# A framework to share courses among universities: the case of a course on power electronics for electric vehicles


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***Abstract*— The paper describes the organizational framework and contents of a newly developed course on power electronics for electric drive vehicles. The course is developed and taught synchronously among three universities, with each institution individually managing student registration and assessments, and course administration. The participation of instructors and students from different institutions increases the impact of the course. In addition to the regular classes, followed on campus and remote, the high quality material generated by the instructors is available for the students, including a repository of recorded video lecturers and conferences given by specialist in key topics. Interaction with instructors and among students is promoted using a collaborative on-line tool.**



***Key words; Electric Vehicles, Collaborative learning, Power Electronics.***


## I. INTRODUCTION

The traditional approach to content creation and delivery in university courses is shown in Fig. 1. These courses typically use textbooks as references and adapt the materials to the scope and the objectives foreseen in the course syllabus. Theoretical concepts and supporting design-oriented exercises are key materials helpful to propose a case study learning strategy and to assess the acquisition of competences. In the case of masters programs, the supporting documents of the courses are usually more diverse and specific, although in interdisciplinary programs, where basic background is commonly revisited, the teaching oriented material is also frequently utilized.

At present, a large portion of university courses make use of online websites for organizational or material dissemination purposes. Some of them include e-learning tools for self-study purposes as in [1], and to facilitate interactions among authors, instructors and students. More recently, courses built by a single professor or institution are offered for dissemination among students worldwide, such as the open course initiatives in [2-4]. Material from these courses can be incorporated in educational programs of universities or any other institution.

This paper introduces a new framework for course delivery as shown in Fig. 2. The novelty of the experience presented here is that the course is designed so that instructors and students from different universities participate on-line concurrently. The process of generating course materials, including syllabi, lectures and assignments, is shared among instructors, both lightening the burden on each individual instructor and increasing the quality of the generated materials. Additionally, the concurrent course delivery among each institution allows collaboration among students from remote locations through online tools. All administrative aspects, including admission, grading, and institutional credit for both instructors and students are handled locally at each participating institution.

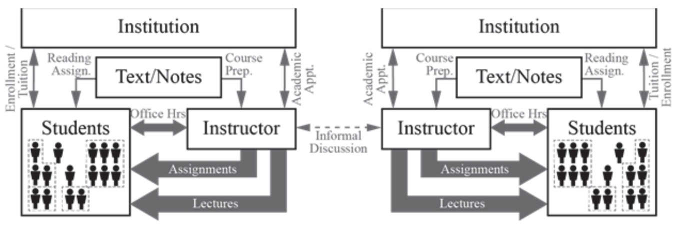



Figure 1. Traditional model of course delivery at two institutions. Note that the same structure is repeated at both institutions, while any interactions are typically limited to informal discussions between the instructors.

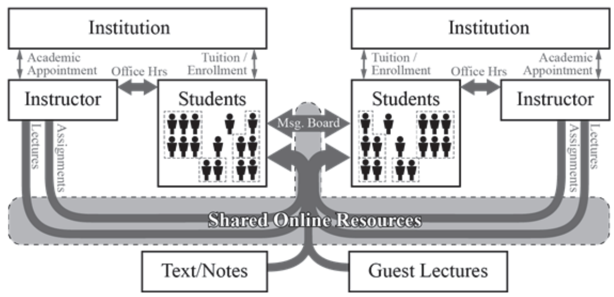



Figure 2. New framework to share courses among universities. Content development and delivery is shared through collaboration among instructors across universities.

The developed framework for sharing a course among universities is applicable to courses in any discipline. As a test case, it has been demonstrated in an electrical engineering course titled “Power Electronics for Electric Drive Vehicles”, which has been taught twice, in Fall 2012 and in Fall 2013, shared among Utah State University, the University of Colorado Boulder, and Universidad de Cantabria, Spain. The course includes components of power electronics, electric machines, battery modeling, and control system design with a prerequisite of an undergraduate degree in Electrical Engineering (interdisciplinary Industrial and Telecommunications Engineering in Spain) or instructor approval. The course is offered on campus to graduate students and senior undergraduate students and online to practicing engineers in industry for professional development. The course is one of four courses in a professional certificate program sponsored by the US Department of Energy (DOE) GATE Center of Excellence in Innovative Drivetrains in Electric Automotive Technology Education (IDEATE) [5]. The connection to the IDEATE center provides important guidance on the relevance of topics to industry through the industry advisory board, which includes major automotive OEMs and suppliers.

The paper is organized as follows. Section II is devoted to the organization of the course, and the teaching methodology. In Section III, the contents of the course are presented in detail, highlighting the activities related to acquiring competences in modeling and control design of the EV drive train stages. Section IV describes exams and exercises considered for grading student work and the responsibilities acquired by the participants, with conclusions presented in Section V.

