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Learning Energy Storage in Hybrid/Electric Vehicles

Erasmus Mundus Master Course in Sustainable Transportation & Electrical Power Systems

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***Abstract*— The "Erasmus Mundus Master Course in Sustainable Transportation & Electrical Power Systems" is supported by three universities, located in Spain, Italy and United Kingdom, and a Polytechnic Institute in Portugal. One of the main goals is the training of qualified staff in areas related to electrical energy management, emphasizing in power systems for electric propulsion vehicles and renewable energies. Among others, the subject "Energy Storage and Recovery in Power Systems and Hybrid/Electric Vehicles" is considered a keystone in the Master. During third semester, the students who follow the technical track, have to develop small projects and tasks related to electric vehicles, battery management, power stages for battery charger and so on. This paper show the goals and the results obtained in these topics. All of these topics are partially collected in one subject, with a high practical content. The students have to learn not only the theoretical topics, but they have to elaborate a project, in a work team and use modern laboratory equipment as well. It should be noted that the students have to work and collaborate in a multicultural environment, with students and professors. This paper describes the subject methodology, and the results obtained.**

Keywords —Electric vehicles, batteries, power topologies, supercapacitors, flywheels, EMI, energy storage, standardization, education.

I. INTRODUCTION

The main goal of the "Erasmus Mundus Master Course in Sustainable Transportation & Electrical Power Systems", EMMC STEPS [1], is the training of qualified staff in areas related to electrical energy management, emphasizing power systems for electric vehicles and renewable energies. The Master presents a double approach: scientific and professional. In the scientific thread, training focuses on the design of two main applications: Electrical Power Systems; and Electrical and Hybrid Traction Systems. On the other hand, in the professional thread, training is focused on the management of electrical energy. Thus, the subjects of this thread have been designed attending to two main issues, which are the management of energy in large consumers and the generation and transmission of electrical energy in a liberalized market.

Three main lines have been considered as keystones in the Master:

- Electrical Power Systems
- Electrical and Hybrid Vehicles
- Energy Efficiency and Renewable Energies

The above mentioned lines are among those areas of knowledge identified by the ANEP (Spanish Governmental Agency for Evaluation and Prospective Tasks) as strategic sectors in the Spanish National Program of Projects of Fundamental Investigation. In particular, the tasks and skills gained by one student after completing the Master are directly related to one of the following topics:

- Environment and Innovation in Ecosystems.
- Energy.
- Transport and Infrastructures.
- Industrial Sectors.

The EMMC STEPS is promoted by a partnership led by the University of Oviedo (ES), together with the University of Nottingham (UK), the University of Rome (IT) and the Polytechnic Institute of Coimbra (PT). Prestigious international universities, as the University of Wisconsin-Madison and the University of Illinois (USA), the University of Santa Maria (BR) and the University of Yeungnam (KOR), and 16 global leading companies in energy and transportation sectors are associated members [1]. Companies offer internships, and some senior staff contribute to teaching courses.

II. THIRD SEMESTER: ENERGY STORAGE

During the first year, the students have been studying and preparing basic concepts, such as Digital Signal Controllers (DSC), CAD software, simulation software, and more advanced topics [1]; bearing in mind this knowledge, they are ready to get topics that require another skills, as an assertive & proactive attitude, teamwork abilities as well as to handle complex laboratory equipment, such as impedance analyzer, complex oscilloscopes, programmable loads and an Anechoic Room, among others. In order to do that, the subject called "Energy Storage and Recovery in Power Systems and Hybrid/Electric Vehicles", for the Sustainable Transportation branch, constitutes a good way to practice the aforementioned topics.

This subject is supervised by professors who are specialists in the different topics and from three different countries: Spain, Portugal and United Kingdom. In this way, high academic standards are obtained, and the students take advantage of different specialists in different areas. This subject is coordinated by professor Juan Diaz and comprises the fields developed in the next paragraphs.

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It should also be pointed out that this subject is also given together to the students of the "local" University of Oviedo Master's in Electrical Energy Conversion and Power Systems.

