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ACES - Control Avançat de Sistemes d'Energia

IOC-DT-P-2010-02
Gener 2010

Institut d'Organització i Control
de Sistemes Industrials

On the role of virtual laboratories in an undergraduate power electronics introductory course

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***Abstract*— This paper describes the design and implementation of a virtual laboratory (VL) to support the students learning process of basic concepts on power electronics. Described VL is based on Easy Java Simulations (EJS), a free open-source environment which allows professors to easily design, implement and maintain VL that fit their pedagogical needs.**

The integration of this type of VL in a *Power Electronics Introduction* course is discussed. Concretely, how the VL is jointly used with regular theoretical sessions and hands-on laboratories in order to achieve desired pedagogical goals is described. The hands-on laboratory is also described and compared with the VL.

***Index Terms*— Virtual Laboratory, Power Electronics, Buck converter, Boost Converter, Hands-on laboratory.**

I. Introduction

Almost any electrical power domestically or industrially consumed has been processed by a Power Converter (PC) before it reaches the final consumption. As a consequence, PC play a key role in generation, transport and adaptation chain [1], [2], [3]. This relevance has made that most engineering undergraduate curriculum incorporate a Power Electronics (PE) introductory course. PE is based on principles different from the ones used in traditional electrical and electronics devices and contains complex dynamics difficult to teach and understand for undergraduate students. In order to improve students' learning process and to increase the interest of undergraduate students in power system dynamics, a great effort has been carried out in order to introduce new technologies in the learning process.

A tool that has proved efficient to shortcut and simplify the access to new concepts and technologies is interactivity [4][5]. Interactivity allows one to understand qualitatively the influence of parameters in the system behavior without the need of an in-depth knowledge of a certain subject. Most students understand linear circuits, but get confused when switched behavior is introduced. Due to this inherent difficulty it is convenient that students develop a mental model for this type of behavior. Interactivity can play a key role in the construction of this mental model.

Nowadays computers allow developing graphical and interactive programs that reproduce the feelings obtained in a regular laboratory. These programs are usually name Virtual Labs (VL) [6]. In contrast to hands-on laboratories, VL allow an unconstrained use in both time and space. This unlimited access makes VL to play a key role in the emerging pedagogical methods behind the spirit of Bologna Process and the European Credit Transfer System (ECTS).

In addition, VL allow developing certain experiments that would be difficult or dangerous in a hands-on laboratory. This last property is of great relevance for students taking the first contact with a certain technology.

In order to take profit from this pedagogical benefits most academic communities have been working to develop computer tools to support students learning process, between others math's [7], physics [8], chemistry [9] and automatic control [10] can be mentioned. Power electronics community has not been an exception to this pedagogical trends [11][12]. Works in this area can be grouped in three main groups:

- Pedagogical applications and multimedia contents [13][14]. These types of applications are designed to illustrate theoretical and technological concepts or to complement traditional materials. Usually a graphical and intuitive environment allows navigating certain concepts.
- Virtual Laboratories [15][16]. These environments reproduce a certain physical environment by numerical simulation and mathematical models in a graphical and interactive manner. VL are designed to provide feelings similar to one obtained in a hands-on environment.
- Remote Laboratories [17] [18] [19]. These tools offer a graphical interface to access an existing physical reality placed in a remote place. Some of them allow choosing between different types of experiments in a reconfigurable platform.

A key point that one should take into account when developing a pedagogical tool is choosing the appropriate implementation tool. A pedagogical tool is a dynamic system that must be maintained and updated in order to fit the varying pedagogical needs. Development and maintenance is usually done by limited programming skills professors and students. Taking into account these constraints several computer tools have been used to developed pedagogical tools in the Power Systems field, SPICE (Simulation Program with Integrated Circuit Emphasis) [20] and similar simulations software offer very precise results with most relevant components predefined but graphical and interactive interfaces must be developed; MATLAB [21] [16] [22] is another tool extensively used offering similar capabilities and difficulties; by far Labview [11] [18] [23] is the tool that has been used the most, especially when instrumentation and remote elements are present. Most of these developments are based on expensive proprietary software. JAVA based environments [15] constitute a completely different approach. This type of environments allow complete flexibility at the cost of code programming which might be a limitation in some cases, in contrast they

1) Introduction to power processing.
2) DC/DC power converter synthesis.
3) Steady State converter analysis and design.
4) Converter Dynamics and control design.
5) AC/DC Conversion. Controlled Rectifier.
6) DC/AC Conversion.

Fig. 1
COURSE CONTENTS.

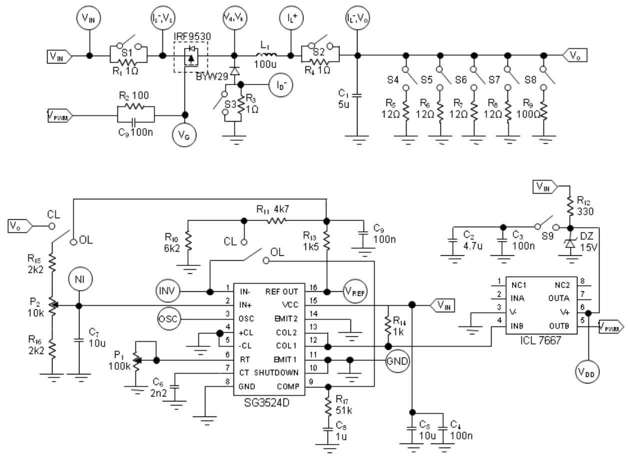

Fig. 2
HANDS-ON LABORATORY BOARD SCHEMATIC CIRCUITRY.

