 2002, he has been a Research Engineer at the Institut Supérieur de l’Electronique et du Numérique (ISEN)-Toulon, in charge of electronics service. He is also a research member of Circuits Design Team at the Institut Matériaux Microélectronique Nanosciences de Provence ‘IM2NP’. His research focuses on the microelectronics and electronics applications to analog and digital signal processing.