A. Batteries used in EV. Standard tests and Test rigs

During the Master, basic concepts about storage systems are supplied. One of the components most important to store energy in vehicle applications are batteries. Although the time restrictions in the course are important, the information regarding batteries is focused on the following tasks:

a) Types of batteries.
b) Chemical reactions in several galvanic cells.
c) Elements of a battery cell.
c) Voltaic cell potentials and the parameters that can affect it.
d) Charge/discharge process (efficiency, State of Charge, State of Health, etc.).
e) Electric model of a battery.
f) Fast charging methods.
g) Applications.

Once the students have the theoretical information, they have to apply the knowledge gained designing their own battery cell. To increase the motivation, this task is proposed as a competition where the award is an increase (up 20%) of the final mark in this subject. This activity is included in the lab sessions and aims to improve design capabilities. The selection of materials to obtain a high voltaic cell potential or how to reduce the series resistance are two of the main features to be taken into account.

After the battery is designed and built (Fig. 1), the redox reactions and the electrical model [2][3] of the battery should be addressed in the final report. Using the battery prototype the evolution of input voltage and charging current can be measured during a current step. This information is used to obtain all parameters required to define the electrical model (Fig. 2). Finally some simulations should be carried out to compare the actual behavior with the model obtained. The battery design with better characteristics: higher storage energy, higher parallel resistance and lower series resistance will be presented in class.

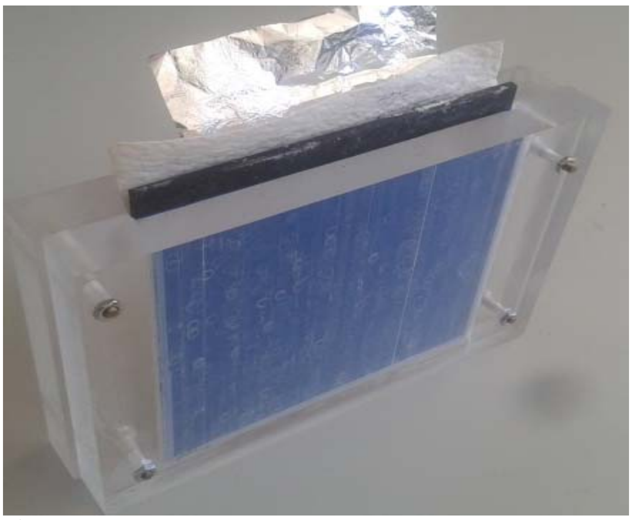

Fig.1. Battery prototype.

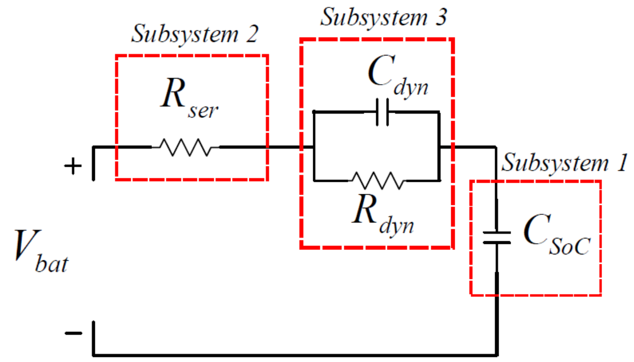

Fig. 2. Battery Electrical model.

At a more technical level, examples of setting up and testing a battery system for an electric vehicle [4] are given as can be seen on Fig. 3.

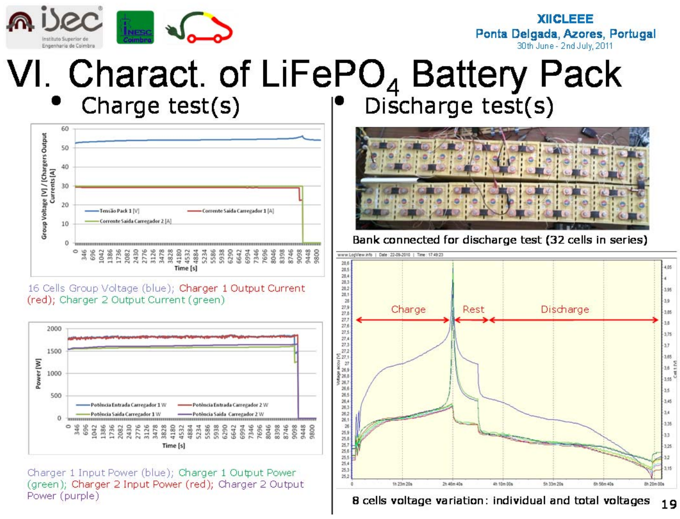

Fig. 3. Characterization of a LiFePO4 battery pack and charger [4].