## II. ORGANIZATION OF THE COURSE

The course follows a sequence consistent with the block diagram of a generic electric vehicle (EV) drivetrain, as shown in Fig. 3; including: *i*) a battery and battery management system to balance the state of charge of the battery cells, *ii*) a bidirectional DC-DC converter to decouple the motor drive and battery voltages through a shared DC bus *iii*) a three-phase DC-AC inverter, which supplies power to an ac motor from the dc bus controlled by the dc-to-dc stage, and *iv*) the controllers of the power converters.

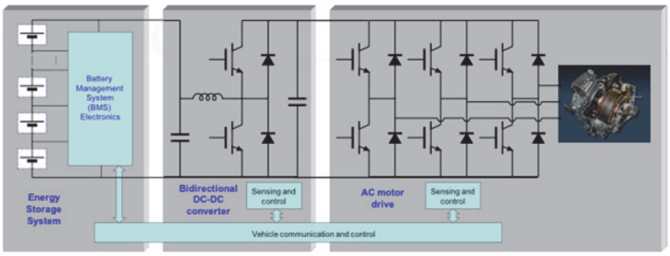



Figure 3. Electrical model of an EV drive train

The explanation of the operation principles of each component and converter stage of the generic vehicle is supported by training in modeling the different blocks (battery, switched-mode power converters, magnetic elements, electric motors and controllers) using Matlab-Simulink®. The models are dimensioned using realistic specifications acquired from vehicles such as the Toyota Prius, Nissan Leaf, Chevrolet Volt, etc.

The unique syllabus is coordinated and assumed by the different participating universities. Lecture material development and course management activities are distributed among the different instructors. All universities have regularly scheduled course meeting times and a dedicated faculty member who is assigned to teach the course and who attends the course meetings. Individual lectures or lecture modules can be recorded by any of the instructors. In the course test case described in this paper, the course materials are developed jointly, but most of the lectures are recorded by the instructor at one institution using one of the available systems such as Echo360 [6]. The recorded video lectures are posted in an online repository following the conclusion of the lecture. At the remaining universities, these recordings are used during the scheduled class meeting time. The local instructor attends these showings, remaining present to field any questions that arise and pausing the lecture to discuss core concepts and ensure student comprehension.

The recording of each lecture requires that the classrooms at each institution participating in lecture generation have certain hardware and software resources available. To support quality and clarity of lectures, the classrooms must have video and audio recording capabilities that support time-synchronized recordings of the instructor and annotations, either on an electronic white-board, document-camera, or touchscreen computer. In the course considered here, a touchscreen computer was used, with slides projected at the front of the local class and annotated in real time.

The video and audio of each 50-minute class is recorded and stored using the Echo360 [6] platform. The original slides, along with the ones resulting after the instructor annotations during the class, are organized and stored in an online repository so the students from all institutions can consult them.

The course further promotes the collaborative learning through the web tool Piazza [7] where a course forum, participated-in by the students and instructors, is created to post questions and comments arising throughout the course. Each initial post generates a thread of answers and clarifications opened to all the participants. Questions and answers can receive an assessment and Piazza sends e-mails to the participant with information about the activity in the forum. The shared nature of the course increases the potential impact of the web forum as a tool in course instruction; students from all universities have equal access, expanding the breadth of peers available for students to engage in discussion concerning course topics.

The course on electric vehicles includes additional materials, which make it more attractive and equip the students with additional training whose value exceeds the scope of the syllabus. These materials include: 1) A practical tutorial on modeling with Matlab-Simulink® including the data capture, model development starting from the differential equations that describe the system to model and techniques to properly present the simulation results. 2) Guest lectures given by specialists about battery technology, including the control of its state of charge, electric machines and wireless energy transmission. 3) On-line access to essential bibliography [8-10], using the university textbook access resources. In the case of the Spanish participation, the specific books have been purchased for the student. These additional materials are more easily incorporated into the course due to the already-present shared online repository that facilitates the dissemination of baseline simulation models and electronic resources, and allows the expertise of local guest lecturers to be shared among universities more easily.

## III. Details of the Course Contents

During 15 weeks (one semester) 42 lessons are presented to equip the students with fundamentals of the architecture, modeling and simulations of the electric drive trains and the modeling and analysis of the power electronics in an EV.

After the administrative announcements and the presentation of the course overview, the first topic, transportation and electrification, compares representative figures of energy consumption, cost, range, and emissions of vehicles using internal combustion engines (ICE) versus EVs. The purpose of this first lesson is three-fold. First, motivational, because it presents the course as a tool for the students to get involved in a field of engineering focused on achieving a more efficient use of the electrical energy, resulting in benefits for the environment. Second, it introduces the students to the analysis of the technical solutions, developing models inspired by the Design-Oriented Analysis proposed by Prof. Middlebrook [11], which results in a top-down approach from the complete system descending to the details of subsystems and components. Third, the initial top view justifies the presentation of trends and technology challenges, which is also motivational for the students, who envision possible jobs as engineers in the field of the course.