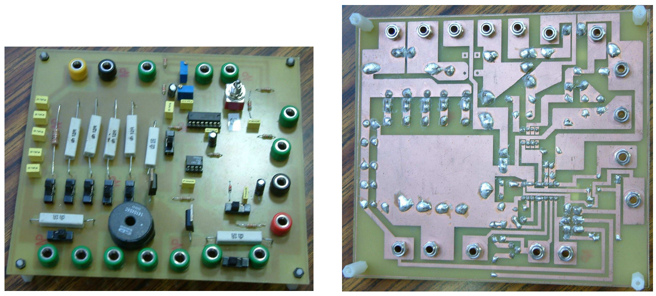

Fig. 3
HANDS-ON LABORATORY BOARD PICTURES

can be distributed freely and can be used trough the internet naturally. A tool that has been successfully used to develop virtual and remote laboratories is Easy Java Simulations (EJS) [24] [25] which automatically generates JAVA code from high level specifications. This environment has been used in the development of VL laboratories used in our course.

Although it is possible to use a PE remote laboratory, in our opinion it is convenient to preserve the hands-on laboratory in introductory power electronics subjects, so students can see the connection between concepts, models, simulations and the real devices. In the following sections the case of our *Power Electronics Introduction* course will be described. The paper is organized as follows: section II introduces the course goals and the academic environment, section III describes the hands-on laboratory supporting the learning process, section IV describes how the virtual laboratory has been developed and which are its functionalities and capabilities, section V discusses how previously described VL and hands-on laboratory are used together in the different steps of the learning process, finally section VI exposes several conclusions and ongoing works.

II. POWER ELECTRONICS INTRODUCTION COURSE

The pedagogical goals of this course are introducing students to most relevant concepts and most relevant configurations in power converters. Figure 1 contains the course syllabus, these contents are covered by traditional books on power electronics [1][2][3] which are used are basic references for the course. Students attending to the course have previously followed a couple of subjects on circuit theory and linear electronics. As a consequence, the analysis of linear circuits appearing in power converter and basic linear controllers designed in the frequency domain can be used along the course.
The course is organized in the theoretical sessions, hands-on laboratory sessions and students personal work. Theoretical concepts are introduced in a two hour session once a week while hands-on laboratory sessions are developed in 3 laboratory sessions of 2 hours distributed along the quarter. During the quarter assessments are proposed to the students which must do on their own as personal work. This distribution corresponds to a total of 5 ECTS.

Theoretical sessions are develop following a conventional approach were the professor introduces theoretical concepts using slides, the blackboard and the VL according the specific needs of each topic (section V will provide more details on this). Hands-on laboratory sessions are concentrated in DC/DC converters study and personal work is based in combining the VL and analytical developments.

III. HANDS-ON LABORATORIES

A. Board setup description

In order to support hands-on laboratories sessions a board has been built for the DC/DC step-down regulator. The board is composed by a Buck power stage with its switching control stage. The regulator can operate in both open-loop (with no output voltage feedback) and closed-loop behaviors.

Figure 2 shows a schematic circuitry of the implemented board. It is important to note that this board is composed by a set of cheap and easy to obtain components, this making the board easy to maintain, construct and replicate. In order to simplify the use of the board and introduce flexibility the board contains several connectors (banana jack) and slide switches. The connectors allow the interconnection with the

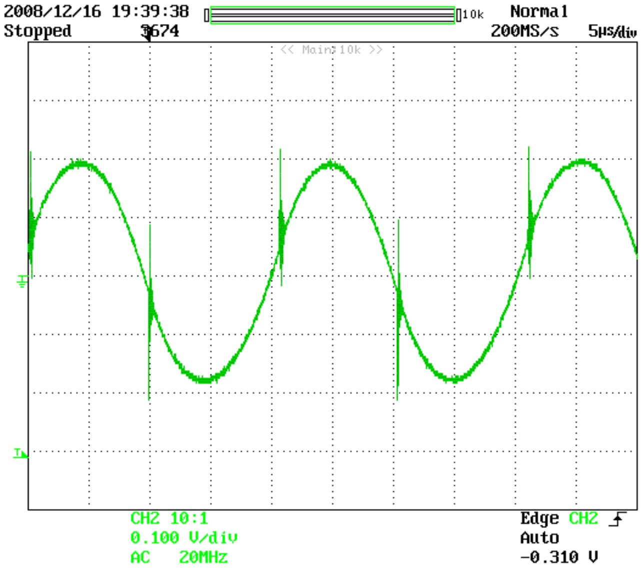

Fig. 4
Detailed view of the steady state output voltage in the hands-on laboratory for a 6Ω load (using a PWM frequency of 50kHz).

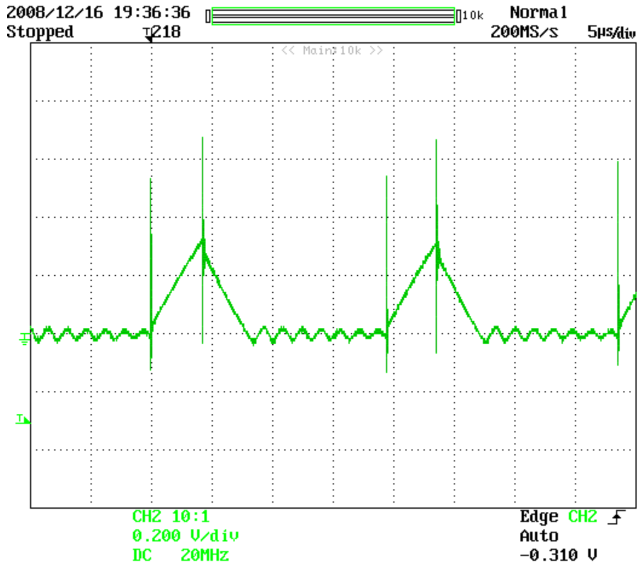

Fig. 5
Detailed view of the steady state inductor current with load of 100Ω (using a PWM frequency of 50kHz and a sensor gain of $1\frac{V}{A}$).

