Novel Laboratory for Experimental Education in Electronic Engineering*

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This paper describes a novel laboratory for experimental work in electronic engineering in the fields of power electronics and electric machine control. The learning methodology has been developed to improve the technical skills and motivation for experimental work and theory comprehension. The laboratory facilitates training with software and hardware elements in quasi industrial electronic systems: the main pedagogical objective through experimental work is the transfer of academic knowledge to professional practice. The addition of remote operation of these systems and the educational resources shared on its own web platform expands the learning activities out of the campus area. The possibility of total access to parameters and variables in the educational electronic converters proposed, which are difficult to manage in commercial equipment, promotes students interest and academic proficiency. A better use of the hands-on laboratory equipment and the simulation software in real designs are topics within the scope of the proposed laboratory.

Keywords: engineering education; power electronics; computer applications; control systems

1. Introduction

The importance of experimental laboratories in engineering education is not in doubt: they play a fundamental role in the engineering student's acquisition of practical skills. These skills are the foundation for the engineering student who is going to work not only in research and development but mainly in an industrial context [1–3]. Different engineering educational areas, such as electric propulsion systems and renewable energy generation, have focused on the negative impact on the environment with problems associated with fossil fuels [4]. This has led to an important increase in interest in power electronic systems. The significance of these issues has been the motivation for developing the Shared Hybrid-Virtual Experimental Laboratory (SHVEL) [5].

Over the years subjects associated with high voltages and currents present in electric energy converters and problems related to the cost of experimental laboratories and the high ratio of students to professors have been lead practical studies in the electronics laboratory to solutions based on simulation software [6]. Moreover, the workbench equipment in hands-on laboratories is usually not sufficiently flexible for incorporating new tasks. This can become a difficulty when technological changes must be incorporated into educational models [7].

To complement and improve this situation, there has been an increasing interest by scientists and researchers in the development of new solutions based on combining internet technologies, traditional engineering techniques and the experimental laboratories [7, 8]. This combination allows more active learning activities.

The Web 2.0 technologies have given a new focus to classroom educational methodologies [9]. The extension of these ideas into experimental laboratories allowing the integration of theoretical materials and concepts with experimental devices, tools and applications in a given industrial context releases the experimental activities out from the constraint of the campus.

Disassemble/Analyze/Assemble (DAA) activities, resulting from the application of reverse engineering and product dissection techniques, have been used for innovative industrial design applications [10]. The application of DAA activities in education environments has been a recent development. The main objectives are: to increase motivation, promote knowledge transfer, and create an environment in which students can adapt and apply their knowledge in the development of original solutions [11].

The laboratory presented here introduces a novel philosophy for managing experimental work. It consists of: using real and virtual tools for experimental practice in quasi industrial equipment [12–14]; the educational features of simulation software; a traditional hands-on laboratory and the internet [15, 16]. All of these characteristics contribute towards the creation of an experimental learning environment and the professional development of engineering students [17].

The following sections present: the laboratory, two experiments, students' analysis, learning uses, assessment and the final conclusions.

2. The laboratory

Figure 1 shows the proposed educational environment, where the Shared Hybrid-Virtual Experimental Laboratory (SHVEL) is included. The laboratory is composed of three basic resources: the experimental work methodology, the SHVEL units, and the web platform [18]. The SHVEL is related to the classroom, the hands-on laboratory and off-campus educational activities. Specific theory concepts outlined in the classroom are associated with the technical resources included in the SHVEL. The experimental work, the simulation models, and the practical designs can be related to the specific parts and functional blocks of the SHVEL units.

The pedagogical objectives of the SHVEL are: to improve student motivation for working on experiments in real power electronic systems; developing their technical skills in different areas [19], and enhancing knowledge through a better understanding of abstract theoretical concepts, which are difficult to explain in a theoretical study environment.

For undergraduate students a basic electrical and electronic knowledge is required when working in the SHVEL. The possibility of manipulating quasi industrial equipment involves responsibility. When more theoretical and technical support is needed, students are more closely supervised by teaching and laboratory staff. In this case, the number of students who can work simultaneously in the SHVEL needs to be limited.

2.1 Hardware and software resources (SHVEL Units)

There is a paucity of publications that deal with learning techniques and methodologies in engineering laboratories. However the importance of these educational environments is unquestionable [2]. In the last few years different publications [1, 7, 13] have proposed innovative solutions to enhance training in experimental laboratories.

The most outstanding technical characteristic of the proposed laboratory is its flexibility. The aim is to create an open environment, within the power electronics area and its industrial applications that allows student interaction. In order to create this environment, the proposed laboratory integrates complete power electronic systems divided into modular functional blocks [10, 11]. These blocks incorporate normalized inputs and outputs, and have clearly defined functions in the system.

The access level of the system resources, for both the controller and the controlled system, can be considered as the major advantage of the proposed laboratory. The preparation of the electronic system environment is an important first step that will allow the later interaction of students, of different educational levels, with the hardware and software modules designed for the experimental work. A basic knowledge of Digital Signal Processors (DSP) and its programming tools is the basis for the development of an accessible and secure environment.