The second section of the course presents the EV from the complete system point of view. Basic equations of vehicle dynamics are given which model the system summarized in the block diagram presented in Fig. 4, which is used to observe physical variables such as speed, force, torque, energy, and distance in a standard drive cycle. Students are trained in assimilating the Matlab/Simulink® models developed by the instructors with different levels of hierarchy and the scripts used to introduce data and generate graphical representations of the results. The two main blocks of the top level model are the driver and the EV itself, as shown in Fig. 5. The vehicle speed and the reference speed are inputs of the driver model, the output being the torque command. The driver model is used to review linear controller design fundamentals. On the other hand, the EV model's input is the torque command and the output is the vehicle speed and other internal mechanical and electrical variables, which are directly observed or they are combined to determine the EV performance, e.g. efficiency. Table I presents the considered vehicle and motor parameters; including input and output dynamic variables, and constructive parameters. Simulations performed with this model are used to illustrate the benefits of regenerative breaking. From Fig. 6, one can infer that the average traction power is much smaller when the negative power corresponding to the breaking process is recycled instead of dissipated.

In this section, structures of hybrid (HEV), plug-in hybrid (PHEV) and electric vehicles (EV) are discussed, comparing the series hybrid, parallel hybrid and series-parallel hybrid architectures. The series HEV model is studied as a case example to assess the role of the electric system to produce energy savings.

The third section of the course is titled "Electric drivetrain components: analysis, modeling, simulations and design considerations." Following the diagram in Fig. 3, this section is focused on the components technology, power converters architecture and modeling and control of *i*) Battery systems, *ii*) Bidirectional DC-DC converters and *iii*) Inverters with the AC motor drives. An additional subsection is dedicated to *iv*) Principles of operation and standards of battery chargers.

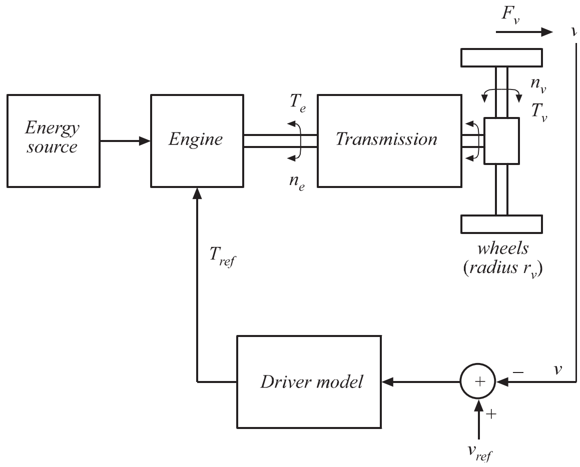



Figure 4. Block diagram of a vehicle as a feedback system

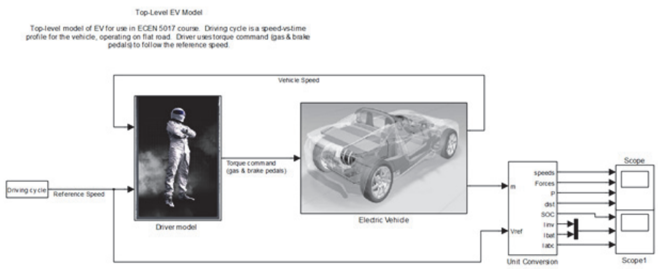



Figure 5. Top-level EV model

TABLE I. Vehicle and Motor Parameters

| Vehicle / wheel level | Motor / engine |
|---|---|
| $v$: Vehicle velocity (speed) | $g_{ratio}$: Gear ratio |
| $F_v$: Vehicle tractive force | $n_e$: Motor rotational speed [rpm] |
| $T_v$: Torque at the wheel | $\omega_e$: Motor angular speed [rad/sec] |
| $n_v$: Wheel rotational speed [rpm] | $T_e$: Motor/engine torque [Nm] |
| $\omega_v$: Wheel angular speed [rad/sec] | $K_e$: Torque constant |
| $P_v$: Vehicle tractive power | $P_{e\_max}$: Maximum motor power |

| Vehicle / wheel level | Motor / engine |
|---|---|
| $M_v$: Vehicle mass | $T_{e\_max}$: Maximum motor torque |
| $r_w = r_v$: Wheel radius | $v_b$: Base speed, torque/power limit boundary |
| $C_r$: Rolling resistance coefficient | $x$: Motor speed factor, ratio $v_{max} / v_b$ |
| $C_d$: Aerodynamic drag coefficient | $t_a$: Time spec to accelerate to speed $v_f$ |
| $A_v$: Vehicle front area | $\eta_m$: Motor efficiency |
| ρ: Air density | |