power source and measurement instruments used during the experimental sessions while slide switches allow reconfiguring the board according to the different experiments which must be performed. Figure 3 shows a picture of the upper and lower view of the board. This board has been proven to be a robust and efficient environment to develop power electronics introductory practical experiences. Although similar boards have been built in other institutions [11][26] [27], presented one contains an integrated and reconfigurable environment which allows to generate a comprehensive set of experiments, hence it can be used during all the course. The DC/DC step-down regulator has been designed to easily visualize most relevant phenomena with standard instrumentation available in a teaching laboratory. The board has been prepared to easily measure most relevant signals such as the Mosfet gate voltage, the input current, the inductor current, the output current, the output voltage and some of the signals managed by the control stage. In order to measure both the sensibility of the power converter in open-loop and the load and line regulation in closed-loop behavior the can be externally varied from 8 to 15 volts whereas the resistive load can be selected on board from the set 3, 4, 6, 12 and 100Ω.

B. Experiments

Hands-on sessions are attended at the laboratory and they are centered in the study of the Buck converter by using the board previously described. Students worked the following guidelines:

- Session 1: Introduction to the Buck converter.
  In this session, the students are introduced to the Buck converter implementation. They are asked to identify the

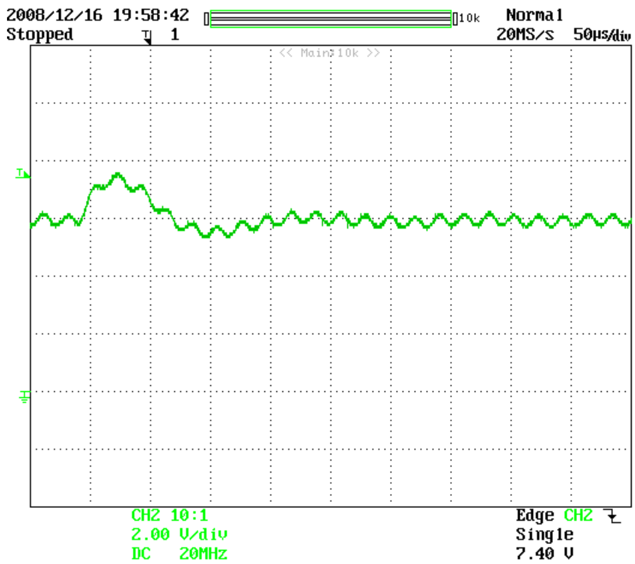

Fig. 6
Generic view of the output voltage when switching the load from 3Ω to 6Ω in the hands-on laboratory (using a PWM frequency of 50kHz).

board components and to relate them with the schematic circuitry. They configure the system in open loop by selecting the proper connection of slide switches. Under these conditions they are asked to display in the oscilloscope the most significant switching signals, namely the Mosfet gate voltage, the Mosfet source voltage and the cathode diode voltage. From these measures they can easily understand the fundamentals of switching and the principles of the power processing. Additionally, they can learn how the pulse with modulator works and how the driver manages the control signal to switch the power Mosfet.

- Session 2 : Study of Buck converter in steady-state open-loop behavior.
  During this second session the students are required to analyze the influence of the duty cycle over the output voltage in steady state behavior. They are asked to measure steady state waveforms such as the output voltage and current ripples (Figure 4 and Figure 5) in continuous and discontinuous conduction modes. Note that the discontinuous conduction mode can be easily obtained by fixing a resistive load of 100Ω. In addition the influence of the resistor load and voltage source variations are analyzed and the power converter sensibility function is characterized. The results are compared with the theoretical ones which have been previously calculated.
- Session 3 : Closed-loop converter dynamics.
  In this session the students are asked to identify the control system components and analyze the effect of uncertainty in the closed-loop behavior (load resistor or voltage source variations). The load and line regulations are measured in order to test the regulator performance. Finally, students measure with the oscilloscope the output voltage transient response when the converter suffers sudden load changes (see Figure 6) and validate the controller design.

IV. Virtual Laboratory

A. Development Tool: Easy Java Simulations

When beginning a new software project it is important to choose the most appropriate tool to develop it. Usually VL are developed by academics with few time, few economic resources and limited programming skills. In addition the development of virtual laboratory is a dynamic affair because it must be constantly maintained and updated in order to fit the teaching needs and platform changes.

Easy Java Simulations (EJS) [24][25] is a free and open-source interactive tool developed to build VL in a very simple and straightforward manner. In order to code VL, EJS uses a model-view-control paradigm, in other words, the VL laboratory is decomposed in three almost independents parts:

1) Model: Variables and relations between these variables. This includes the differential and algebraic equations describing the physics behind the system. EJS contains several numerical integrators and event detectors allowing to simulate any type of system including nonlinear or hybrid[1] ones.
2) View: The view corresponds to the virtual laboratory outputs. These outputs are constituted by different windows which contain generic graphics and representations of the systems. These representations can be in a realistic or schematic form. EJS provides direct methods to plot variables or constructed 3D or 2D scenes in a structured and hierarchical form. All these outputs are continuously updated according to the model evolution.
3) Control: This part contains the actions that a user can perform on the simulation. A complete Graphical User Interface (GUI) can be constructed easily. A part from traditional actions like *start*, *stop* and *reset*; the control part allows to introduce interactivity. Any action over the view or the model can be introduced so that the user can easily interact with the simulation.

This decomposition allows simplifying the application design and maintenance once it is ready. All three parts can be developed at high level without writing a single line of code[2]. Although designed and analyzed separately, these three parts are deeply interconnected during execution.