Freescale's DSP 56000E family has been selected as the basis of these educational tools and the free communication software FreeMaster for the remote operation. This software allows the user, student and professor, to create their own interface
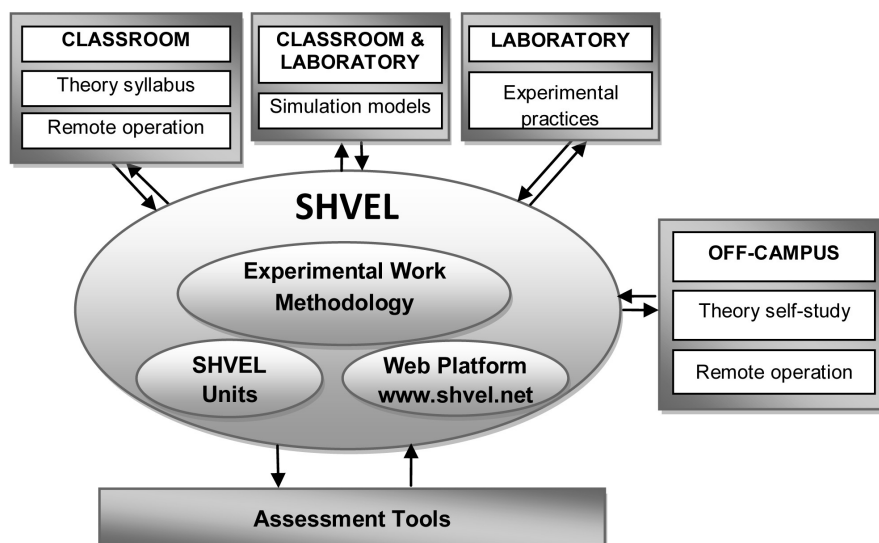

Fig. 1. The proposed educational environment.

for operating the modular converters, through the use of Hyper Text Markup Language (HTML) and Visual Basic Script programming [20]. It also allows communication with programs such as Excel® and MATLAB®, which permits a better mathematical and graphic processing of the exported system data.

A SHVEL unit, also named the Design Integration Modular Environment (DIME), and an example of its functional dissection process, are shown in Fig. 2. These units constitute the student's shared environment for experimental work. Their technical features are:

- Total access to the hardware resources: the DSP integrated peripheral, the instrumentation sensors and analog boards, the power electronic block and electronic switch drivers.
- Total access to the software resources: the estimation and control algorithms, the modulation methods and the algorithms for digital processing of signals.

- The remote operation of the SHVEL unit through a FreeMaster interface titled Control Page that allows the operation of the system and the dynamic change of control system reference inputs.
- The remote parameter measurement and visualization through FreeMaster's Scope and Recorder tools [20] for all defined variables and parameters in the DSP control program.
- And, finally, the capability for the incorporation of new designs into this modular system by the students, for all the above hardware and software resources. Figure 2 shows an example of the Hall Sensor Boards designed by the students for measuring voltage.

2.2 The experimental work methodology

The work methodology in the SHVEL is shown in Fig. 3 and it is based on the functional dissection techniques applied to industrial artifacts [9]. The
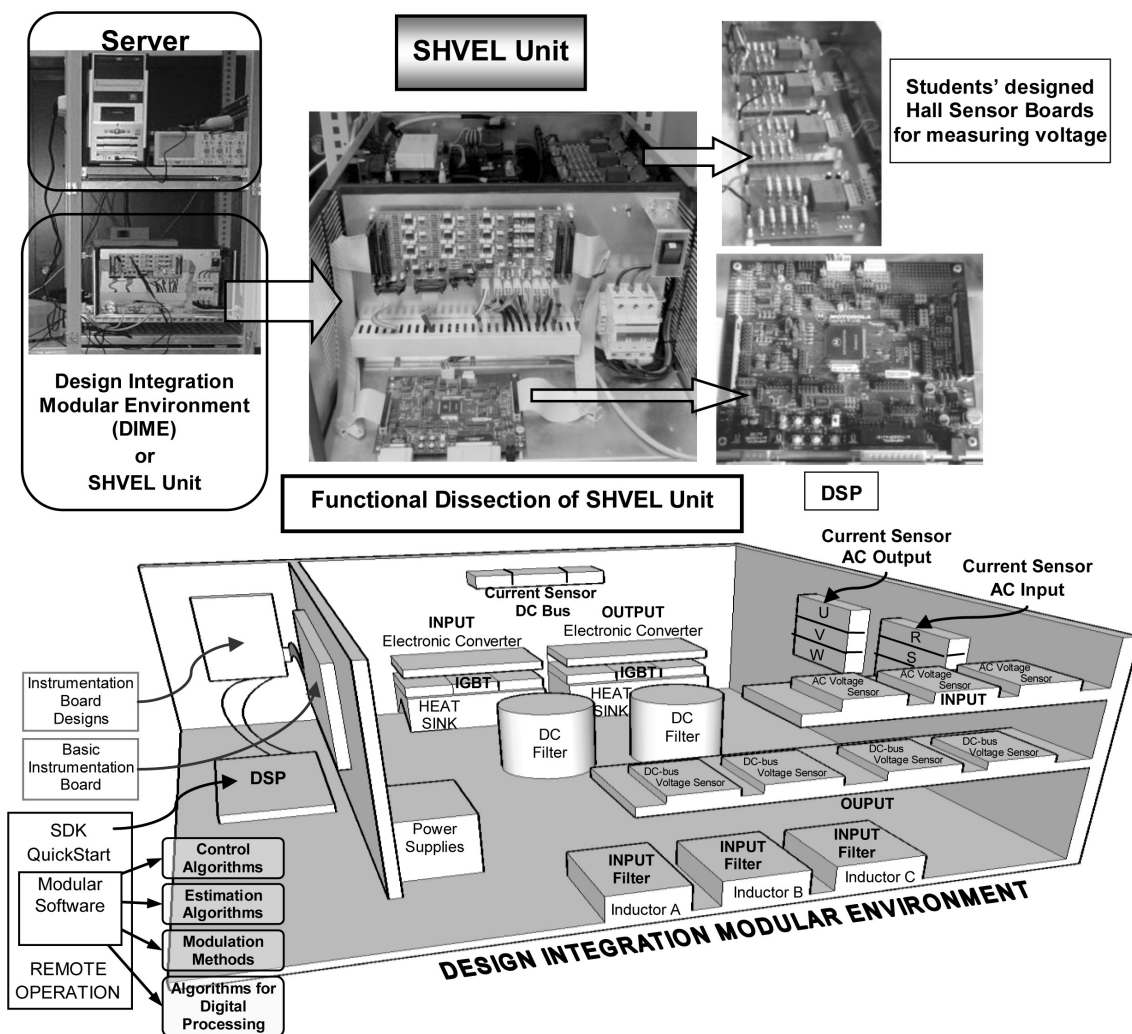

Fig. 2. SHVEL unit.

difference in a power electronic converter is that the physical shape or mechanism of each piece has no relationship to its task. The term "functional" is used based on the relationship between input and output signals for each part that makes up the power electronic system.