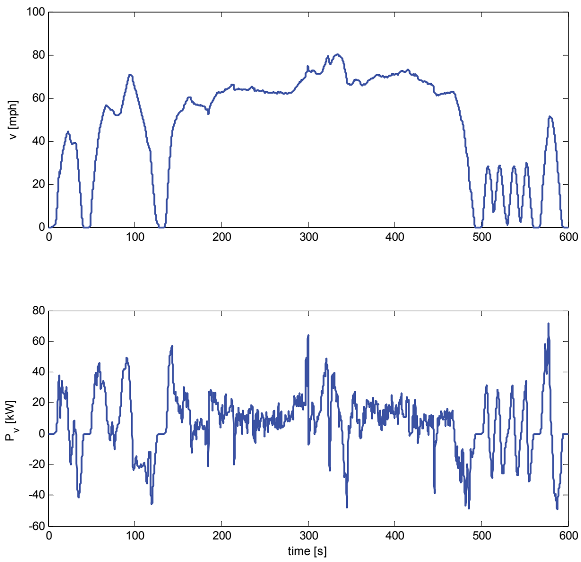



Figure 6. Vehicle speed $v$ and traction power $P_v$ for the test vehicle in a given drive cycle

TABLE II. BATTERY PERFORMANCE METRICS

| Energy | Power | Cost | Safety | Lifetime |
|---|---|---|---|---|
| Available energy storage between charging cycles | Instantan-eous power available | Initial investment | Hazardous chemical content | Number of charge / discharge cycles to 80% capacity |
| A·h rating | "C" rating: peak discharge current | Total energy cost over life of battery | Outgassing | Depen-dence on % discharge and peak currents |
| Specific energy, Wh/kg, energy density Wh/dm$^3$ | Specific power, W/kg, W/dm$^3$ | | Risk of fire from damage or heating | |

## A. Battery systems

The physical principles and basic chemical oxidation-reduction reactions that explain the battery charge and discharge process are explained using the lead–acid and nickel-metal hydride technology examples. Topics, such as the application limits and performance and evolution of the technology are presented by comparing key battery parameters of the different available technologies in several charts taken from specialized sources. Battery performance is assessed with the parameters included in Table II. Technical information of the batteries utilized in the 2004 Toyota Prius and the battery packages of the Nissan Leaf and the Ford C-Max Energi illustrate the size, cost and basic performance achieved by today's technology.

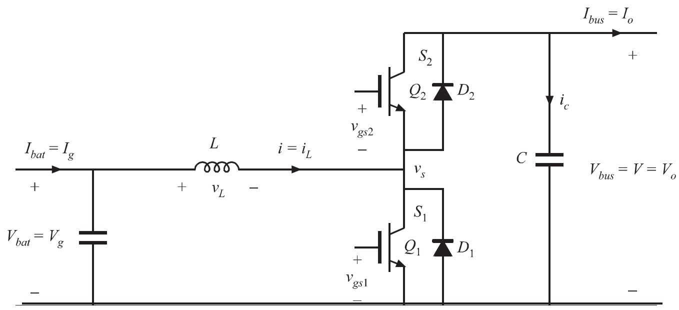



Figure 7. Bidirection Buck (or Boost) DC-DC converter

In order to study the battery response in the EV, a dynamic circuit model, based on [12], is developed. The model relates the state-of-charge (SOC) of the battery with the open-circuit voltage, including the deviation caused by the temperature. The model is completed with the effects such as the series resistance, the voltage hysteresis and the diffusion delay to predict the voltage across its terminals.

Battery systems are composed of an array of cells. Students learn how to estimate the number of cells and the connection arrangement needed to meet given specifications. Different proposals and practical circuits oriented to balance the SOC of the different cells along with the latest advances on battery technology, estimation and control of the SOC are presented in a guess lecture.

## B. Bidirectional DC-DC converter

Following [7], principles of operation and analysis of switched-mode pulse-width modulated (PWM) power converters are introduced with the two-switch topology shown in Fig. 7, used either as a Boost or as a Buck converter when the power flows from the battery to the DC bus or vice versa, respectively. Piece-wise linear approximation is used to present the voltage and current waveforms of the converter operating at constant switching period, $T$, and controlled by the duty cycle, $D$, of the PWM command signal. Steady-state analysis is performed using the small-ripple approximation. Inductor volt-seconds balance and capacitor charge balance calculations result in the converter ideal average voltages and currents relations modeled by a dc transformer model, whose conversion ratio depends on $D$. Later, the current and voltage ripples are calculated. In a second step, a more realistic model of the converter is built by adding parasitic elements to represent power losses, i.e. inductor conduction and core losses, capacitor conduction losses and power semiconductor devices conduction and switching losses.

In order to get a good estimation of the power dissipated in transistors and diodes and the impact on the converter efficiency, an approach to power semiconductor technology is introduced, avoiding the details of the physic phenomena and giving special emphasis to the analysis of switching transients. Some students receive a background seminar on semiconductors to reinforce this section.

