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Multidisciplinary Power Electronics Courses with On-line Simulation Tools*

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The advent of renewable energies, electrical vehicles and smart grids are expanding the teaching of Power Electronics into areas such as mechanical or energy engineering. In this multidisciplinary context, the adaptation of the existing resources to the new profile of students is becoming a major need. Aiming to fill this gap, the University of Malaga offers specifically designed multidisciplinary course for students who are unfamiliar with Power Electronics. These courses follow a blended top-down approach and use a custom made free-software on-line simulation tool to improve the interactivity and visualization. The top-down project-based approach allows an active role of the student and the ready-to-use easy java simulation applets eases the asynchronous study of Power Electronics converters in a friendly environment. The accuracy of the applets is verified by simulation and experimental results and the didactic benefits of the course are demonstrated by questionnaires and tests.

Keywords: power electronics; simulation tool; multidisciplinary; non-electrical students.

1. Introduction

Power Electronics is a discipline that encompasses a wide range of real-life applications in industrial, commercial and residential environments [1]. To name a few, electric and hybrid vehicles in the automotive industry, photovoltaic and wind energy conversion systems in the renewable energy industry or high voltage direct current (HVDC) and flexible AC transmission systems (FACTS) in power systems are examples of those areas where the use of power electronics is growing at an unrelenting pace [2, 3]. The growth experienced by these applications has motivated a recent development of the Power Electronics technology [4–7]. For this reason, the Power Electronics teaching/learning process, together with the understanding of the emerging applications, is becoming a main concern both at undergraduate and graduate levels [2, 3], [8–10].

Traditionally, the teaching of Power Electronics has been restricted to students of electrical and electronic engineering degrees. However, Power Electronics applications [11] are becoming highly multidisciplinary and this field is spreading into areas such as mechanical engineering or energy engineering, where students do not have such a deep knowledge of electronics and control disciplines. The new profile of students requires an adequate adaptation of the existing resources and the design of more specific courses in accordance with the new audience background. Led by this need, the School of Engineering, in the framework of the University of Malaga Life Long Learning Program, has designed a course to satisfy the Power Electronics training needs of those engineering students with a scarce electrical/electronic background. The course uses a top-down structure to fit better the multidisciplinary nature of the course [2] and a methodology that combines both direct lectures and hands-on working in a simulation-based environment. Applications such as automotive industry, renewable energy industry and power systems are described in direct lectures at the beginning of the course in the while a project-based approach is followed in the last part of the course. This blended top-down approach aims to satisfy better undergraduate mechanical engineering students who wish to acquire knowledge and skills in the field of Power Electronics and its applications.

Even though the advantages and disadvantages of using simulation tools versus experimental testing have been widely discussed, it is well accepted that hands-on work using simulations tools can be very useful to beginner students in Power Electronics [12, 13]. However, using traditionally licensed software (PSIM [14], SABER [15], PSpice [16] or MATLAB/SIMULINK Power Electronics toolbox [17–20]) with this new profile of students with a scarce electrical/electronic background presents several drawbacks:

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- It is necessary to learn how to use the simulation tool before starting to study the desired topic.
- The creation of rich and varied graphical interfaces that helps the understanding of the physical phenomena is not an easy task and high programming skills are required to develop useful applications with a basic level of interactivity.
- Standard simulation results do not explain to the students, step by step, how the circuits work.

Considering the drawbacks of using licensed software and the new profile of students with a scarce electrical/electronic background, the University of Malaga took the initiative of designing a new and innovative software tool with the following features [21, 22]:

- On-line operation.
- Use of license free software.
- Avoid the need for end-users to install any software.
- Provide different converters and let students change the topology and control parameters.
- Show oscilloscope-like waveforms.
- Include animations to highlight main electrical parameters (current path, voltages) as well as the switching states of each device.
- Quantify some quality parameters such as, for example, the ripple percentage of the output voltage.