The functional dissection of the whole SHVEL unit for the experimental work is outlined in the introduction to the subject in the classroom. The experiments are developed in functional blocks depending on the learning objectives for the specific subject, such as Power Electronics, Automatic Control, Analog Techniques, Digital Techniques and Electric Machine Drives, among others.

Before starting the experimental work the students can observe the functionality of the SHVEL unit and analyze the behavior of a particular block. This capability allows the students to visualize and understand the objectives of the experiment.

The experiment consist of a five stage process that must be executed and evaluated, step by step, before obtaining the solutions.

In the first stage, the experiment's goals, its technical specifications and the required hardware and software tools are defined. The dissected functional blocks and their parameters are also identified.

In the second stage, the models and simulations of these blocks are developed (in this case, PSIM® and MATLAB®/SIMULINK® are used). The external and internal variables in the models are defined. This definition allows a posterior connection between models for obtaining more complex designs.

In the third stage, the effects of possible model uncertainties and of their environmental conditions are analyzed. The validation of the designed models is based on the output signal normalizations, despite the input signal variations. The progressive adjustments lead the experiment towards an optimum solution.

In the fourth stage, the analysis of electronic circuits and software algorithms in the SHVEL unit and their comparison with the simulation results reinforce the theoretical knowledge. The relationship between simulation and physical components are reviewed, focusing on aspects such as integration simplicity, security and cost. The simulation models are proposed for practical designs.

In the fifth and final stage, the results obtained by the students are debated, and the conclusions about the best designs are approved by the laboratory staff. The analysis of the possible components, hardware and/or software, which can be incorporated into the SHVEL unit as an industrial solution, is a fundamental part of the concluding experiment.

2.3 The web platform

The web platform is composed of the documentation area, the SHVEL units' remote activities and the web tools, Fig. 4. The web platform integrates the necessary theory resources for the experimental work, and the commercial information about the hardware and software components implemented in the SHVEL units [18]. The developed software for remote operation and visualization of SHVEL units is also included. Finally, the chat, e-mail and calendar web tools play a fundamental role in the daily work agenda and in the improvement of social skills related to the engineering education, such as teamwork and communication. The controller diagram is an example of graphical navigation within the documentation area: the students can click on each functional block and access the theory and commercial documentation related to the tasks and practical implementation of this block.
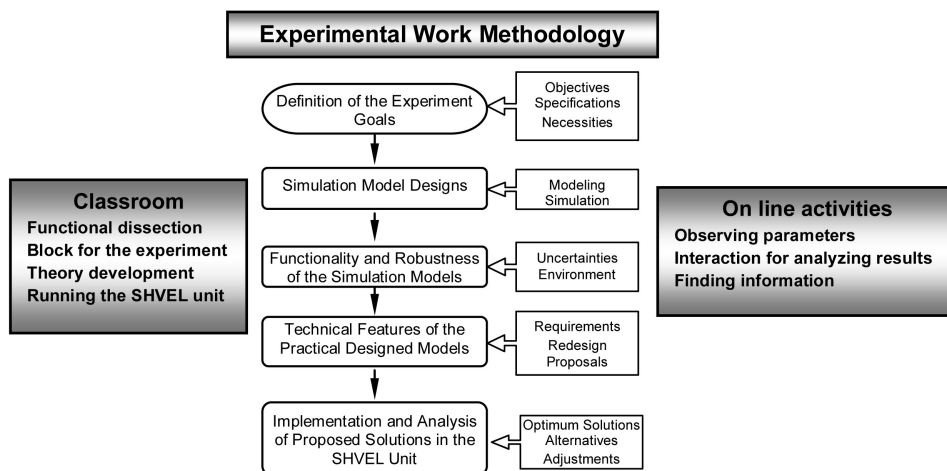

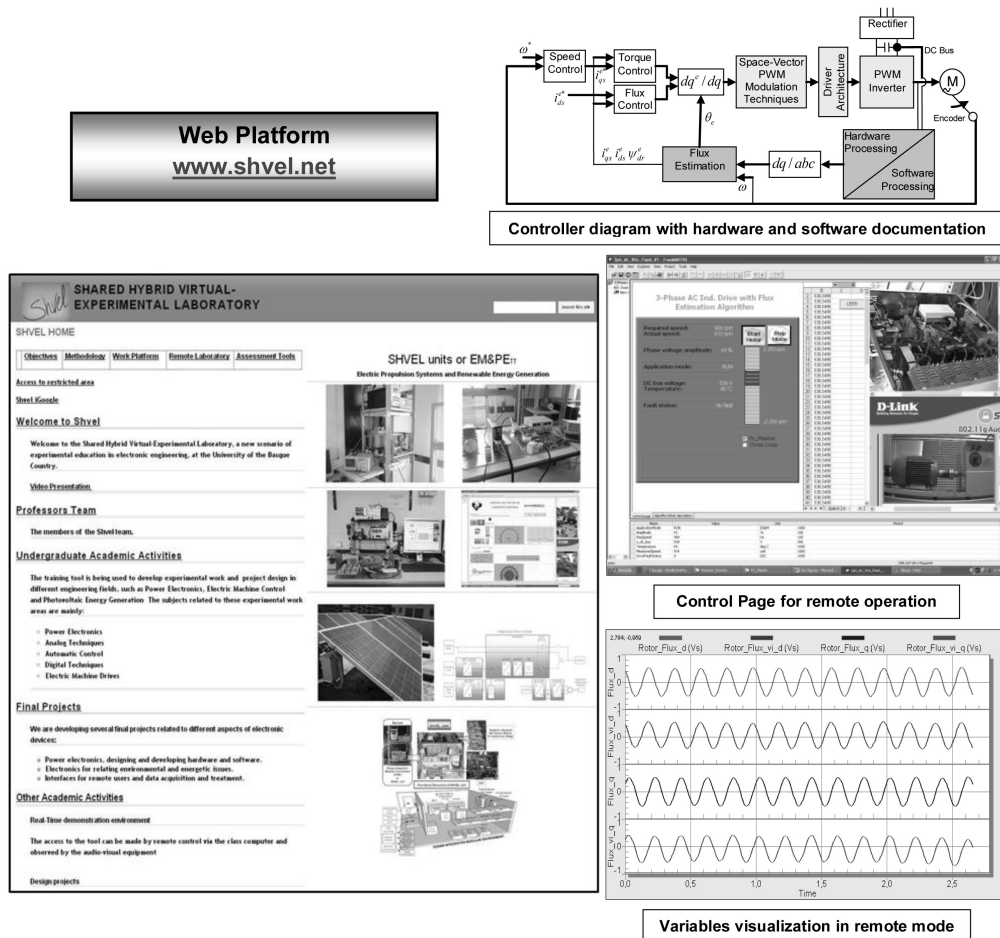**Fig. 3.** The experimental work methodology.