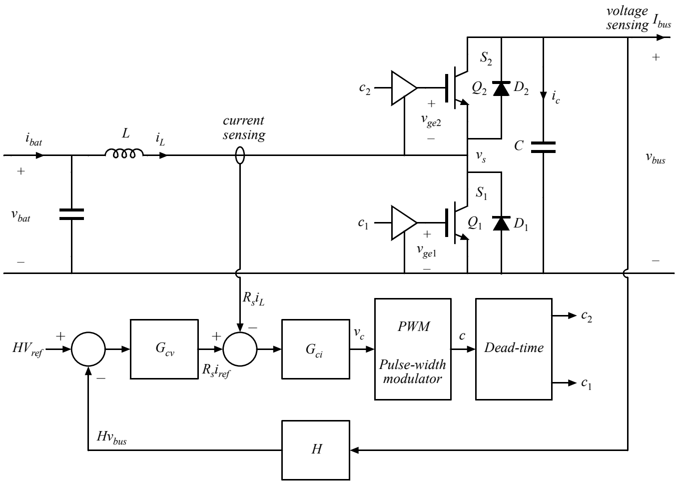



Figure 8. Bidirectional DC-DC converter feedback control

Steady-state converter model is modified to incorporate the effect of the conduction voltage drop across passive components and semiconductors and to account for the semiconductors switching losses, resulting in a more accurate calculation of the relation among the electrical variables and efficiency. Emerging technologies in semiconductor devices and concepts and examples thermal management are also introduced in this subsection.

The dynamic behavior of the bidirectional DC-DC converter is also modeled and analyzed by defining the state equations of the averaged variables and the circuit that represents the dynamic simulation model. The ac perturbation of this model is used to obtain the small-signal ac response of the averaged variables. From the linear small-signal model, the transfer function that represents the plant to be controlled is extracted. The design technique of the feedback control actions for the input current, $i_L$, and output voltage, $v_{bus}$, in a double loop system as shown in Fig. 8, are presented with the objective of meeting specified properties of the response by fixing the low-frequency high gain, bandwidth, and phase margin.

Fundamentals of the linear control theory applied to a multi-loop case are revisited. Students are trained to solve the controllers design in the Laplace (frequency) domain, testing the response by simulations performed also in the time domain, acquiring experience in defining control actions in consistency with the speed of the different subsystems.

### C. AC machines

Starting from the Faraday's and Ampere's laws, electromechanical devices are introduced by presenting the principles of magnetic circuit analysis and the design of inductors with magnetic cores. The relations between electrical and mechanical variables are first introduced with the operation of a single-phase, two poles permanent magnet synchronous machine (PMSM). The two-phase two poles PMSM illustrate the Park's transformation of the electromechanical equations of the motor from the stator reference frame (axis *a-b*) to the rotor reference frame (axis *d-q*) to eliminate the phase voltages and currents dependence on the rotor position and resulting in the proof of the motor torque, $T_m$, dependence on the $q$ component of the stator current, $i_q$ while $T_m$ is not dependent on $i_d$. Therefore, $i_q$ is the control variable to adjust $T_m$, while $i_d$ is set to zero for maximum $T_m$ operation or it can be modulated to reduce the equivalent magnetic flux linkage (flux weakening operation) and achieve higher rotating speed at lower torque. In steady state, rotor reference frame voltages and currents are all DC.

Those concepts are applied next to the three-phase PMSM with $P$ number of poles. The electromechanical steady-state equations limit the torque vs. speed operation area of the motor. The above mentioned field weakening technique extends the speed range and the motor operation area. Deeper information on different electrical machines with possible application in EV, including the research topics and the analysis unification by using the rotor reference frame, is presented in guess lectures.

With the dynamic equations in the *d-q* reference frame, a Simulink® model of the PMSM is built as presented in Fig. 9, whose inputs are the supplied voltages, $v_d$, $v_q$, and the electrical rotational speed, $\omega_r$, while the outputs are $i_d$ and $i_q$. The resulting $i_q$ and $\omega_r$ are post-processed to get the torque, $T_m$, and the electrical and mechanical angular position, $\theta_r$ and $\theta_m$, respectively. The input voltages in the *d-q* frame are calculated after applying the Park's transformation to the stator reference phase voltages ($v_a$, $v_b$, $v_c$) generated by the 3-phase inverter, which acts as the AC motor drive (see Figs. 3 and 10). The phase currents in the stator frame ($i_a$, $i_b$, $i_c$) are calculated by applying the inverse of the Park's transformation to $i_d$ and $i_q$.