This work describes the newly designed multidisciplinary course in Section 2 and the on-line simulation tool in Section 3, showing a comparative analysis with commercial simulation software and laboratory experiments. The assessment of the tool implementation in the specialization course is included in Section 4 and the main conclusions are drawn in Section 5.

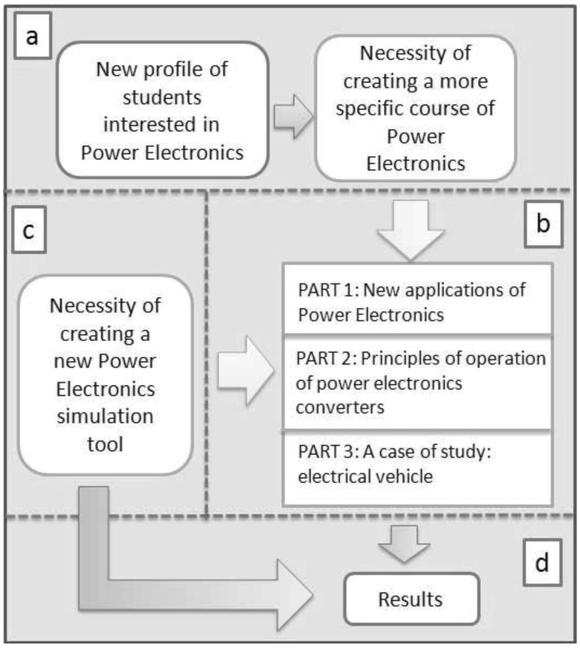

Fig. 1. Followed steps in the design of the Power Electronics course.

2. Course description

Due to the new profile of students, the course has not a classical structure where the converters are explained in the first place and the applications are shown at the end. Instead, the course has been structured following a top-down strategy [2], beginning with an overview of the different fields of application of Power Electronics, following with the identification and description of the converters employed in these applications, and finishing with the principle of operation of the converters, involved in a mechanical application such as an electrical vehicle, a fashionable example of the Power Electronics applications, using the developed simulation based tool.

The course has been designed according to the scheme of Fig. 1 and has a total of 60 hours divided into three different parts:

- Part 1 (10h.), where the presence of the Power Electronics in the automotive, renewable energy and power system industry is presented.
- Part 2 (25h.), where the converters and its principles of operation are explained.
- Part 3 (25h.), consisting on a case of study where students are asked to simulate the Power Electronics converters included in the drive of a simplified electric vehicle (Fig. 2).

There have been two editions of the course: the first edition in 2013 and the second edition in 2014. The first edition used specific software for the simulation of Power Electronics (PSIM [14]). However, some of the previously described shortcomings of using commercial software were identified in the 2013 edition and this motivated the creation of a specifically designed simulation tool that could fit better the course students. This newly created tool

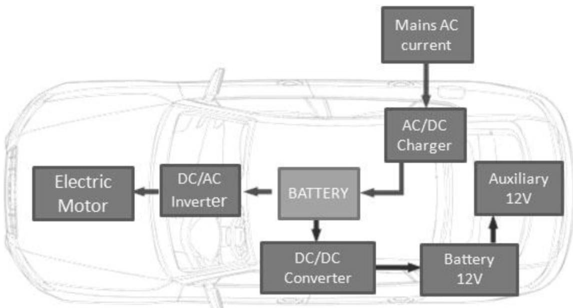

Fig. 2. Simplified block diagram of an electric vehicle.

was used and validated in the second edition of the course (2014).

3. On-line simulation tool

3.1 Description of the tool

The simulation tool, based on the free-software Easy Java Simulation (EJS) [23] applets [24–26], has been developed to make easer the study of Power Electronics at the undergraduate level in engineering courses with a new profile of students who are unfamiliar with electronic engineering. The applets represent the operation of the main Power Electronics converters with a high degree of interactivity and visualization, allowing the representation of the converter dynamic behaviour, which is difficult to illustrate in a traditional manner.