Fig. 4. The web platform.

2.4 Assessment tools

There are different assessment tools in the SHVEL for obtaining the students' feedback with two main objectives: to discern the level of enhancement of learning through practical work and the continuing improvement of the SHVEL environment. Table 1 shows a simple six-question survey form intended to obtain the students' feedback related to the first proposed objective. This questionnaire is completed by all students who are working in the SHVEL. Moreover a suggestion box is provided for students who have any opinions or recommendations.

3. Experiments in the SHVEL

This section of the paper contains two examples of experimental tasks related to induction motor applications. These experiments incorporate and highlight many of the goals of the SHVEL. The students need to measure voltages and currents in real conditions, to process energy within efficient parameters, to connect systems with different levels of power and to analyze diverse behavior models. All

of these tasks are related to the controller diagram in Fig. 4 and with the hardware and software components shown in the functional dissected SHVEL unit in Fig. 2.

Table 1. Questionnaire for students' feedback survey

Theory learning
A.1 The SHVEL is a useful tool for improving the theory lectures in the classroom.
A.2 The SHVEL is a useful tool for improving the learning out of campus.

Simulation software use
B.1 The SHVEL improves the use of simulation as an educational tool.

Technical proficiency
C.1 The SHVEL improves your experimental technical skills.

Motivation
D.1 The SHVEL increases motivation in studying electronic engineering.

Professional development
E.1 The SHVEL improves your professional development.
Scale: Strongly disagree – Completely agree

	1	2	3	4	5
	☐	☐	☐	☐	☐
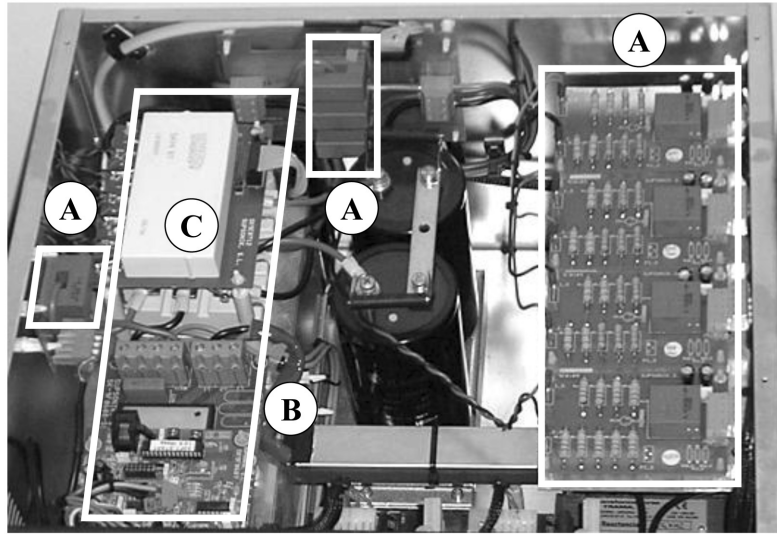
Fig. 5. Instrumentation prototype boards with Hall sensors (A), the power electronic block (B) and switch driver (C).

The experiments have been selected to demonstrate the experimental learning features of the SVHEL, and the integration of the maximum number of components. In Fig. 5 it is possible to observe the physical structure of one SHVEL unit composed of some of these hardware components.

The first experiment presents different induction motor flux estimation models, with the hardware and software necessary to implement them. The second experiment presents the development of a pulse-width modulation (PWM) inverter, the study of the effect of different modulation techniques, and the driver architecture. All these blocks are included in the controller diagram in Fig. 4. These experiments are integrated in the experimental work program of different subjects of the Industrial Electronics and Automatic Engineering degree and the Control and Automation and Robotic Engineering Master, at the University of the Basque Country.

Through the use of the SHVEL the students can observe the series of problems that emerge and how they can be resolved or mitigated. The experimental work methodology provides a common framework for analyzing the global architecture of the SHVEL unit in the experiments and for proceeding step by step in the dissected tasks, clarifying the technical necessities of these tasks. The web platform provides shared documentation and communication possibilities, which allow students to manage the experiments efficiently.