### D. AC motor drive

The 3-phase inverter bridge topology is introduced to the students as the parallel connection of three Buck converter circuits, shown in Fig. 11. Switches operate in two *v-i* quadrants, so that the current can flow in either positive or negative direction and therefore the power can also flow in both directions, what makes the converter in Fig. 11 the same as the one in Fig. 7. To achieve the low frequency ac output voltage, the Buck converter command, i.e. the duty cycle $D$ in the PWM case, follows a sinusoidal function. The same sinusoidal function with $2\pi/3$ radians phase difference is applied to each Buck converter branch to generate the balanced 3-phase motor supply voltages ($v_a$, $v_b$, $v_c$).

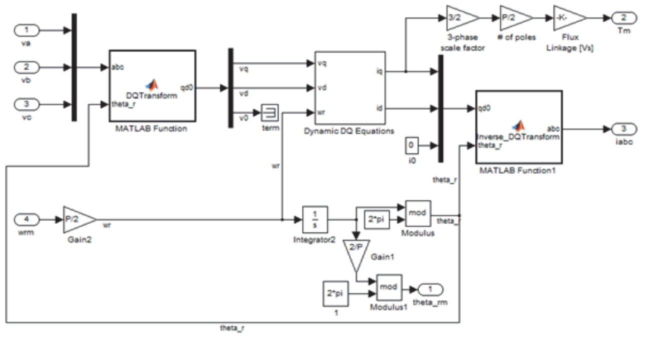



Figure 9. PMSM dynamic model in Simulink®.

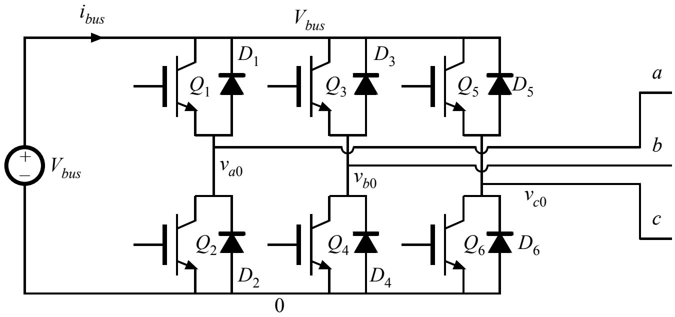



Figure 10. 3-phase inverter.

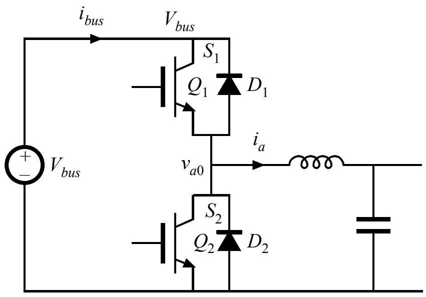



Figure 11. Buck converter.

The average equivalent circuit (Buck) model of each branch is used to build the model of the 3-phase inverter, whose inputs are the DC bus voltage, $v_{bus}$, and a reference control voltage which includes information of the amplitude of the ac component of the duty cycle ($D_m/2$) and the electrical angle, $\theta_r = \omega_r t + \theta_{ro}$. Phase currents $i_a$, $i_b$, $i_c$ and therefore, the DC bus current, $i_{bus}$, results from plugging $v_a$, $v_b$ and $v_c$ to the motor model.

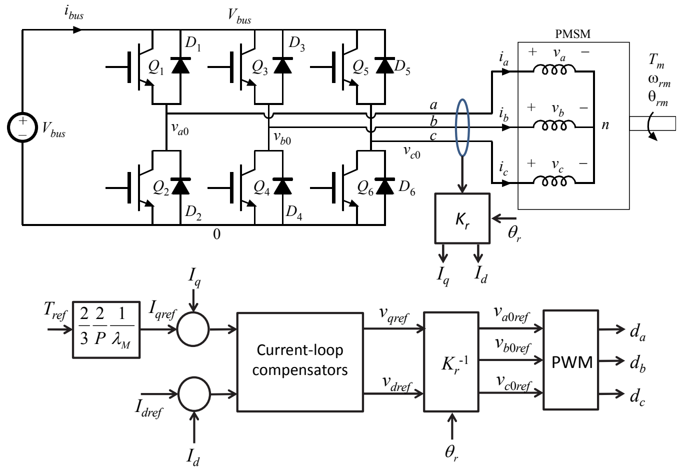



Figure 12. Block diagram of the PMSM controller.

## E. PMSM control

Dynamic equations of the PMSM and the average model of the 3-phase inverter are used to determine the ac small-signal model of the plant, whose inputs are the duty-cycle commands of each inverter branch ($d_a$, $d_b$, $d_c$) and the main output is the phase currents ($i_a$, $i_b$, $i_c$) from which the torque, $T_m$, can be calculated. The outputs rotational speed, $\omega_r$, and angular position, $\theta_r$, are used to calculate the Park's and the Park's inverse transforms.