Once the VL high level description has been provided, EJS takes care of all the low-level procedures needed to construct the final application. EJS translates into JAVA code all the definitions and specifications previously introduced. This JAVA code can be distributed as independent programs running in any platforms or can be integrated in a HTML page running as applets. In addition to VL description it is possible to integrate HTML pages which contain the VL description, the instructions needed to run practical experiences in the VL or the concrete exercises to be done. Once the VL has been build, it can be used to generate movies which can be easily integrated in multimedia material. According to previously described characteristics, EJS has been considered an ideal tool to develop our VL.

B. Virtual Laboratory Development

The VL has been designed to support in a comprehensive manner all the concepts used in the course and to reproduce as much as possible the hands-on laboratory (section III). As consequence, the main window reproduces the converter circuit implemented. This view offers three main possibilities: schematic, logical and the averaged model one. As an example, Figure 7 offers the schematic logic circuit for the Buck converter, Figure 8 offers the averaged logic view of the Boost converter while Figure 15 offers the schematic circuit of a magnetically coupled converter[28]. These different display modes can be used in different steps of the learning process.

Power converters are devices combining continuous elements (resistors, capacitors and inductors) and semiconductor devices acting as switches (diodes and transistors), as a consequence they can be seen as hybrid systems, i.e. the power converter can be seen as set of linear models and a selector determining the concrete set of equations in each time instants. These types of models provide a very accurate description of the power

[1] systems defined by several ODES and transitions between them

[2] When needed JAVA code can be inserted in the system

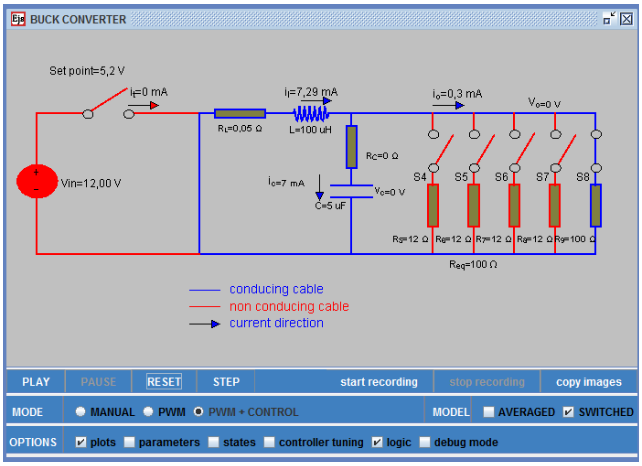

Fig. 7
BUCK CONVERTER VIRTUAL LABORATORY MAIN WINDOW (SWITCHED-LOGIC DISPLAY MODE).

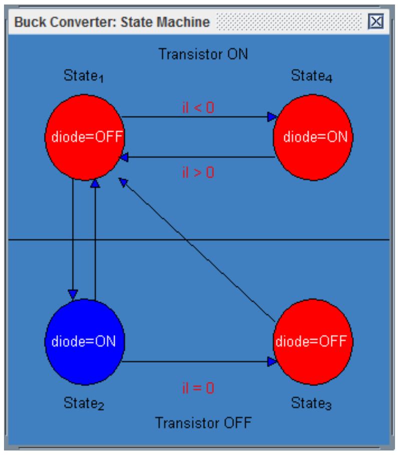

Fig. 9
BUCK CONVERTER VIRTUAL LABORATORY STATE MACHINE DIAGRAM WINDOW.

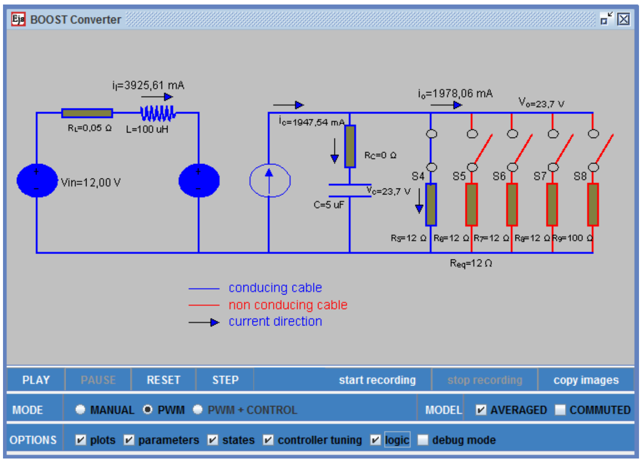

Fig. 8
BOOST CONVERTER VIRTUAL LABORATORY MAIN WINDOW (AVERAGED-LOGIC DISPLAY MODE).

converter behavior, and are usually named switched models. Although these models are very convenient for simulation they are not for analysis or controller design, for this purposes averaged models are used; unfortunately averaged models do not take into account switching phenomena, so switching ripple is not taken into account and discontinuous modes cannot be analyzed through them.

Both types of models are used during the course and, as a consequence, both models have been integrated in the VL. The VL allows using the switched or the averaged model depending on the concrete experiment to be done; additionally both models can be worked simultaneously in order to compare their results.

Models can be introduced in EJS as a set Ordinary Differential Equations (ODE), a set of constrains between variables and events to be detected in order to switch between models. An alternative manner is using a algebraic manipulator like Maple to develop the concrete set of equations and automatically generate code which can be directly integrated in EJS. This second approach has been used during the VL development since this procedure is very straightforward and provides a simple methodology to develop, maintain and update the models describing the power converter behavior.

The VL main goal is to support the learning not to reproduce exactly the system behavior; according to this principle concepts and qualitative behavior are more important than quantitative results. As a consequence, semiconductor devices are modeled as ideal switches in order to preserve interactivity and maintain simulation time short.

EJS allows packaging all VL in one stand-alone application, this allow distributing all laboratories and documentation as a simple e-book. This capability has been used to distribute to the students the different VL and all documents used during the course in a homogenous environment.