Other tools for simulation of Power Electronics converters in Java can be found in the web, such us Interactive Power Electronics Seminar (iPES) of the Zurich University [26]. This tool has the inconvenience that the software employed, Gecko Circuits Research [27], requires the payment of a license. The University of Sao Paulo has developed an interesting power electronics tool in Java which integrates PSpice [24]. However, while the possibilities of this software are similar to the tool presented in this paper, the Sao Paulo software does not include the commutation inductance effect in the ac-dc converters.

A total of 30 applets, representing the main ac/dc, dc/dc, dc/ac, ac/ac converters have been implemented. Each applet can operate with different control parameters and initial conditions, highly increasing the number of simulation possibilities. The Java applets developed in this EJS-based simulation tool include: non-controlled rectifiers (ac/dc), phase-controlled converters (ac/dc), continuous-continuous converters or choppers (dc/dc), inverters (dc/ac) and ac/ac controllers.

The graphical user interface (GUI) for the applets, regardless of the topology (ac/dc, dc/dc, dc/ac, and ac/ac), has been divided into four interconnected areas (Fig. 3).

- *Area 1 (heading)*: with four tabs including the simulation data (input parameters, load) and results (waveforms and calculation results).
- *Area 2 (electronic circuit schematic)*: showing the Power Electronics converter to be analyzed. The circuit is animated during the simulation according to the parameters introduced in *Area 1*. Thereby, the switches are opened and closed allowing or not the current circulation, shown in green color.
- *Area 3 (graphic screen)*: where the waveforms of the simulation variables are displayed: input voltage versus output voltage, output current, switch voltage drop and other variables of the simulated converter.
- *Area 4 (control buttons)*: allowing the user to start, stop or refresh the simulation.

Briefly, the applets allow the students to modify the circuit parameters and immediately observe the changes in the waveforms, the calculation results and the animated circuit schematic. The sequence to run the simulation is the following: the students firstly choose the Power Electronics converter to be analyzed and then they set the input parameters and waveforms to be displayed. After clicking the play button, the simulation starts and the EJS-based view shows the selected waveforms and the animation of the converter (shown during four fundamental periods). Students can observe and study the relationship between the state of the circuit and its waveforms at each time instant. By clicking the tab calculations, students can finally check if their

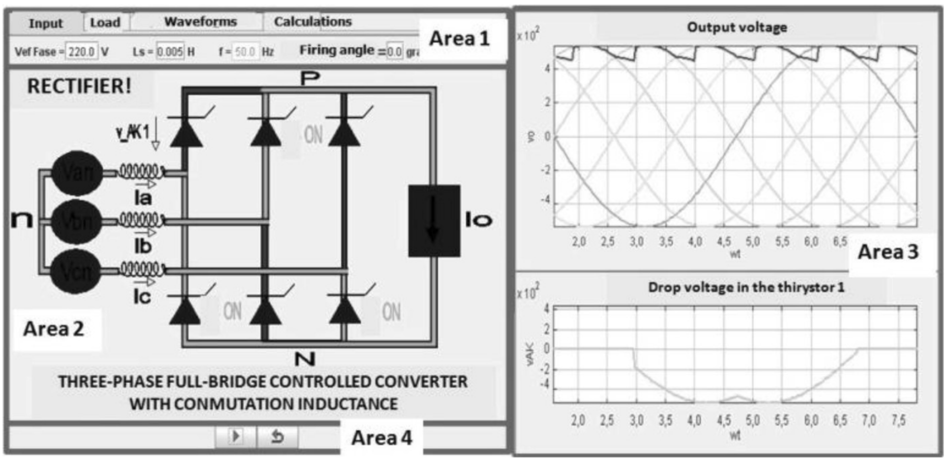

Fig. 3. Structure of the implemented GUI for the simulation applets.

calculations match with the simulation results. At any time, the students can modify the circuit parameters and immediately observe the changes in the animation of the electronic circuit schematic, the waveforms and the calculation results.