PMSM dynamic model in the rotor reference frame retains all dynamics but removes the need to look at angle dependences. The principles applied to the design of linear controllers for the control of the bidirectional DC-DC converter are also used here to design the controllers that adjust the phase currents to achieve the $T_m$ value whose reference, $T_{ref}$, comes from the driver model, as shown in Fig. 5. The variables under control are the amplitude of the *d-q* currents, $I_d$ and $I_q$. The $I_q$ reference, $I_{qref}$, is calculated from $T_{ref}$ while the reference for $I_d$, $I_{dref}$, is either zero for maximum torque operation or a non-zero value to operate in field weakening mode. $I_d$ and $I_q$ loops suffer cross regulation. Students learn how to decouple the control action of the *d-q* current components by adding a feed forward block, not shown in Fig. 12, applied to the output of the current loop compensators to obtain the final reference voltage, $v_{dref}$ and $v_{qred}$, from which the duty cycles of each phase are calculated.

Once the whole EV and driver system is modeled, simulations are performed to verify the result over a drive-cycle example where acceleration, constant speed, and regenerative breaking operation mode are tested and the waveforms of the different blocks of the EV are discussed.

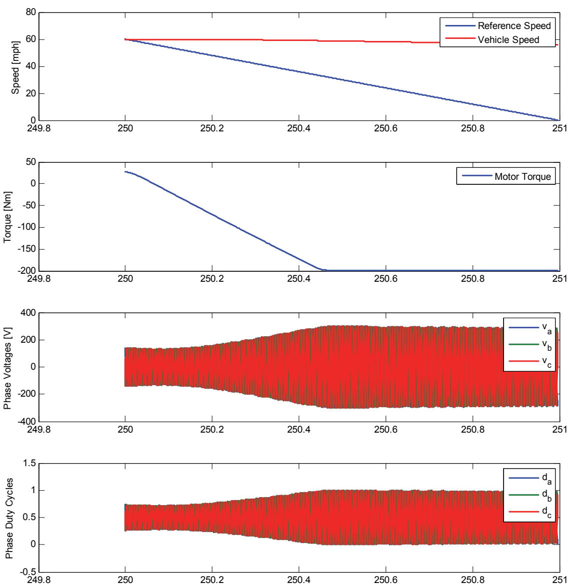
Two examples of simulations performed with the EV model are shown in Fig. 13. Figure 13 (a) shows torque, speed, phase voltages and duty cycles in one second of a breaking sequence while Fig. 13 (b) shows the waveforms details during 0.1 seconds of the same sequence where the change of the power flow direction is observed.

## F. Battery charging infrastructure

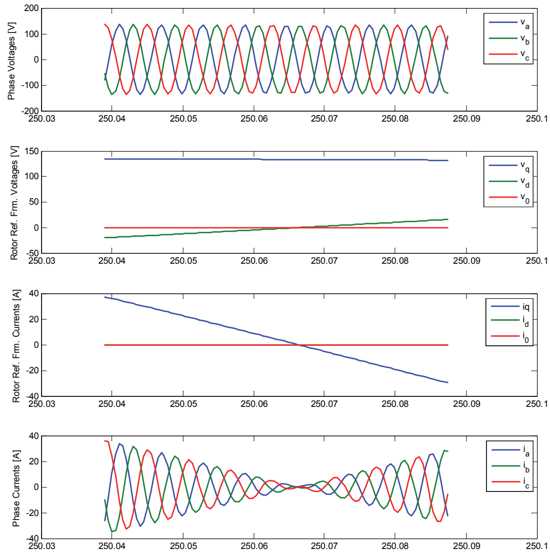
The last lesson of the course is devoted to the battery charging facilities and the power converters with the regulation circuits involved in the transformation from the utility ac source to the battery terminals. An overview of the charging standards highlights the power, communication and safety specifications. This topic is illustrated with some examples of commercially available connectors and charging stations.

The battery charger is presented as the series connection of two power stages. As it is shown in Fig. 13, the first one is an active power factor correction (PFC) AC-DC converter and the second is a DC-DC converter. The minimization of the line current and to comply with the standards related to the power factor and harmonic content of the line current motivate the design of PFC stages to perform the AC-DC conversion. Students are trained to solve the design of a two-loop control system using the averaged modeling technique applied to a Boost converter operating in continuous conduction mode. The fast inner loop is the input current controller, so that electrical load emulates a pure resistor. The slow outer loop stabilizes the DC output voltage. Other PFC solutions, using converters that present inherent resistor emulator behavior when operating in discontinuous conduction mode, are also introduced to the students.

In consistency with the power rate of the charger, a full-bridge isolated DC-DC converter is presented as an adequate option to implement the second stage of the system in Fig. 14 [8]. As in the previous cases, students learn the principles of operation, key waveforms oriented to give the proper dimension to the semiconductors, role of magnetics components, average and small-signal ac modeling and the design of the controller.