C. *Virtual Laboratory Functionalities*

In order to simplify its usage all VL offer the same GUI, see as an example the Buck and Boost converter main windows in Figure 7 and Figure 8, respectively. As it can seen the applications contain an animated scheme of the concrete converter where all converter parameters can be interactively changed.

The VL offers three main working modes:

- MANUAL mode: In this mode the PC transistor is operated by the user. The user can turn off and on this element by clicking with the mouse over it. This operation mode has been designed to introduce the user in the commutation switched behavior and the main concepts related with the converter dynamics. In the Buck converter VL, this mode can be used to describe the generation of a certain average value by combining

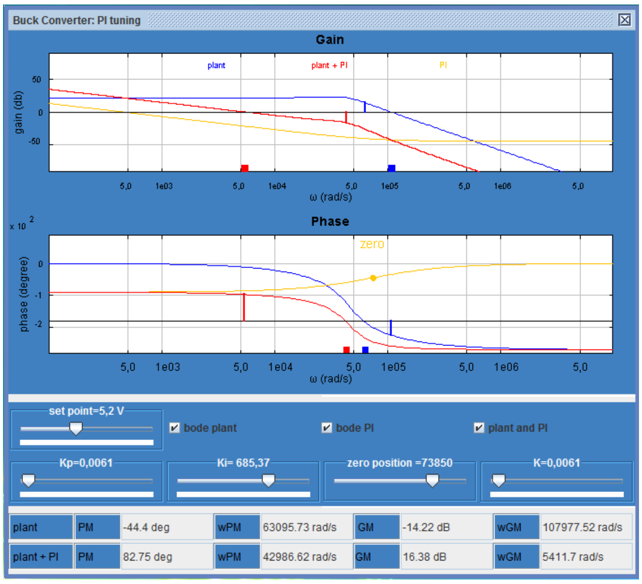

Fig. 10
BUCK CONVERTER VIRTUAL LABORATORY PI CONTROLLER TUNING WINDOW.

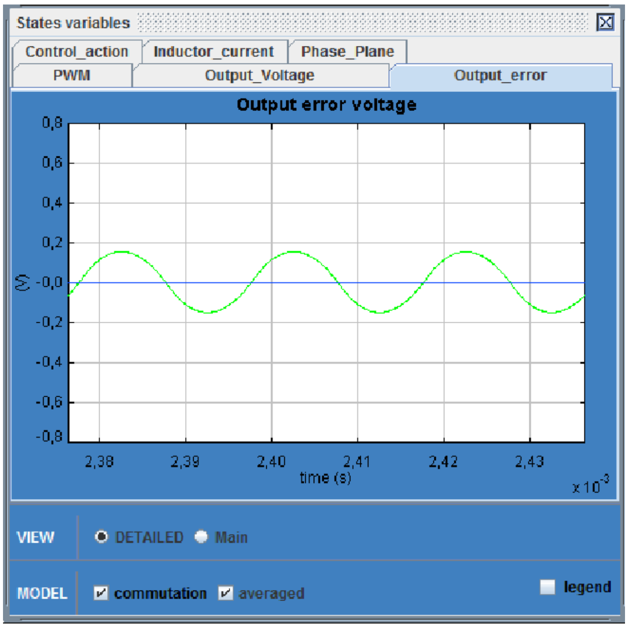

Fig. 11
DETAILED VIEW OF THE STEADY STATE ERROR EVOLUTION IN THE VL FOR A 6Ω LOAD AND THE NOMINAL PARAMETERS FROM THE HANDS-ON LABORATORY (USING A PWM FREQUENCY OF 50kHz).

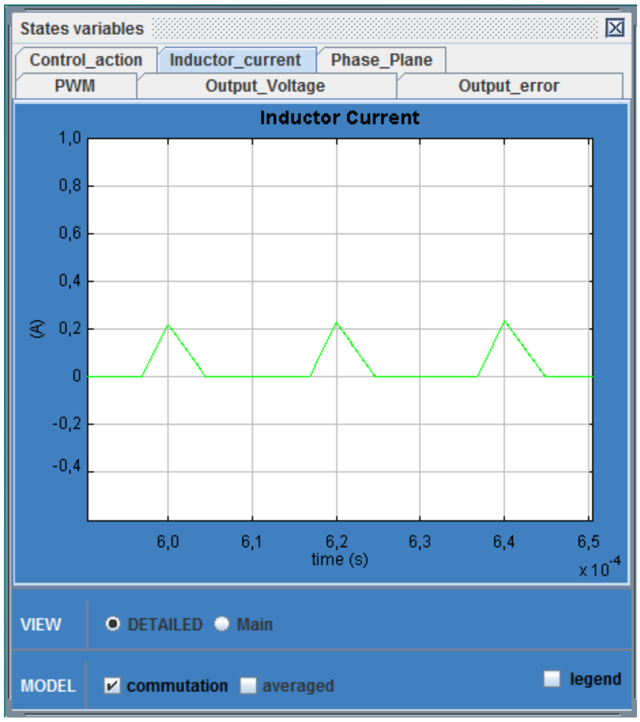

Fig. 12
DETAILED VIEW OF THE STEADY STATE INDUCTOR CURRENT IN THE VL WITH LOAD OF 100Ω AND THE NOMINAL PARAMETERS FROM THE HANDS-ON LABORATORY (USING A PWM FREQUENCY OF 50kHz).