This allows the students to gain further insight on some implementation, monitoring and battery control details as well as taking contact with some commercially available devices and its evaluation and setting up. Some of the authors' experience on conversion and development of a small electric vehicle ("Projeto VEIL"), with simulation and road tests vehicle and battery monitoring [5]-[7], is also presented, like in Fig. 4 and Fig. 5.

A more advanced topic, some research on multiple energy storage systems management optimization for electric vehicles (MESMO-EV project [8]-[10]), is also introduced as in Fig. 6.

The framework for standardization on electric vehicles, especially regarding International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO), and its technical committees (TC) IEC TC69 – *Electric road vehicles and electric industrial trucks*, and ISO/TC22 – *Road Vehicles* (in particular of ISO TC22/SC21 – *Electrically propelled road vehicles*, replaced in 2015 by the new ISO/TC 22/SC 37 - *Electrically Propelled Vehicles*), is also delivered on a compact form [11]. The students have an assignment on this topic to realize the intense activity going-on on this fundamental field for electric mobility, which currently is on: conductive charging systems, wireless power transfer, electric double-layer capacitors for HEV, conductive power supply system for Light EVs, EVs battery swap systems, V2G communication interface, and safety and test specifications for lithium-ion traction battery packs and systems [12].

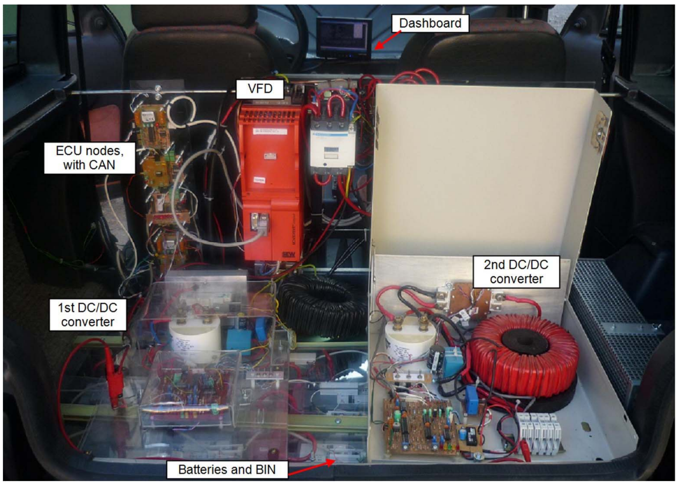

Fig. 4. Electric vehicle VEIL project: DC/DC converters, VFD, batteries banks with battery monitoring system, ECU nodes, touch screen dashboard [7].

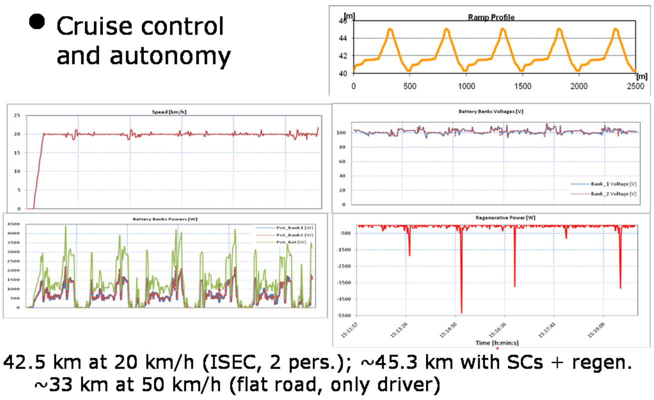

Fig. 5. Some VEIL project road tests results [7].