(a)




(b)

Figure 13. Simulation of a regenerative breaking sequence with the EV model. From top to bottom: (a) Motor speed, torque phase voltages and phase duty cycles in a one second sequence. (b) Detail of the phase voltages, motor voltages in the d-q frame, motor currents in the d-q frame and phase currents in a 0.1 seconds sequence.

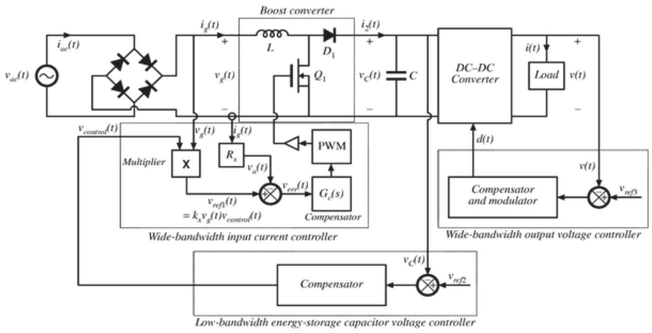



Figure 14. Example of carger implementation using and active PFC and a DC-DC converter [8], Chapter 18.

The lesson is completed with information about research topics which are oriented to improve the charging management and speed, integrate the EV in the grid to get mutual benefits and make the most from renewable energy sources. A specific topic on contactless (inductive) energy transmission for charging EV batteries is also included with a guest lecture.

The course ends with a review lesson oriented to help students prepare for the final exam.

# IV. Students Assessment

Students receive homework assignments roughly each week through the course web site. Questions define case studies through which the students perceive the dimension of parameters such as the processed energy, characteristic time response of the different subsystems involved in the electric vehicle, energy conversion efficiency, etc. The development of Simulink® models and Matlab® scripts, the adjustment of pre-existent models and the study of simulation results are also arguments for the questions in the assignments. For example, students are asked to study the battery charge and discharge sequence according to a given driving cycle, including the effects of acceleration, breaking, aerodynamics, friction, etc., or to design regulators and observe the response of the bidirectional dc to dc converter and the motor drive.

Two exams are given to the students at the middle and at the end of the semester. They include a more complete set of questions and exercises to be solved through mathematical analysis and simulation. The first exam is scheduled after the lesson on Bidirectional DC-DC converter. The final exam includes questions about the entire course. A due date is established to return the exams. Students are committed to guarantee that they solve the exercises individually with no collaboration allowed.

Instructors from each institution are responsible for the supervision of their own students, the review of the homework exercises, grading of the exams and also for applying the academic results in the university program in which the course is integrated.

Collaboration among the institutions participating in the course is very convenient to solve the administration issues. From the academic perspective, it is necessary to find the program in which the course fits, or a course with flexible contents in which the activities of this course on EV are incorporated. At present, there is no formal framework agreement with the Spanish university involved in the course. Consequently, the instructor makes the course on compatible with a course under his responsibility, integrated in a Master of Science program not subordinated to orders published in the National Official Newsletter. The academic results of the course Power Electronics for Electric Vehicles are incorporated to the grade of the local course in a large extent.

The students from each participating university were asked to assess the quality of the course based on three stated learning objectives and the overall course. The learning objectives included (1) learning fundamental principles, generalizations, or theories, (2) learning to apply course material to improve thinking, problem solving, and decisions, and (3) developing specific skills, competencies, and points of view needed by professionals in the field. Students at Utah State University rated the course 4.7 out of 5.0 on accomplishing the learning objectives and 4.5 out of 5.0 overall as a course. Similarly high course assessment results have been obtained from students at at University of Colorado Boulder and Universidad de Cantabria. Students had positive comments on the collaborative environment, such as “appreciated the dynamics of listening to multiple teachers with different perspectives on the topics,” and on the practical application and problem solving nature of the course.

## V. Conclusions

The proposed framework for sharing courses among universities combines elements of on-site and distance education. Recorded classes, presentation slides and annotations developed during the lectures are made available to partner institutions to allow following the course from a different location. However, at each university, classes require the presence of a local dedicated instructor who is responsible for all interactions with local students, including answering questions, engaging in discussions, and administering assignments and assessments. The interaction is effectively reinforced using online forum tools. Grading and administrative management of the course are all done locally at each partner institution. Based on the proposed framework, students from different locations receive the benefit of high quality training; instructors develop materials and improve their competences in collaboration with colleagues at different universities. As a result, the educational resources are utilized more efficiently, increasing the impact of the shared course.

As a case study, the paper describes implementation of the proposed framework in sharing a graduate-level course titled Power Electronics for Electric Drive Vehicles among three universities: Utah State University, University of Colorado Boulder, and Universidad de Cantabria.

The students profile is post-graduate in engineering, which receives competences oriented to pursue a professional career connected the development of products that are gaining market and under permanent innovation. Also, the course fits to professionals who request boosting their competences to participate in the design of new products and R&D projects.

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