3.2 Validation of the tool

Before the EJS-based tool can be used as didactic material in Power Electronic courses, it is necessary to demonstrate its accuracy and applicability. This validation is accomplished by implementing the different Power Electronics converters using three different ways: the corresponding applet, a specific Power Electronics simulation package (PSIM) and real implementation in the laboratory. Although the validation has been carried out for all different converters included in the simulation tool, only the dc/dc step-down (buck) converter is shown here for the sake of example. Independently of the way used to implement the converter, the chosen input parameters are: $V_D = 24\ V$, $D = 0.4$, $L = 0.2\ mH$, $R = 20\ \Omega$, $C = 10\ mH$ and $f_s = 10\ kHz$. The waveforms and numerical results provided by the applet are compared with those obtained from PSIM software and the experimental implementation of the converter in the lab.

3.2.1 Dc/dc step-down converter: applet

Figure 4 shows the developed applet of the dc/dc step-down converter. Once the input parameters are entered, the operation mode (continuous, discontinuous or boundary) is calculated according to the value of the minimum inductance (L_{min}) for continuous operation:

$$L_{min} = \frac{(1-D)R}{2f_s} \qquad \text{Equation(1)}$$

- If $L > L_{min}$: the step-down converter operates in continuous mode.
- If $L < L_{min}$: the step-down converter operates in discontinuous mode.
- If $L = L_{min}$: the step-down converter operates in the boundary between continuous and discontinuous modes.

Once the mode of operation is determined, the applet returns the waveforms and the calculation results: output voltage (V_o), minimum (i_{Lmin}) and maximum (i_{Lmax}) values of the current through the inductance, duty ratio (D_1, only in discontinuous mode) and ripple percentage of the output voltage ($\%\Delta V_o/V_o$) in the continuous mode.

According to the input parameters, the step-down converter works in the discontinuous mode, since equation (1) yields $L_{min} = 0.6\ mH > L = 0.2\ mH$. The waveforms resulting from the applet simulation are shown in Fig. 5.

3.2.2 Dc/dc step-down converter: PSIM commercial simulator package

Now, the dc/dc step-down converter has been implemented using a specific Power Electronics simulation tool: the demo version of PSIM. The schematic of the converter using this software is shown in Fig. 6. With the same parameters already used in the applet, the waveforms obtained using PSIM are shown in Fig. 7. It can be observed that results from PSIM closely match those of the applet (Fig. 5).

The differences between PSIM and applet waveforms can be explained by the fact that the switches have been considered to be ideal in the applet, while PSIM includes some non-ideal features of the switches. However, as far as the didactic purpose is concerned, the differences are negligible and the

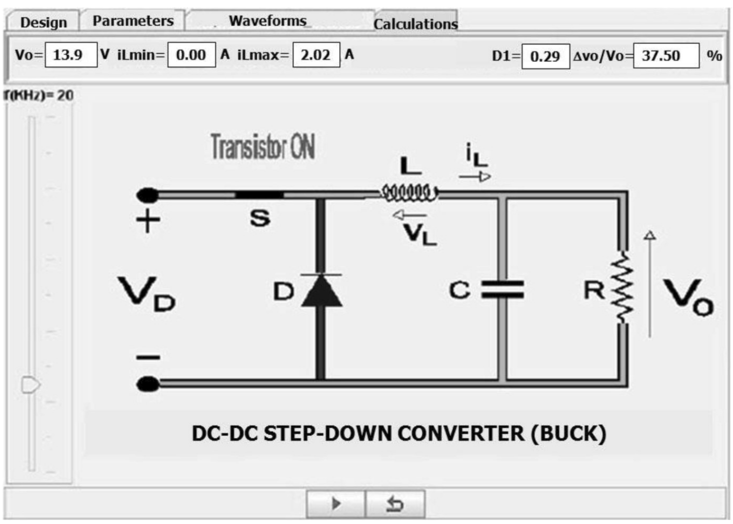

Fig. 4. Dc/dc step-down converter (buck).