3.1 Stator and rotor flux estimation

The flux estimation has been selected as an example of an abstract parameter that is difficult to measure

and to visualize but with a fundamental role in advanced control algorithms of the induction motor drives. The flux models analyzed in theory and developed in the experimental work have been [21]:

$$\psi_s = \int (v_s - R_s i_s) dt \qquad (1)$$

$$\psi_r = \frac{L_r}{L_m}(\psi_s - \sigma L_s i_s) \qquad (2)$$

$$\frac{d\psi_r}{dt} = \frac{L_m}{T_r}i_s + j\omega \, \psi_r - \frac{1}{T_r}\psi_r \qquad (3)$$

$$\frac{d\psi_r}{dt}\left(\frac{L_r}{R_r} + \frac{L_m^2}{L_r R_s}\right) = \frac{L_m}{R_s}v_s - \psi_r + j\omega\frac{L_r}{R_r}\psi_r$$
$$- \left(\frac{L_s L_m}{R_s} - \frac{L_m^3}{L_r R_s}\right)\frac{di_s}{dt} \qquad (4)$$

$$v_{ds} = \frac{1}{3}(v_{ab} + v_{ac}); \, v_{qs} = \frac{1}{\sqrt{3}}v_{bc} \qquad (5)$$

$$i_{ds} = i_{as}; \, i_{qs} = \frac{1}{\sqrt{3}}(i_{as} + 2i_{bs}) \qquad (6)$$

Equation (1) represents the stator flux estimation. The voltage-based, current-based and hybrid rotor flux estimation models are represented by Equations (2), (3) and (4), respectively. The input variables measured are the machine terminal voltages, Equation (5), currents, Equation (6), and the rotor speed. The equations have been considered in the

stationary reference frame (d–q) [21]: where ψ_s and ψ_r are the stator and rotor flux; i_{abc} and v_{abc} represent the phase current and voltage; i_{ds}, i_{qs}, v_{ds}, v_{qs} are the currents and voltages referred to the above mentioned stationary reference frame and expressed in terms of the measured three-phase currents and voltages, being $v_s = v_{ds} + jv_{qs}$, $i_s = i_{ds} + ji_{qs}$. And finally, R_s and L_s are the stator resistance and inductance, R_r and L_r are the rotor resistance and inductance, L_m is the mutual inductance, ω is the rotor speed and $\sigma = 1 - \frac{L_m^2}{L_r L_s}$ the leakage coefficient.

3.2 Output electronic converter: PWM inverter

Voltage Controlled PWM inverters have been extensively used in the industrial world. Different PWM modulation techniques have been studied in order to analyze the following topics: the linear modulation range in Equation (7), the distortion factor d in Equation (8), switching losses in Equation (9) and finally, the motor losses in Equations (10) to (12). These aspects are all related to the efficient energy conversion [22, 23].

$$M_i = \frac{V_1}{V_{1\,six-step}} \quad , \quad V_{1\,six-step} = \frac{2}{\pi} U_{dc} \quad (7)$$

$$d = \frac{I_{hrms}}{I_{hrms\_six-step}} \quad , I_{hrms} = \sqrt{\frac{1}{T}\int_T [i(t) - i_1(t)]^2 dt} \quad (8)$$

$$P_{on} = V_{Son}I_{dc}\frac{t_{on}}{T_s} \, , \, P_{conm} = \frac{1}{2} U_{dc}I_{dc}\frac{(t_{t\_on} + t_{t\_off})}{T_s} \quad (9)$$

$$P_{cop} = \frac{3}{2}\left[R_s|i_s|^2 + \left(i_{qs}\frac{L_m}{L_r}\right)^2 R_r\right] \quad (10)$$

$$P_{cop\_h} = 3 I_{hrms}^2 (R_s + R_r) \quad (11)$$

$$P_{cor} = \frac{3}{2} |\psi_m|^2 \left(k_h|\omega_e| + k_{ed}\omega_e^2\right) \quad (12)$$

M_i represents the index of maximum modulation, V_1 is the amplitude of the fundamental harmonic of the modulated wave in the motor phase and $V_{1six-step}$ represents the amplitude of the fundamental harmonic for the six-step modulation technique.

The distortion factor parameter relates the value of the distortion current for the modulated system to the value of the harmonic current of the converter modulated in a six-step technique.

The loss model in power semiconductors are represented by conduction and switching losses P_{on} and P_{conm}, where V_{Son}, t_{on}, t_{t_on}, and t_{t_off} are the conduction voltage and time, and the turn-on and turn-off transition times respectively. U_{dc}, I_{dc}, and T_s are the DC voltage, DC load current and the transition time.

The loss model in AC machines can be divided into: copper P_{cop}, core P_{cor}, mechanical and stray load losses, where I_{hrms} represents the different harmonic components of the current modulated wave, k_h and k_{ed}, are the hysteresis and eddy design coefficients, ψ_m is the electromagnetic flux and ω_e the rotation speed of the magnetic field.

4. Experimental analysis performed by the SHVEL's students

In this section a summary of the experimental analysis performed by the SHVEL's students will be explained along with the most representative conclusions obtained by them.

4.1 Analysis

First, all the signals that must be measured in each simulation model are analyzed in the SHVEL unit, Equations (1)–(6) for flux estimation and Equations (7)–(12) for power losses. At the same time, in the event that any of these signals requires a software processing procedure, they will also be analyzed.

The use of Hall sensors for current and voltage measurements is evaluated, Fig. 5(A). The use of resistors for these measurements is also analyzed. For the speed, the decision of applying one of the different algorithms for speed estimation [21] or measuring by an incremental encoder is more complicated. In the power electronic block, Fig. 5(B), the security of the converter isolation and the power switch command architecture are established; the SKHI driver (International Rectifier®) for operating the electronic switches is analyzed as an example of a compact integrated driver, Fig. 5(C).

Next, the simulation model and the experimental result are compared. Through different tests and experiments with parameter modifications and input perturbations, the robustness of both systems is analyzed. For the simulation model analysis it is possible to add noise for a more realistic environment.