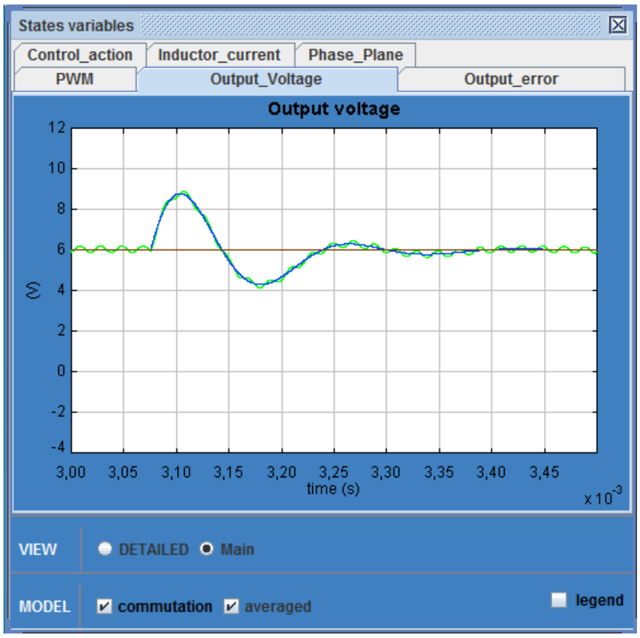

Fig. 13
GENERIC VIEW OF THE CLOSED-LOOP TRANSIENT RESPONSE OF THE OUTPUT VOLTAGE IN THE VL WHEN SWITCHING THE LOAD FROM 6Ω TO 3Ω AND THE NOMINAL PARAMETERS FROM THE HANDS-ON LABORATORY (USING A PWM FREQUENCY OF 50kHz).

only two voltage levels. Differently, when used with the Boost converter, this mode illustrates the amplification by making the circuit live in transient behavior.

- PWM mode: In this mode the PC transistor is operated by a Pulse Width Modulator (PWM) driven by a constant configurable duty cycle. This mode allows studying the open-loop converter transient and the steady state behavior. In addition the influence of most relevant parameters like inductors, capacitance and load can be analyzed. It is also possible to compare the averaged and the switched model by comparing the output of both models under the same circumstances.
- PWM mode + control: In this mode PC transistor is operator by a Pulse Width Modulator (PWM) driven by a controller with a constant reference value. This mode is useful to study the closed-loop behavior of the converter. The parametric control design, the effect of changing loads or parametric uncertainty can be addressed. The benefits of closed-loop control system can be illustrated and the need of this element can be justified.

The evolution of each relevant variable (currents and voltages) can be seen instantaneously over the schematic shown in the main window (similarly as it is done in the hands-on laboratory by using the multimeter). In order to improve the temporal analysis all these relevant variables are displayed in different plots (similar to oscilloscope screens) or can be stored in text files which can be loaded in most popular software applications. In all these plots the averaged output or the switched model output can be displayed (also a combined view can be used), in all these cases a detailed view (few PWM cycles) or a generic view can be selected.
The VL offers the following complementary windows:

- Parameters window: this window allows changing all the converter parameters using sliders and text fields.
- States: this window contains a state machine representation corresponding to system configuration; states determine the circuit topology and the edges correspond to possible transitions between them. Active state is shown in red while the rest is shown in blue (Figure 9 shows the Buck state machine). When a configuration change is detected, the corresponding edge is shown in red while the rest are shown in blue. This window allows studying all possible states in the converter and the used ones in certain circumstances (discontinuous modes can be easily detected with this tool).
- Controller tuning: this tool has been designed to interactively design the PI controller integrated in the hands-on laboratory and the VL (see Figure 10). This window displays the converter frequency response and the combined controller+converter frequency response. All these frequency responses are automatically updated when a certain parameter is changed and gain and phase margins are automatically computed are displayed over the frequency response.

As a conclusion, the developed VL offers a comprehensive environment where most relevant activities in the learning process can take place. Although used models are simple, the VL results are quite similar to the ones obtained in the hands on laboratory; for illustrating purposes, Figure 11 and Figure 4 correspond to the steady state voltage evolution under closed-loop for the virtual laboratory and the hands-on laboratory, respectively; Figure 5 and Figure 12 correspond to the inductor current evolution in discontinuous mode in VL and hands-on laboratory respectively; similarly, Figure 13 and Figure 6 correspond to a load change transient response for the virtual laboratory and the hands-on laboratory respectively. As it can be seen although slightly differences exist the VL and the hands-on laboratory behavior are qualitatively equal so experience obtained in the VL can be easily extrapolated to the real one.

V. THE VL IN THE LEARNING PROCESS

VL constitute helpful tools in a Power Electronic Introduction course. Among others, in our course the VL is used in the following scenarios:

- Theoretical concepts.
  - During lectures.
    Switching between different topologies is one of the most difficult concepts introduced in a power electronics introductory course; although this might seem very abstract when drawn in the blackboard it may look simpler when reproduced in the VL. Allowing the students to interact with the VL during the theoretical explanation allows them to get introduced in these concepts.
    Apart from these conceptual facts the VL laboratory can also be very helpful to illustrate parameter dependency when introducing open-loop converter dynamics and steady-state behavior.
    Also, the need of a control system naturally emerges when using the VL. Developed VL contains an integrated interactive environment to tune the user controller. This tool is also used to justify the concrete controller topology and to show its limitations.
  - Students work
    Although analytical computations are quite important in power electronics, to be able to correctly apply them it is convenient to understand the system behavior, i.e. they must create they own a mental model of the system under study. VL can be very useful in this creation process. As an example, the manual mode introduced in the VL is of great relevance when studying the concepts behind the switching concepts. Although playing with VL can help the students to discover phenomena and hidden dependences it may be time consuming. In order to reduce this time while improving the learning process a set of assessments have been designed to guide the VL use (Figure 14 shows the concrete assignments for the buck and boost converters). These assessments are introduced between lectures as the course goes on.
- The VL and the hands-on laboratory.
  - Once the VL assignment have been completed students can initiate laboratory sessions with a very