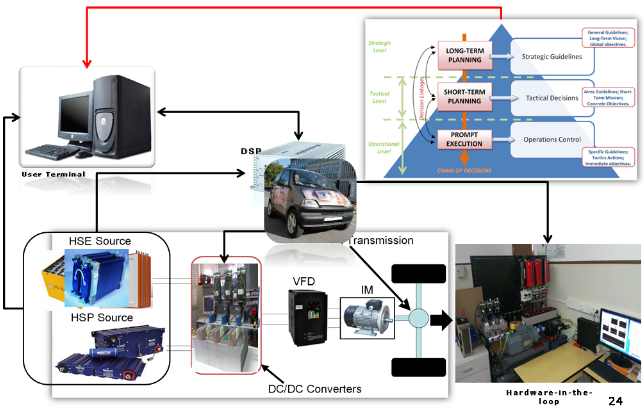

Fig. 6. MESMO-EV project overview.

The professors who lead this part are Alberto Martín, from University of Oviedo, and Paulo Pereirinha, from Polytechnic of Coimbra.

B. Hydrogen

Hydrogen (H_2) is a fuel that can be used as an alternative to electricity for environmentally-friendly vehicles. In contrast to batteries, H_2 has a higher energy per kg than conventional oil-based fuels, yet enables refueling in a similar time. The only tailpipe emissions are water. Within the vehicle, the hydrogen is used to power a fuel cell, which is compact and produces electrical power for the motor(s) while also providing heat for passenger comfort.

This part of the course covers the characteristics of the fuel cell (cf. Fig. 7), and its integration within the electric vehicle power system. The equivalent circuit is quite similar to the battery one, but note that at low currents there is an activation loss represented by R_a, whereas in the mid-range, the voltage gradient is dominated by the ohmic loss, R_o. It becomes clear how the fuel cell efficiency will reduce with increasing current.

This part also looks at the infrastructure required for hydrogen production and delivery; in-vehicle storage systems, performance and safety. Finally, using their knowledge of the individual components, the students are able to suggest appropriate conversion efficiencies, which can be fed into a spreadsheet in class (Fig. 8). A useful comparison can be made showing the advantage of Battery-powered electric vehicles in this respect.

The students are given an assessed task to compare the overall efficiency and carbon emissions from different alternatively-fueled vehicles. This involves some of their own research to find data which takes into account current state of technology of the various options.

Professor Arthur Williams (Nottingham University) is responsible for this topic.

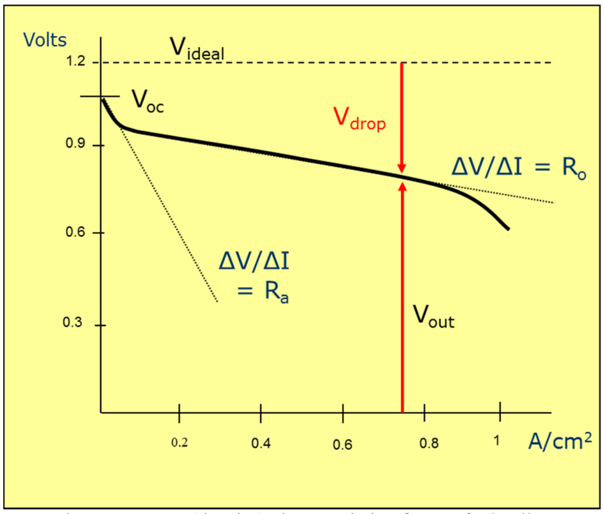

Fig. 7. Voltage - current (density) characteristic of PEM fuel cell.

