Electronic Learning Experience Setup:
Power Electronics and Electrical Drive Education

P.J. van Duijsen*, D.C. Zuidervliet** and J.B. Woudstra**
* Simulation Research, The Netherlands
** The Hague University of Applied Science, Delft, The Netherlands
info@dc-lab.org

Abstract **- A method to teach and instruct the workings of power electronics and electrical drives is presented. The combination and interaction between oral lectures and practical laboratory assignments is presented, as well as the required tools. The structure of the course should consist of individual sections of increasing level regarding subject and details. For each subject the required knowledge level can be examined and a laboratory test has to be passed. Design tools and simulation/animation tools are used throughout the course. The laboratory assignments should follow the theory and simulation/animation is used to show the similarity and differences between theory and practice. A typical power electronics course is given as example and laboratory assignments using a dedicated educational trainer are given.**

Keywords – Education Power Electronics, DC grid, Laboratory, Design, Simulation, Animation, Hardware Trainer, Droop Control, Prosumers

I. Introduction

Teaching power electronics is usually done using textbooks and laboratory assignments. Simulations to enhance the understanding of the working of converters is used for over three decades[1] and animations to visualize the converter operation are also well known[2]. Remote laboratories became feasible with the widespread use of fast internet connections for students[3][4][5]. However all these "gadgets" are an add-on on the curriculum. Important is also how the structure of the curriculum and content is organized in order to teach students from basics up to a professional level. In this paper attention is given how the contents of power electronics courses are developed where there is a strong interaction between the oral lectures and the practical assignments in a laboratory. Especially the step wise building up of the level[6][7] of knowledge during the oral lectures and the practical assignments and the interactions between them will be highlighted in this paper by a number of examples.

To encourage students, special attention is given to the practical assignments on a hardware trainer, which is constructed in the same way as an industrial application[8][9][10]. It allows multiple assignments and includes many measurement connections for important signals. The combination of oral lectures, exercises with online verification, educational simulations/animations and practical assignments on a newly developed hardware trainer are the subject of this paper.

TABLE I. Typical Appliances and Power Level

AC/DC	Application & Power Level		
	Application	***Mobile***	***Grid***
DC-DC	Adapters(a) for mobile phone and computers are the most common seen devices	Low	Low
AC-DC	Powering various appliances, Heating, Cooking	Medium	Medium
DC-AC	Drive Applications; Domestic appliances, Fans, Cooling, Heating.	Low	Medium
AC&DC	Solar Power MMP and Grid connected inverters	Low	Medium
DC-AC	Inverters in Electric Mobility	Medium	
DC-AC	Inverters in Industrial Drives Traction & Wind Energy	High	High

a. AC-DC as well as DC-DC

The Laboratory assignment is built around the theory from the lectures and has to be practiced using simulation, online design tools (self-assessment) and measurements. For the Laboratory assignment a new universal trainer containing four half-bridges with shoot-through protection, adjustable dead-time and current measurement is developed. Digital control is an add-on using an Arduino or TI Launchpad.

The hardware trainer allows students to perform experiments with safe voltage levels below 60 volts and under 200 Watts. Applications range from battery charging, solar panel maximum power tracker, DC – DC conversion to DC – AC conversion for electrical drive speed and position control. The curriculum covers both electrical and mechatronic students on Bachelor level[11]. The main objective in developing a new power electronics course is to combine theory together with a design phase, component selection and calculations, prototype building, measurements and in a final stage the self-reflection of comparing the original design idea with the final obtained results.

II. Why and What?

Before starting the discussion about typical content in a power electronics course, it is wise to first consider what is expected from the student to learn and why this is important[12][13]. The importance of the subject is something that has to be justified when building a curriculum for Bachelor and Master students.

A. Why?

Looking at the current discussion on climate change and the energy transition, taking place from fossil fuel towards green energy, it is easy to justify a course on power electronics. In table I some of the main applications that are of interest in our daily life are summarized. Pointing at the importance of each application will justify the existence of a power electronics course in the overall curriculum.

B. What?

What is it a student has to learn? It starts with an oral lecture where the basics of the theory should be explained. Once there is a thorough basic understanding of power electronics and the waveforms and operation is clear to the student, the component parameters can be calculated. Instead of showing only formulas, now the student is forced to use the formulas and to understand where the formulas are coming from. Based on the knowledge of calculating component parameters, the student can make a first design. Design tools and simulations are helpful in understanding the influence of parameters. Depending on the results from the simulation, the student can do a redesign. Building a prototype in the laboratory is of tremendous value to a student to get a grip on the difference between design, simulation and final measurement results. If building of a prototype would take too much time, a pre-build design can be used and the student can do measurements. The student now has to explain the difference between the calculated and simulation result and the measurements on the prototype.