1) Buck Converter.
   a) Concepts and principles
      Using the Buck converter VL manual mode drive manually the output voltage to a certain level by turning on and off the transistor state.
   b) Steady State analysis
      Using the Buck converter VL PWM mode study the steady state relation between the duty cycle and output voltage. Study The effect of parameter variations over the output voltage. Study the output voltage ripple characteristics. Identify the discontinuous conduction modes characteristics.
   c) Averaged model
      Using the Buck converter VL PWM mode compare the averaged and the switched model. Study both the transient and the steady state transient response in both models. Force the converter to work in discontinuous mode and compare both models.
   d) Closed-loop analysis
      Using the Buck converter VL PWM+control mode analyze closed-loop dynamic response. Tune the controller to obtain a certain gain and phase margins.
2) Boost Converter.
   a) Concept and principles
      Using the Boost converter VL manual mode boost the voltage level and drive manually the output voltage to a certain level by turning in and off the transistor state.
   b) Steady State analysis
      Using the Boost converter VL PWM mode study the steady state relation between the duty cycle and output voltage. The effect of parameter variations over the output voltage. Study the output voltage ripple characterization. Identify discontinuous conduction modes characteristics.
   c) Averaged model
      Using the Boost converter VL PWM mode compare the averaged and the switched model. Study noth the transient and the steady state transient response in both models. Force the converter to work in discontinuous mode and compare both models.
   d) Closed-loop analysis
      Using the Boost converter VL PWM+control mode analyze closed-loop dynamic response. Tune the controller to obtain a certain gain and phase margins.

Fig. 14
ASSIGNMENTS TO BE DONE USING THE VIRTUAL LABORATORY.

nice understanding level, so they can accomplish the requirements quite easily. Technological elements can be introduced in the laboratory sessions due to the fact that main concepts are well understood. Students can reproduce the experimental setup in VL and analyze the characteristic waveforms before they obtain them in the hands-on laboratory prototype. As a consequence, students can focus their study in the new non-modeled behavior that appears in the measured waveforms and analyze the difference between a signal coming from a simulation and a signal from a measurement process.

– VL can also be used to analyze and design other power converters, such as Boost converter. Following the assignments shown in Figure 12, students can design the proper converter parameters and select the semiconductor devices in order to meet given desired steady state requirements and can also design the controller parameters to accomplish both regulation and dynamical specifications. VL can constitute an ideal platform to test and validate the proposed design previously to its hardware implementation and its later experimental verification.

VI. CONCLUSIONS AND FUTURE WORKS

In this work the development of a Virtual Laboratory, its integration in the learning process and its combined use with traditional laboratories in a *power electronics introduction* course has been described.

Presented VL have been built using EJS and automatic code generation with Maple. EJS allows one to design attractive

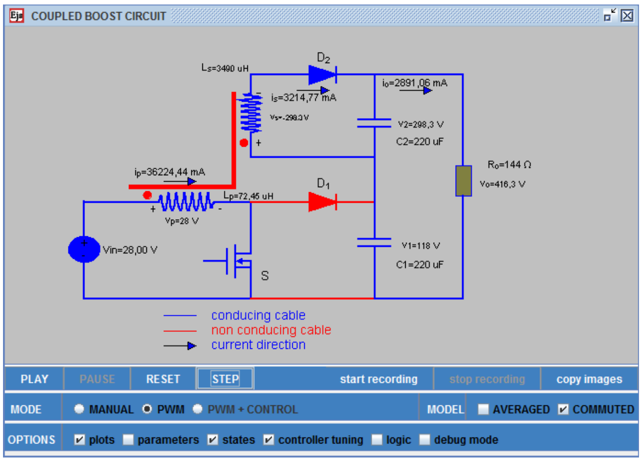

Fig. 15

MAGNETICALLY COUPLED BOOST CONVERTER[28] VIRTUAL LABORATORY MAIN WINDOW (SWITCHED-CIRCUIT DISPLAY MODE).

and interactive views while Maple allows simplifying model construction. This combination is quite suitable for VL development and allows easily maintaining and updating the VL which fits professors' needs.

Developed VL can be used along the complete course due to its comprehensive capabilities; conceptual behavior, open-loop analysis, averaged and switched models, closed-loop behavior and control design are integrated in the VL. So the same environment can be used during the complete learning process. VL laboratories are designed to reproduce the hands-on laboratory so they can be used as a support in pre and post hands-on laboratory sessions, also a set of assessments to done in the VL are given to students. These assessments play a key role in the ECTS framework.

Experience and students' opinion show that proposed VL are very useful to help the student to build their mental model of the behavior of Power Converters. This mental model is based on the combined observation in the hands-on and VL of the power converters under different situations.

It is important to state that develop VL have not been thought to replace hands-on laboratories (composed by instruments, physical connections, commercial components) its main goal is to improve the learning process especially in those aspects related with constructing the students mental model and the relationship between averaged and switched models. In our opinion hands-on laboratory are key component of engineering course especially in introductory technological courses like our power electronics introduction course.

Actually, presented VL cover basic and some advanced[3] DC/DC converters. Currently, AC/DC and DC/AC elements are being developed.

ACKNOWLEDGEMENTS

This work were partially supported by the Spanish government (DPI2007-62582), and the AGAUR (2007MQD00046) projects.

[3]Figure 15 shows the VL main window of a coupled-inductor DC-DC[28].

REFERENCES

[1] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Wiley, 2002.

[2] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*, 2nd ed. Springer, 2001.

[3] P. T. Krein, *Elements of Power Electronics*, ser. Oxford Series in Electrical and Computer Engineering. Oxford University Press, USA, 1997.

[4] S. Dormido, S. Dormido, R. Dormido, J. Sánchez, and N. Duro, "The role of interactivity in control learning," *International Journal of Engineering Education*, vol. 21, no. 6, pp. 1122–1133, 2005.