		Battery Vehicle (Electricity from CCGT plant)								
Electricity Production		Electricity Distribution		Battery Charging		Battery Efficiency		Drive Eff.		Overall Efficiency
58%	x	90%	x	92%	x	92%	x	91%	=	44%
		Fuel Cell Vehicle (Electrolyser)								
Electricity Production		Hydrogen Electrolysis		Hydrogen Distribution		Fuel Cell Efficiency		Drive Eff.		Overall Efficiency
58%	x	82%	x	90%	x	45%	x	91%	=	19%
		Petrol Vehicle								
Petrol Refining		Petrol Distribution				Engine Efficiency		Transmission Eff.		Overall Efficiency
92%	x	97%			x	18%	x	97%	=	16%
		Fuel Cell Vehicle (Gas Reformation)								
Gas Refining		Hydrogen Reformation		Hydrogen Distribution		Fuel Cell Efficiency		Drive Eff.		Overall Efficiency
95%	x	75%	x	90%	x	45%	x	91%	=	29%
		CNG Vehicle								
Gas Refining		Gas Compression				Engine Efficiency		Transmission Eff.		Overall Efficiency
95%	x	98%			x	20%	x	97%	=	18%

Fig. 8. Spreadsheet of System Efficiency comparison.

C. Capacitors & Supercapacitors.

Energy storage is one of the goals of this subject, and also recovering energy whenever it will be possible and feasible; the specific issues in recovery energy in braking systems (in Electrical Vehicles) are addressed in two parts of the subject, leaded by professors Juan Díaz and Juan Manuel Guerrero, from Spain. One part is devoted to capacitors and supercapacitors, while the other is related to flywheel storage systems.

During last years, the supercapacitors have evinced characteristics that make them a good alternative for batteries, in terms of energy storage and particularly on power density. The theory of supercaps is presented as well as the traditional capacitors. This topic also helps to introduce to the students using specific and complex laboratory equipment. In Fig. 9, an impedance-gain analyzer is shown; the students have to learn and use it intensively.

The students have to design a high-power converter, using real components. They are encouraged to characterize the reactive components in such a way that they can do the simulations as much as close to the real power topology as possible. The students present a theoretical design and simulation of a Serial Resonant Converter (SRC) using the first harmonic approach, the extended describing function, etc. [13], with components selected either in the lab (and in this case they have to obtain a valid model) or commercial; once again, they have to obtain a model using the parameters supplied by vendors; whatever the choice, they have to present the calculus and simulations using models for all the reactive elements, as much complex as they can, and with an life-expectancy for them, based on thermal analysis [14][15].

This part is linked with group work, in which they have to design a PRC for a battery charger, the complete power stage; to do it, the students count with theoretical analysis, as output voltage/power plots, and so on, using normalized parameters.

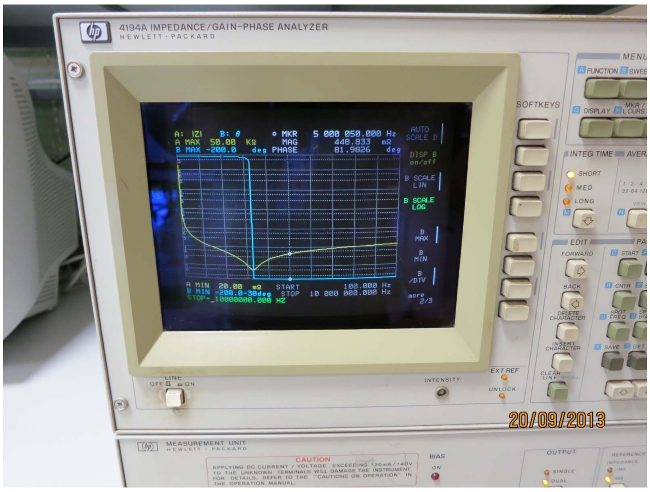

Fig. 9. Complex laboratory equipment used by the students (impedance-gain analyzer).

D. Flywheels & Regenerative Braking.

The flywheel concept has been used historically for power-smoothing. More recently it has been applied for energy storage applications. Both power systems and electric vehicles can be benefited from the use of flywheels.

In this part of the subject the students are exposed to the working principles of the flywheels, the critical subsystems, and the goal applications, especially in their areas of interest. The most recent advancements in this field are included in the course syllabus. The course specifically includes the following topics:

- Historical uses of flywheels.
- Flywheel components.
- Flywheel Energy Storage System (FESS) fundamentals.
- Characteristics of FESS.
- Comparison with other ESS.
- Applications.
- Commercial developments.
- HEV applications.
- Transmission, electrical machines, power electronics, control systems and bearings.
- Gyroscopic effects.
- Safety issues.