Figure 6 shows some dissected functional blocks taken out of the SHVEL unit and the initial prototypes of these blocks for using them in more secure conditions, for example, in lower currents and voltages. The functionality of the blocks is the same as in the SHVEL unit but the students can manage their inputs and outputs for more flexibility and a better comprehension of their technical features and their possible improvements. In the pro-
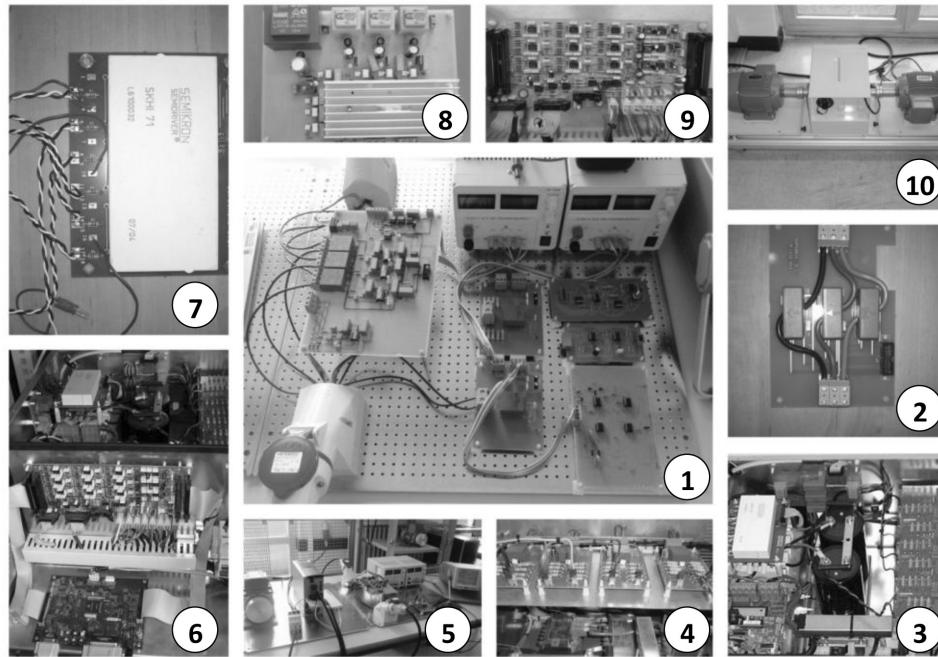
Fig. 6. Dissected functional blocks: Hall sensor boards (1, 2, 3, 4 and 5), SHVEL unit (6), switch driver (7), power block prototype (8), instrumentation board (9), and induction motors (10).

posed experiments seen in Fig. 6, it is possible to recognize the Hall sensor boards for measuring currents and voltages (1, 2, 3, 4, 5 and 6), switch driver circuits and modules (6 and 7), different power blocks prototypes (6 and 8), instrumentation prototype boards (6 and 9) and the induction motors (10). The same methodology can be applied to the DSP software for programming specific peripherals, such as, analog-to-digital converters (ADC), pulse-width modulators (PWM) and timers (TMP).

Finally, the developed experimental work is presented, discussed and evaluated, focusing on determining the best options for obtaining improved designs. Topics such as functional behavior, cost, security, and integration simplicity are considered.

The capability of creating and updating a technical database of all the experiment's notes and designs by the students into a form of reference library is an additional resource tool in the web platform documentation area [18].

4.2 The main solutions of SHVEL's teams

Figures 7–10 show the main solutions developed by the students after designing different software and hardware tasks when working in the voltage model flux estimation and in the power electronic inverter experiments. All of them are shown using the Free-Master platform as the system remote control server and as a visualization platform. The possibility of remote operation, parameter visualization and the

measurement of the SHVEL units are some of the most obvious differences and advantages of the proposed laboratory.

The students can control the electric machine, modify control parameters and visualize any system variable in oscilloscope mode for slow events and in recorder mode for fast events.

Figures 7 and 8 show, for example, the problem in the behavior of the algorithms that estimate the electromagnetic flux in the rotor of an induction motor and the given solution. These graphs have been obtained through the Recorder tool of the FreeMaster program and permit the analysis of the saturation effect of the flux in the voltage model in Fig. 7, indicated as Rotor_Flux_vi, and the further correction based on the student contributions, in Fig. 8, through the design of analogical and digital filters, and the substitution of pure
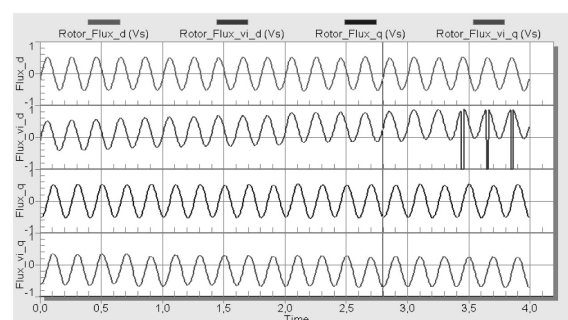
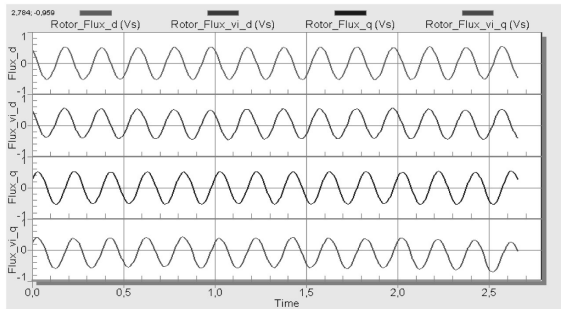**Fig. 7.** Magnetic flux deviations in the voltage model.

Fig. 8. Magnetic flux in the corrected voltage model.

integral function algorithms by first order functions [21].

In Figs 9 and 10 it is possible to analyze the result of two of the PWM modulation techniques programmed and applied in the power inverter: one continuous SVPWM and the other one discontinuous DPWM2 [22, 23].