[5] J. Sánchez, S. Dormido, and F. Esquembre, "The learning of control concepts using interactive tools," *Computer Applications in Engineering Education*, vol. 13, no. 1, pp. 84–98, 2004.

[6] S. Dormido, "Control learning: present and future," *Annual Reviews in Control*, vol. 28, pp. 115–136, 2004.

[7] L. Healy and C. Hoyles, "Software tools for geometrical problem solving: Potentials and pitfalls," *International Journal of Computers for Mathematical Learning*, vol. 6, no. 3, pp. 235–256, January 2002.

[8] F. Esquembre, "Computers in physics education," *Computer Physics Communications*, vol. 147, no. 1-2, pp. 13–18, 2002.

[9] B. Woodfield, H. Catlin, G. Waddoups, M. Moore, R. Swan, R. Allen, and G. Bodily, "The virtual chemlab project: A realistic and sophisticated simulation of inorganic qualitative analysis," *Journal of Chemical Education*, vol. 81, no. 11, pp. 1672–1679, 2004.

[10] F. A. C. Herías and J. S. Moreno, "Recursos didácticos basados en internet para al apoyo a la enseñanza de materias del área de ingeniería de sistemas y automática," *Revista Iberoamericana de Automática e Informática Industrial*, vol. 2, no. 2, pp. 93–101, April 2005.

[11] W. G. Hurley and C. K. Lee, "Development, implementation, and assessment of a web-based power electronics laboratory," *IEEE Transactions on Education*, vol. 48, no. 4, pp. 567–573, November 2005.

[12] V. Fedák and P. Bauer, "E-learning in education of electrical drives and power electronics: Opportunities and challenges," in *International Conference on Electrical Drives and Power Electronics*, Dubrovnik, CROATIA, September 2005.

[13] H. J, H. Funato, S. Ogasawara, O. Dranga, and C. Tse, "Multimedia based e-learning tools for dynamic modeling of dc-dc converters," in *IEEE International Conference on Industrial Technology, 2005. ICIT 2005.*, December 14-17 2005, pp. 17– 22.

[14] J. Marcos, C. Quintans, A. Nogueiras, J. Doval, A. Lago, and C. Martinez-Peftalver, "E-learning system for power electronics converters," in *37th IEEE Power Electronics Specialists Conference. PESC '06.*, June 2006, pp. 1– 6.

[15] U. Drofenik and J. Kolar, "Interactive power electronics seminar (ipes)-a web-based introductory power electronics course employing java-applets," in *IEEE 33rd Annual Power Electronics Specialists Conference, 2002. PESC'02*, vol. 2, 2002, pp. 443– 448.

[16] C. D. Vournas, E. G. Potamianakis, C. Moors, and T. V. Cutsem, "An educational simulation tool for power system control and stability," *IEEE Transactions On Power Systems*, vol. 19, no. 1, pp. 48–55, FEBRUARY 2004.

[17] S.-C. Wang and Y.-H. Liu, "Software-reconfigurable e-learning platform for power electronics courses," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2416–2424, June 2008.

[18] K. Cheng, C. Chan, N. Cheung, and D. Sutanto, "Virtual laboratory development for teaching power electronics," in *IEEE 33rd Annual Power Electronics Specialists Conference, 2002. PESC'02.*, vol. 2, 2002, pp. 461– 466.

[19] B. Kamiski and D. Sobczuk, "Distant learning of pulse width modulation techniques for voltage source converters," in *13th Power Electronics and Motion Control Conference. EPE-PEMC 2008.*, September 2008, pp. 2378–2382.

[20] Y. Ouyang, D. YABO, Z. MIAOLIANG, H. YUEWEI, M. SONG, and M. YUNJIE, "Ecvlab : A web-based virtual laboratory system for electronic circuit simulation," *Lecture notes in computer science. ISSN 0302-9743*, vol. 3516, pp. 1027–1034, 2005.

[21] L. Vanfretti, "A comprehensive virtual laboratory for teaching power system dynamics and control at undergraduate level," Electrical, Computer, and Systems Engineering Department at Rensselaer Polytechnic Institute, Troy, NY;, Tech. Rep., http://www.rpi.edu/∼evanfrl/pdfs/t1.pdf.

[22] V. F. Pires and J. F. A. Silva, "Teaching nonlinear modeling, simulation, and control of electronic power converters using matlab/simulink," *IEEE Transactions on Education, VOL. 45, NO. 3, AUGUST 2002*, vol. 45, no. 3, pp. 253–261, august 2002.

[23] J. M. Jiménez-Martínez, F. Soto, E. de Jódar, J. A. Villarejo, and J. Roca-Dorda, "A new approach for teaching power electronics converter experiments," *IEEE Transactions on Education*, vol. 48, no. 3, AUGUST 2005.

[24] F. Esquembre, "Easy java simulations: a software tool to create scientific simulations in java," *Computer Physics Communications*, vol. 156, no. 2, pp. 199–204, January 2004.

[25] ——, *Creacion de simulaciones interactivas en Java*. Pearson Educación - Prentice Hall, 2005.

[26] S. A. Shirsavar, "Teaching practical design of switch-mode power supplies," *IEEE Transactions on Education*, vol. 47, no. 4, pp. 467–473, NOVEMBER 2004.

[27] S. S. Ang, "A practice-oriented course in switching converters," *IEEE Transactions on Education*, vol. 39, no. 1, pp. 14–18, FEBRUARY 1996.

[28] Q. Zhao and F. C. Lee, "High performance coupled-inductor dc-dc converters," in *Proceedings of Applied Power Electronics Conference and Exposition, 2003. APEC '03. Eighteenth Annual IEEE*, vol. 1, 2003, pp. 109– 113.