This part of the subject is imparted during 7.5 hours. Due to the safety issues inherent to the use of flywheels this section does not include a companion lab class.

A survey has been conducted during term 2015-2016 to learn the students' opinion about this part of the subject. The question was stated this way: "Taking into account the short time for this part of the subject, would you rather have devoted this 'flywheel' part to learn about some basic flywheel control using some simulation software package? What about active magnetic bearings? Any other related topic? Comment on that."

The question was answered by the 12 students in the subject:

- Three of them consider the subject is right as it is, especially due to the limited time for it.

- Seven consider it would be benefited with some simulation class including a basic system. Another one would focus the simulation in an HEV application. However, three students explicitly consider simulation are unnecessary.
- Three of them would increase the focus on the control of active magnetic bearings, although recognize the limited time for it.
- Three students see as necessary the inclusion of a lab class explaining the parts and behavior of the flywheel with an actual device.

Attending to the results of this survey efforts will be put in preparing a simulation including the main concepts related with flywheel operation. To make the inclusion of this new content possible, the commercial developments section of the actual syllabus will be shortened or removed. It is also planned to include some simulation class on control of active magnetic bearings in the future. However, at this point it is not clear what of the current sections must be sacrificed to allocate time. Although we own an actual flywheel in our labs, the wish of a hands-on class is not possible for the moment due to the aforementioned safety concerns. Besides, a descriptive class would imply to strip the flywheel system down which is impractical.

A written exam is the assessment method for this part of the subject. In general, all the students get at least a pass mark (> 5/10), and most of them a higher score (> 7/10).

E. Resonant Power Topologies: a Real 1 kW Battery Charger Project, to be Developed as a Group Work.

During this part of the subject, the students have to design, select the suitable components and built a full converter (in open loop) able to deliver 1 kW, being the input the mains and an output voltage of 48 Volts. The aim of this part of the subject is to develop a real project, in which the students have to manage delivery time for components, make a real planning of the tasks, and the most important part: they have to be able to identify and split the different tasks among them. The deadlines become in this way a reality that they have to bear in mind.

The students are encouraged to read technical papers presented in the different IEEE conferences, journals, in order to prepare their work. Doing so, the students assume that from these sources, they can obtain valid information, and they get used to do it regularly.

The different tasks identified are:

- Reactive elements calculation and characterization, in order to fulfill the given specifications. Also, the simulations using the models are required.
- Power semiconductor selection, as well as the needed circuitry for them: This includes driver design, snubbers if needed, and so on.
- Control circuitry, in such a way that duty cycle and frequency can be modified. The students are encouraged to use the well-known DSC TMS2833XX, since they have been working with it.
- Bus-bar, heatsinks calculations, assembly.
- Students' Coordination, lab tests including not only power tests, but EMI as well [16].
- Final report and class exposition.

Some of the results of the project are shown in Figs. 10, 11 and 12: the final power stage, with the control and driver circuit, in a singlePCB, based on POWER MOS transistors, is shown in Fig. 10. The EMI results for one prototype, obtained in the anechoic room are shown in Fig.11 where it can be seen that the corresponding emissions are below the CISPR 22A and 22B standard's limits. Finally, the current and voltage waveforms are shown in Fig. 12.

The professors responsible for this part are Alberto Martín Pernía and Juan Díaz.

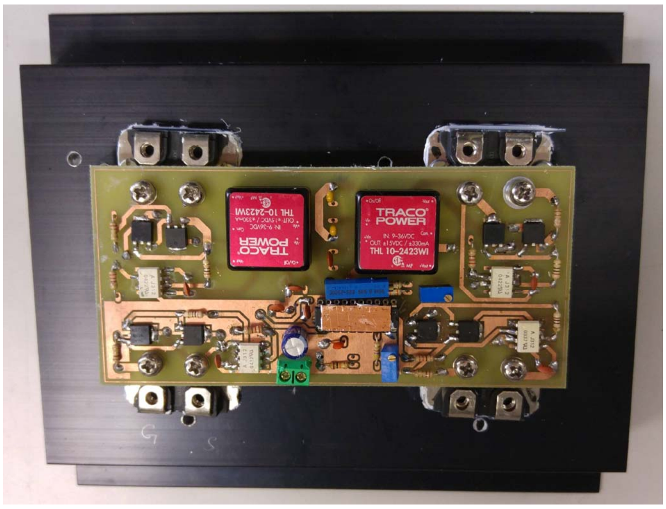

Fig. 10. Students power stage prototype.