The loss analysis is made based on the temperature variations in the induction motor and in the three-phase power block heat sink, through the modification on the modulation technique and the switching frequency [22, 23].

The command circuit architecture of the electronic switches of the power converter has a significant affect in AC drives. The substitution of power supplies with transformers by bootstrap capacitor circuits has played an important role in the internal
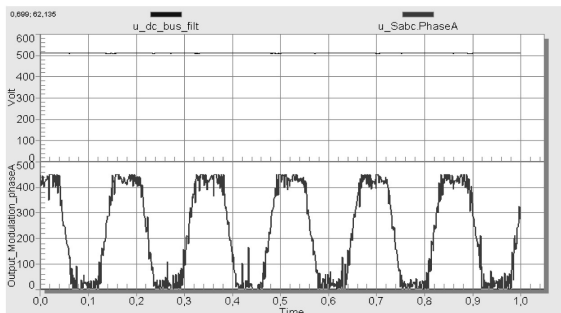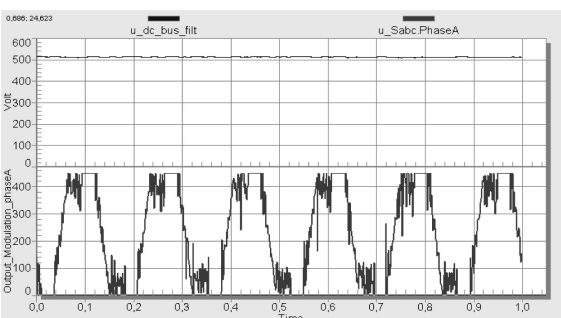

Fig. 9. Space vector modulation (SVPWM).

Fig. 10. Discontinuous modulation (DPWM2).

Table 2. List of experiments in the SHVEL for induction motor drives

Steady-state operation of an induction motor
Uncontrolled induction motor drives
Input electronic converter: uncontrolled, controlled and semi-controlled rectifiers
PWM modulators
Output electronic converter: PWM inverter
3-phase AC induction motor control with V/Hz speed open loop
3-phase AC induction motor control with V/Hz speed closed loop
DC–DC converter for dynamic braking
Electric variables in vector representation: axes transformation
Field oriented control principle
Dynamic modeling of an induction motor
Stator and rotor flux estimation
Speed estimation methods
3-phase AC induction motor with vector control
3-phase AC induction motor with sliding mode control
Continuous and discontinuous space vector PWM modulation techniques
Advanced input electronic converter: PWM rectifiers
Measuring of electrical parameters: voltage and current sensors
Measuring of mechanical parameters: speed and torque sensors
Analog and digital filter design
Instrumentation board design
Switch driver design. Power supplies

consumption of energy in the equipment and also in its size, weight and cost.

The proposed experiments are a small sample of the possibilities of experimental analysis, measuring of variables, electronic design and remote operation in the laboratory. Table 2 lists the various experiments with induction motor drives that the SHVEL can support.

5. SHVEL other learning uses

The SHVEL presents many possibilities for improving theory comprehension. In the classroom, via the class computer, the SHVEL unit can be accessed via the remote control and observed by the audio-visual equipment. This capability allows the professor to design the class lecture of the day and to demonstrate to the students in real time specific subject matters. This application can be observed in any level of detail in the modular real system. The Control Page in Fig. 4 shows a computer screen in which the remote control of the system can be accessed, commanded and monitored via two cameras. In the first camera, top right, the modular converter and any of the introduced designs in the system can be observed and in the second camera, bottom right, the behavior of the electric machine can be seen and heard.

In the engineering graduate final project the SHVEL units present the optimal characteristics required for the experimental section. The multidisciplinary character of the proposed laboratory allows working in electronic hardware (analogical circuit, instrumentation, power electronic switches,
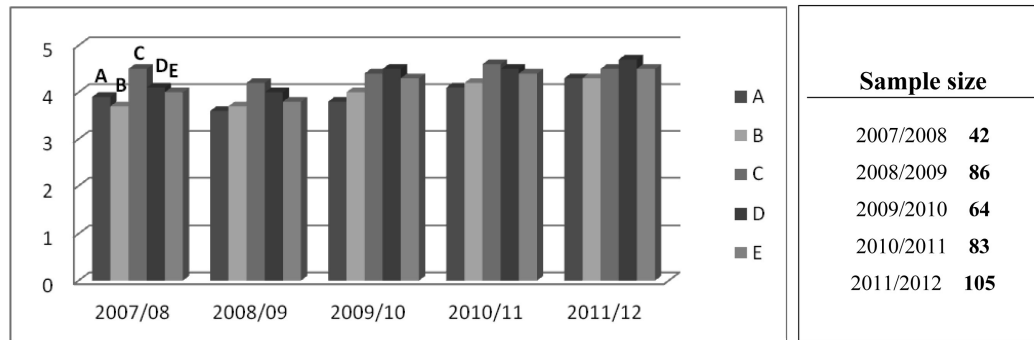
Fig. 11. Satisfaction survey about the SHVEL use.

filters, etc.), in microelectronic software (microprocessor classical and advanced control algorithm programming, communication drivers, etc.), and, finally, graphic user environments (HTML, Java, Visual Basic, etc.).

The SHVEL can function as a research and development laboratory, as it allows the testing and analysis of theoretical advancements when the technical specifications to be implemented are feasible, in a physical environment.

6. Assessment

The proposed environment is different from the classical approach to laboratory work and is more closely related to today's changing technological industrial and life style demands. The technological capability for experimental work through the web platform leads to the laboratory growing out of the campus constraint.

As this environment involves the manipulation of quasi industrial equipment, a basic technical knowledge is required that limits individual student use of the SHVEL. This real environment and its educational and technical challenges develop competencies such as teamwork and creativity. The students' interest in the experimental laboratories, in this fundamental part of their academic education, is enhanced by their knowing that their contributions can be integrated and tested in the SHVEL.