III. Course Structure

A course should contain theory and laboratory assignments. Each topic should be assessed during the oral lecture and, if possible, in the laboratory.

A. Theory

Every oral lecture or self-assignment needs written text to explain the theory. Various other media can accompany it, as long as there is a story that can be told to the student explaining the matter he has to understand. Although webinars and other video tutorials are helpful, a written transcript helps the student to go through the material at his own pace. Learning is practicing, the student should have enough worked-out short problems or questions and answers to rehearse and practice the topics. Let us take the example of a buck converter. First the students learn the input-output relations and next they have to understand how to set the inductor current ripple by choosing an inductor value. By just explaining the voltage levels during switching, the voltage over the inductor can be derived from which with known operating frequency the inductance value can be obtained as

$$0 < t < T_{on} \Leftrightarrow L\frac{di_L}{dt} = U_{in} - 0 \qquad (1)$$

$$T_{on} < t < T_{off} \Leftrightarrow L\frac{di_L}{dt} = U_{in} - U_{out} \qquad (2)$$

In either case the student should be able to calculate the value of L for continuous conduction mode. To verify the result he could use a simulation, but a design tool might be faster to use. Figure 1. shows how a design tool[14] is used to verify the peak inductor current when a fixed inductor value of 150uH is selected.

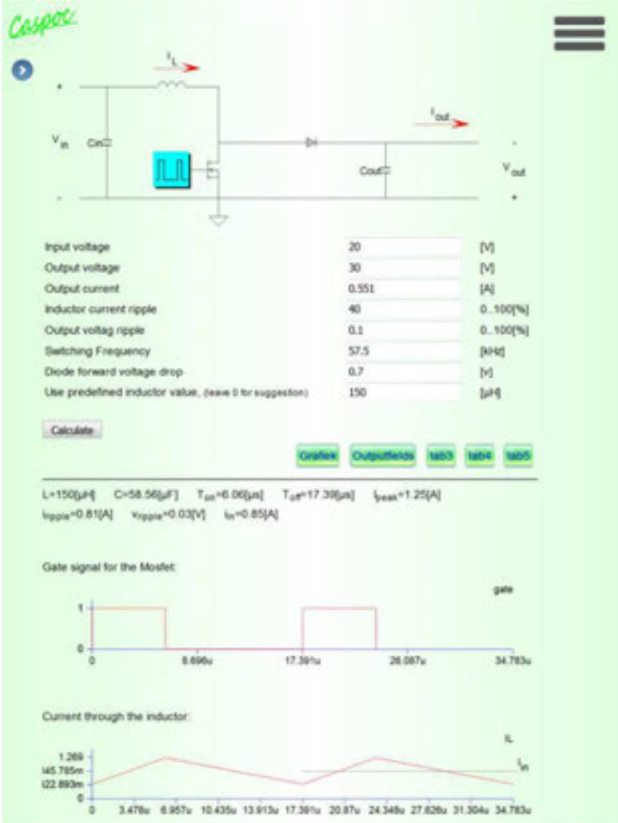

Figure 1. Design tool to prove the inductance value according to an assumed inductor current ripple.

By choosing a zero value for the inductor, the tool will suggest an inductor value to achieve the desired current ripple. This inductor current ripple value is relative to the average inductor current and is default set to 40%.

Using (1) and (2), the student can see the relation between the inductor current ripple and the value of the inductor and the value of the switching frequency. Using the design tool, he can directly see the influence graphically. Not only does it give a numerical insight, but also the waveform is directly available and shows that by decreasing the inductor value, the converter will eventually go from continuous mode into discontinuous mode.

By using the design tool, the student can get a better feeling of the relations between the component parameters and the current and voltage waveforms. Since the waveforms are presented in their actual voltage and current scale, the student directly will get an impression of typical component values. He will get more insight in the approximate size of the components for a typical operating frequency. This will be of help when going to the next level in the course, where he has to test the operation of the converter in a simulation to verify the waveforms.