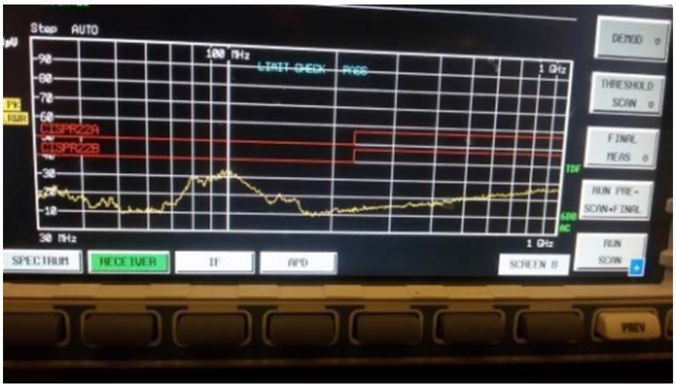

Fig. 11. EMI results obtained (below CISPR 22A and 22B standard's limits).

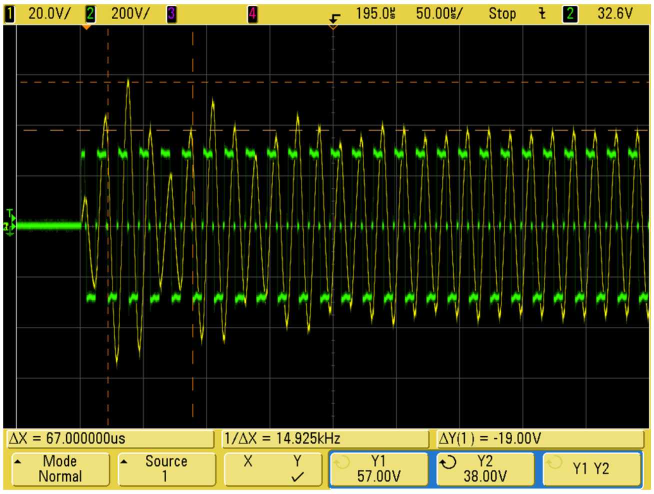

Fig. 12. Waveforms obtained with the students' prototype.

III. Conclusions

The teaching methodology used in the subject "Energy Storage and Recovery in Power Systems and Hybrid/Electric Vehicles" of the EMMC STEPS has evinced positive results, as far as motivation in the students is concerned.

The subject assessment consists on:

- Final formal written exam (Juan Manuel Guerrero): worth 1.7 points (over 10, the total grade).
- Battery prototype (A. Martin Pérnia): worth 0.85 points.
- EMI tests in anechoic room: (A. Martin, worth 0.85 points)
- Fuel Cell assignment (A. Williams): worth 1.7 points.
- Standardization assignment (P. Pereirinha): worth 1.7 points.
- Battery charger prototype (Juan Díaz), worth 1.6 points.
- Capacitors, and resonant converter design (Juan Diaz) worth 1.6 points.
- The final mark is finally agreed by all the professors.

Nowadays, after the Master Thesis, several students have continued developing their PhD in topics close to this subject: power topologies for EVs, control systems and so on. So the first conclusion is that the methodology used contributes to show an attractive offer for the PhD. On the other hand, the students have learned and got the abilities needed to work in technological environments, and which is the most important, to work in a group work.

On the other hand, a workbench for resonant converters has been built by students, in such a way that they can implement and test different control strategies, bus-bar techniques and so on; the surveys carried out evince that the students acquire more skills due to the work in the lab; it is necessary to keep in mind that is not only lab work, there is an important theory and research tasks for them as well.

As a general conclusion, this is a broad and quite interesting subject, benefiting from several professors' experiences and extensive lab work, besides an important theoretical component, clearly improving the students' competences on Energy Storage in Hybrid/Electric Vehicles.