An assessment of the accomplishment of the objectives is revealed in Fig. 11, which represents the results of a satisfaction survey, based on the questionnaire in Table 1. Since the introduction of the SHVEL in 2007/08 it is possible to observe the high acceptance during the first academic year. Students' feedback in the second academic year marked a decline. This was due to an increase in student numbers, initial problems with the remote control and a changing experimental work schedule. The succeeding academic years, with increasing student numbers, have revealed a steady continuing overall improvement.

7. Conclusions

The University of the Basque Country is immersed in a great transformation adapting their current degrees to the new European Space for Higher Education. To meet these new goals the educational environment and laboratory outlined in this paper have become a fundamental part of the students' acquisition of experimental skills and professional development in the field of power electronics and its applications.

The presented laboratory achieves the proposed objectives: first, to promote the transfer of technical knowledge through experimental work, secondly, to improve technical skills and motivation with the linking of theory, simulation and real design in quasi industrial equipment, thirdly, to expand the experimental work out of the hands-on laboratory through the use of remote control for the analysis of the behavior of the integrated modular elements and, lastly, the professional development for the theoretical and practical execution of each experimental task.

References

1. S. A. Shirsavar, B. A. Potter and I. M. L. Ridge, Three-Phase Machines and Drives-Equipment for a Laboratory-Based Course, *IEEE Trans. on Education*, **49**(3), 2006, pp. 383–388.
2. L. D. Feisel and A. J. Rosa, The role of the laboratory in undergraduate engineering education, *Journal of Engineering Education*, 2005, pp. 121–130.
3. K. B. Baltzis and K. D. Koukias, Using Laboratory Experiments and Circuit Simulation IT Tools in an Undergraduate Course in Analog Electronics. *Journal of Science Education and Technology*, **18**, 2009, 546–555.
4. K. H. Solangi, M. R. Islam, R. Saidur, N. A. Rahim and H. Fayaz, A review on global solar energy policy, *Renewable and Sustainable Energy Reviews*, **15**, 2011, pp. 2149–2163.
5. F. J. Maseda, I. Martija, A. Garrido, I. Garrido, O. Barambones and I. Martija, Shared hybrid virtual-experimental laboratory for training in power electronics techniques, *Proc. ISC, Orlando*, 2008, pp. 140–145.

6. L. Vanfretti and F. Milano, Facilitating constructive alignment in power systems engineering education using free and open-source software, *IEEE Trans. on Education*, **55**(3), 2012, pp. 309–318.
7. C. Lazar and S. Carari, A remote control engineering laboratory, *IEEE Trans. on Industrial Electronics*, **55**(6), 2008, pp. 2368–2375.
8. T. W. Gedra, S. An, Q. H. Arsalan and S. Ray, Unified power engineering laboratory for electromechanical energy conversion, power electronics, and power systems, *IEEE Trans. on Power Systems*, **19**(1), 2004, pp. 112–119.
9. W. W. Fong, From Web 2.0 to Classroom 3.0, *Lecture Notes in Computer Science*, 6837/2011, pp.298–305.
10. M. Ogot and G. Kremer, *Engineering Design, A Practical Guide*, Pittsburgh, PA. Togo Press LLC, 2006.
11. O. Dalrymple, D. A. Sears and D. Evangelou, The motivational and transfer potential of Disassemble/Analyze/Assemble (DAA) Activities, *Journal of Engineering Education*, **100**(4), 2011, pp. 741–759.
12. A. Ndtoungou, A. B. Hamadi and K. Al-Haddad, An improved approach to better understand power electronics variables, *International Journal of Engineering Education*, **27**(1), 2011, pp. 200–213.
13. D. Hercog, B. Gergic, S. Uran and K. Jezernik, A DSP-based remote control laboratory, *IEEE Trans. on Industrial Electronics*, **54**(6), 2007, pp. 3057–3068.
14. T. Undelandand and N. Mohan, Meeting the challenge: revitalizing courses in power electronics and electric drives, *Nordic Workshop Power Industrial Electronic*, Norpie, 2002.
15. A. S. Patil and Z. J. Pudlowski, Instructional design strategies for interactive web-based tutorials and laboratory procedures in engineering education, *World Transactions on Engineering and Technology Education*, **2**(1), 2003, pp. 107–110.
16. M. Wu and J. H. She, Internet-based teaching and experiment system for control engineering course, *IEEE Trans. on Industrial Electronics*, **55**(6), 2008, pp. 2386–2396.
17. J. A. Rossiter, Which technology can really enhance learning within engineering?, *International Journal of Electrical Engineering Education*, **48**(3), 2012, pp. 231–244.
18. Shared Hybrid-Virtual Experimental Laboratory (SHVEL), http://www.shvel.net, Accessed 9 January 2013.
19. D. A. Strong, An approach for improving design and innovation skills in engineering education: the multidisciplinary design stream, *International Journal of Engineering Education*, **28**(2), 2012, pp. 339–348.
20. Digital Signal Controller DSC56000E, CodeWarrior development software tools, Quick Start and FreeMaster, free software and documentation, Freescale Semiconductor Inc., Austin, TX, http://www.freescale.com, Accessed 17 December 2012.
21. J. Holtz, Sensorless control of induction motor drives, *Proceedings of the IEEE*, **90**(8), 2002, pp. 1359–1394.
22. J. Holtz, Pulsewidth modulation for electronic power converters, *Proceedings of the IEEE*, **82**(8), 1994, pp. 1194–1214.
23. A. M. Hava, R. J. Kerkman and T. A. Lipo, A high-performance generalize discontinuous PWM algorithm, *IEEE Transactions on Industrial Applications*, **34**(5), 1998, pp. 1059–1071.

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