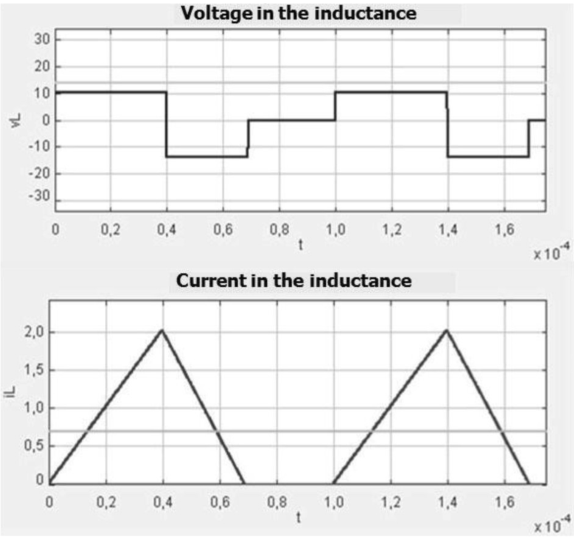

Fig. 5. Main frame of the Java tool corresponding to the dc/dc step-down converter (buck) in discontinuous mode: waveforms.

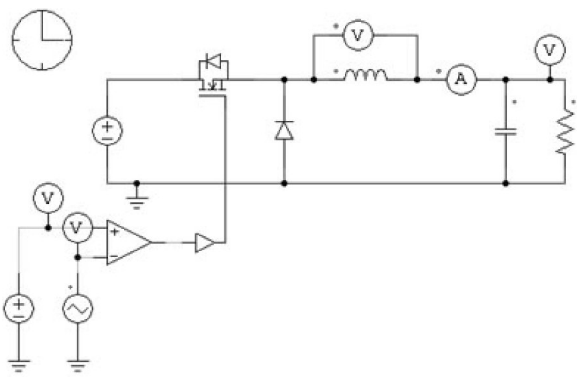

Fig. 6. Dc/dc step-down converter (buck) schematic in PSIM.

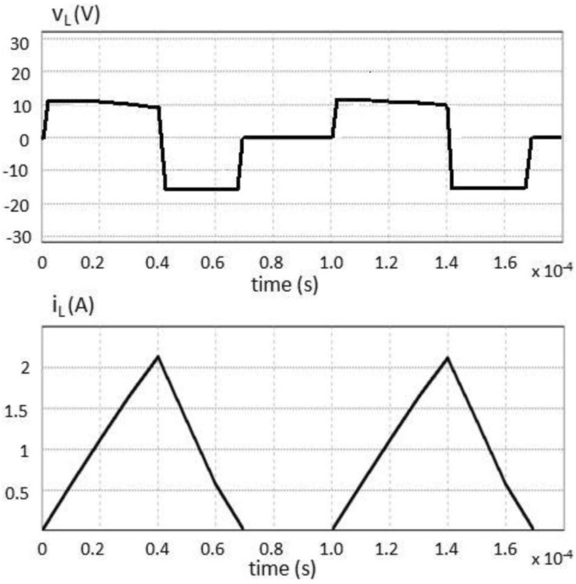

Fig. 7. Main frame of the PSIM software, corresponding to the dc/dc step-down converter (buck) in discontinuous mode: waveforms.

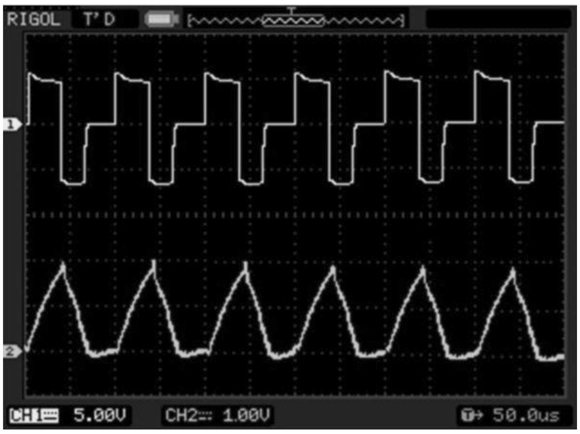

Fig. 8. Oscilloscope waveforms, corresponding to dc/dc step-down (buck) converter in discontinuous mode.

applet accurately describes the converter performance allowing on-line use of the tool.