References

[1] Erasmus Mundus Master Course in Sustainable Transportation and Electrical Power Systems, www.emmcsteps.eu/course .

[2] R. Kroeze and P. Krein, "Electrical battery model for use in dynamic electric vehicle simulations," in Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, June 2008, pp. 1336–1342.

[3] H. Zhang and M.-Y. Chow, "Comprehensive dynamic battery modelling for phev applications," in Power and Energy Society General Meeting, 2010 IEEE, July 2010, pp. 1–6.

[4] P. G. Pereirinha, A. Santiago, J. P. Trovão, "Preparation and Characterization of a Lithium Iron Phosphate Battery Bank for Electric Vehicle", 12th Portuguese-Spanish Conference on Electrical Engineering, XIICLEEE, Ponta Delgada, Portugal, June 30 –July 2, 2011.

[5] P. G. Pereirinha, J. Trovão, A. Marques, A. Campos, F. Santos, J. Silvestre, M. Silva, P. Tavares, "The Electric Vehicle VEIL Project: A Modular Platform for Research and Education", Proc. of the European Ele-Drive Transportation Conf. 2007, EET-2007, 30th May - 1st June 2007, Brussels, Belgium, in CD-ROM.

[6] P. G. Pereirinha, J. P. Trovão, "Comparative study of multiple energy sources utilization in a small electric vehicle", 3rd European Ele-Drive Transportation Conf. EET-2008 - Geneva, March 11-13, 2008.

[7] P. Pereirinha, J. Trovão, L. Marques, M. Silva, J. Silvestre, F. Santos, "Advances in the Electric Vehicle Project-VEIL Used as a Modular Platform for Research and Education", EVS-24, The 24th Int. Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition, Stavanger, Norway, May 13-16, 2009, in CD-ROM.

[8] J. P. Trovão, V. D. N. Santos, P. G. Pereirinha, H. M. Jorge, C. Henggeler Antunes, "A Simulated Annealing Approach for Optimal Power Source Management in a Small EV,"IEEE Transactions on Sustainable Energy, vol. 4, issue 4, pp. 867-876, October 2013 (http://dx.doi.org/10.1109/TSTE.2013.2253139).

[9] J. P. Trovão, P. G. Pereirinha, H. M. Jorge, C. Henggeler Antunes, "A multi-level energy management system for multi-source electric vehicles – An integrated rule-based meta-heuristic approach", (Elsevier) Applied Energy , Vol. 105, May 2013, Pages 304-318, ISSN 0306-2619. (http://dx.doi.org/10.1016/j.apenergy.2012.12.081).

[10] "MESMO-EV: Multiple Energy Storage systems Management Optimization for Electric Vehicles" project. IPC-ISEC, Polytechnic Inst. of Coimbra and INESC-Coimbra, www.dee.isec.pt/veil/mesmoev.htm.

[11] P. G. Pereirinha, J. P. Trovão, "Standardization in Electric Vehicles", 12th Portuguese-Spanish Conference on Electrical Engineering, XIICLEEE, Ponta Delgada, Portugal, June 30 –July 2, 2011.

[12] P. G. Pereirinha, J. P. Trovão, V. Santos, "Electric Propulsion Vehicles Standardization: Where Are We?", Int. Conf. On Modern Electrical Power Engineering, ICMEPE-2016, Las Palmas de Gran Canaria, Spain, July 6-8, 2016.

[13] E. X. Yang, F. C. Lee, and M. M. Jovanovic, "Extended describing function technique applied to the modelling of resonant converters," in Proc. VPEC, 1991, pp. 179–191.

[14] Unlytic thermal data for life expectancy, application Notes, Electronic Concepts Inc.May 3, 2002.

[15] Current Ratings and Dissipated Power in DC and AC Applications Electronic Concepts Inc.May 3, 2002.

[16] V. Kus y P. Drabek, "The education of EMC -the strategy and teaching overview at the UWB", 2011 IEEE International Symposium on Electromagnetic Compatibility (EMC), 2011, pp. 976-981