3.2.3 Dc/dc step-down converter: physical implementation in the laboratory

In this case, the dc/dc step-down converter has been implemented in one of the workstation available in the Power Electronics laboratory at the University of Malaga. Each workstation includes the following instruments: digital oscilloscope, waveform generator, dc-ac power supply, three-phase passive load, digital multimeter, differential voltage probe, clamp, Power Electronics training modules (didactic commercial equipment allowing different topologies of power electronics converters).

Figure 8 shows the screen of the oscilloscope with the resulting waveforms, again using the same parameters as in the applet and PSIM results. The voltage in the inductance is shown in channel 1 (upper trace) and the current through the inductance is represented in channel 2 (lower trace). In this case, the current is measured by a clamp with ratio 1V/1A.

Experimental results (Fig. 8) are in good agreement with the simulation results obtained using the applet (Fig. 5) and PSIM software (Fig. 7). As far as the teaching of Power Electronics is concerned, the three described methods (applet, PSIM and experiment) provide a similar behaviour and can be used for illustrative purposes of the dc-dc buck converter. Nevertheless, the applet has some unique features that can be advantageous for teaching purposes: on-line simulation with free software, a wide range of predesigned Power Electronics converters, animated interface and high flexibility.

In order to compare the numerical results in the analysis of the dc/dc step-down converter, the output voltage (V_o), minimum (i_{Lmin}) and maximum (i_{Lmax}) values of the current through the inductance

Table 1. Comparison among numerical results

	V_o	i_{Lmin}	i_{Lmax}	D_1
Applet	13.90 V	0	2.02 A	0.29
PSIM simulation	14.10 V	0	2.10 A	0.29
Experiment	13.95 V	0	2.01 A	0.30

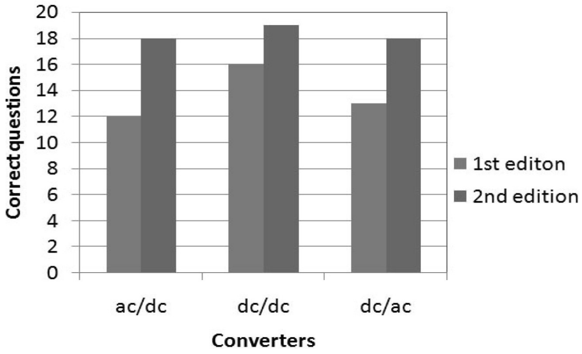

Fig. 9. Test results: comprehension of the principles of operation of the converters.

and duty ratio (D_1, only in discontinuous mode) are shown in Table 1 for the three implemented methods (applet, PSIM and experiment). Numerical results from Table 1 confirm the good agreement shown in Fig. 5, Fig. 7 and Fig. 8 and validate the applet to be used for educational purposes.

Once the performance of the entire developed applets were validated through comparison with commercial simulators (PSIM) and experimental results, the tool is being used in the third edition (2015) of the Power Electronics specialization course for mechanical engineers at the University of Malaga.

4. Assessment: impact of the developed tool

An average of 40 students attended both editions. Since the first edition of the course (2013) used the PSIM software to exemplify the operation of the different converters, it is possible to compare the marks obtained by the students and their satisfaction both before and after the applets were used for teaching purposes.

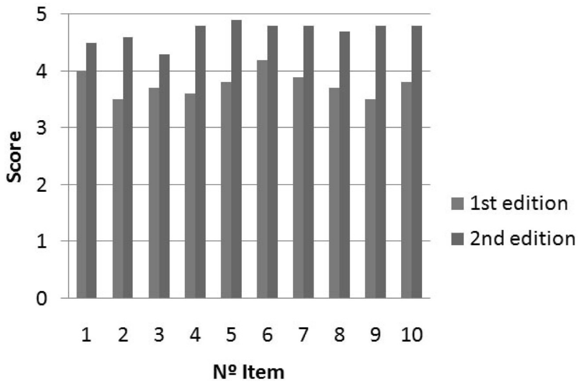

Fig. 10. Survey results: students' perception of the methodology and simulation tasks.

As indicated above, the converters involved in the electric vehicle were simulated using PSIM in the first edition and Java simulation tool in the second edition of the course. After performing the simulations, the students answered a survey with twenty questions regarding the understanding of the principles of operation of each converter: ac/dc, dc/dc and dc/ac (cognitive dimension). Figure 9 shows the number of correct answers in each edition.

The number of correct responses in the second edition is 34 % higher than in the first edition (50 % in ac/dc items, 19 % in dc/dc items and 38 % in dc/ac items), showing a better overall understanding of the Power Electronics principles. The most remarkable improvement corresponds to the ac/dc related concepts, being these items the most difficult to analyze and understand by the students [28].

Moreover, in order to evaluate the students' satisfaction with the methodology and simulation tool (affective dimension), a survey was anonymously answered by the students. The survey consists of 10 questions and the score ranges between 1 (I strongly disagree) to 5 (I strongly agree). Fig. 10 shows the data from Table 2. Results show that the incorporation of the tool has improved the general satisfaction of the students. The items with a higher degree of improvement are those related to questions 3, 4, 5 and 9, pointing that the students perceive the applets as an easy-to-use

Table 2. Survey passed to students

Nº	Item	1st edition	2nd edition
1	The methodology employed is adequate	4.0	4.5
2	The course is easy to follow and the level of understanding is acceptable	3.5	4.6
3	The course and simulations are well orientated to real applications	3.7	4.3
4	The simulations help to a better comprehension of the Power Electronics converters	3.6	4.8
5	The simulations are easy to use and understand	3.8	4.9
6	The simulations improve the competences acquired	4.2	4.8
7	The simulations help to solve the difficulties arising during the analysis of the converter	3.9	4.8
8	The simulations are adequate to explain the concepts	3.7	4.7
9	Evaluate the simulations used in the course	3.5	4.8
10	I am satisfied with the course	3.8	4.8

Table 3. Historical data of the Power Electronics System subject (R: registered; D: done; P: passed)

Academic year	R	D	P	% D/R	% P/R	% P/D
1st edition (2013)	14	11	10	78.57%	71.42%	90.90%
2nd edition (2014)	26	24	22	93.30%	84.61%	91.66%

tool that enhances their understanding, being well oriented to industrial applications. The global course satisfaction (item 10) is increased by 26% (from 3.8 to 4.8), indicating that the EJS-based applets can be an intuitive and comprehensible tool for students with poor programming skills and a scarce background in the electrical/electronic field.

Finally, in Table 3, the mark statistics are drawn. It represents three ratios: D/R, P/R, P/D (D: done, R: registered, P: passed). It can be observed that due to the implementation and use of the described simulation tool (2014), instead of using commercial software (2013), the ratio P/D has been increased considerably and, in general, results have been thoroughly satisfactory.

5. Conclusions

Even though there is a wide range of possibilities to simulate Power Electronics converters, most of the existing tools require licensed software, installation in the end-user terminal and some programming skills. This works shows that EJS can be used as a powerful tool to implement applets that provide students with free-software ready-to-use on-line simulators. The applets allow different settings for the input/output data/display but do not require any programming skills. The interface is didactically designed to explain the Power Electronics converter operation step-by-step with a high level of interactivity and it is especially suitable for engineering students with a scarce electronic background. The accuracy of the different applets has been verified by comparison with simulation and experimental results, and the implementation in the specialization courses at the University of Malaga proves that the tool can effectively motivate students to understand the principle of operation of the power converters. The EJS-based simulator can be open-accessed and it can be shared as a didactic tool for university teaching.

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