The results from the design tool are directly applicable in a simulation/animation of the circuit[14]. Using the values like the operating frequency, inductor and output capacitor, he can directly set up a simulation/animation of the circuit and will very probably get nearly the same waveforms as presented by the online tool. This save the student time for trial and error to choose component values, run a simulation and based on the waveform, make changes to the component values.

The simulation/animation is primarily needed to show the operation of the circuit and especially the current paths when, for example in a buck converter, the switch is closed and when the freewheeling diode is conducting.

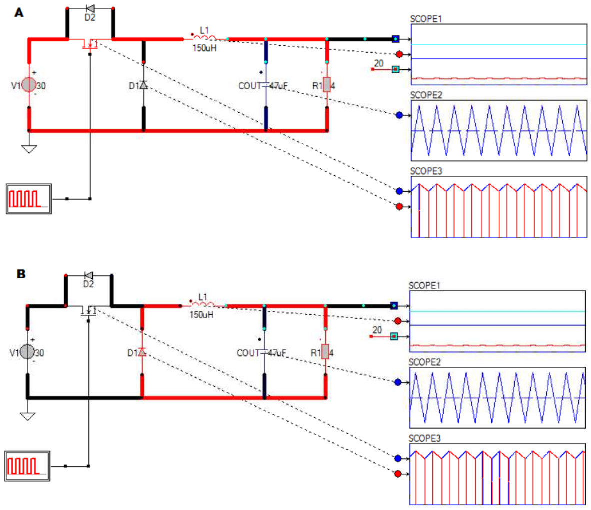

Figure 2. The current path when the Mosfet is turned-on(A) and when the freewheeling diode is conducting(B).

In Figure 2. The current path in the circuit is colored according the current level during the animation. In this way the student sees the current path periodically changing between Mosfet and diode and will see that the freewheeling always follows the on-time of the Mosfet.

By decreasing the inductor value in the animation of Figure 2, the inductor current will eventually get discontinuous. In the animation the student will see that in that case the current path through the freewheeling diode will gradually change from red(maximum current) to black(no current). If the animation was recorded using the Freeze and Go-Back function [1], the student can step through the animation and see the position in time on the actual waveform, the current path in the circuit as well as the value of each current, voltage and control signal in the animation. Stepping through the animation, the student can observe the changing of currents and voltages and how this affects the operation of the circuit. Using the Freeze and Go-Back feature he can trace signals and relate them to the switching operation in detail.

B. Laboratory

A laboratory should start with insight in the basic operation of the circuit that is going to be build or examined. Simulation is required here to quickly look at the operation of all sections and components and to give the student a basic understanding on the size of components and the to be expected current and voltage ranges in his circuit. Building a circuit in practice is an experience, students should go through in order to understand that in practice things behave different from what is expected from theory. Especially the influence of parasitic elements and thermal behavior becomes clear during a laboratory exercise. Most importantly at this stage, the students will see that the measured voltage and current waveforms differ from what is expected from theory.

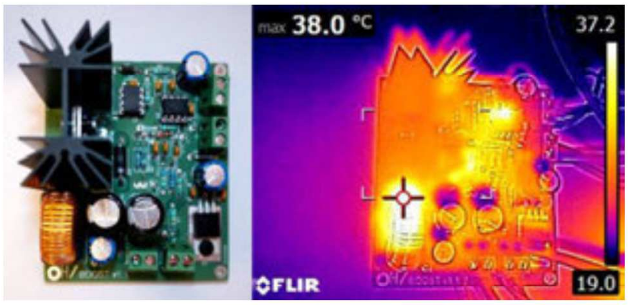

Figure 3. On the left the assembled boost converter and on the right a thermal image indicating severe losses in the inductor .

Figure 3. shows an assembled current mode controlled Boost converter and the thermal image when operating. The students can observe the losses in the inductor core material and this will give raise to thinking about core selection.

Through hole components are preferred during the first laboratory experiments, as they are easier to handle for inexperienced students, but also allows easier probing on the PCB during testing. The control IC is mounted using a socket that allows different circuit operations when the IC is not mounted. For example, the duty cycle for the boost converter can be injected using an external signal generator when the current mode control IC is removed. For newer components, an IC Socket Adapter to use SOP or similar SMD packages on a through hole PCB can be used.

The assembly of the PCB should be done step-wise and each step should be accompanied with measurements to verify the operation. For the boost converter in figure 3, the power circuit consisting of the inductor, Mosfet with gate driver and output capacitance is build first and the duty cycle is set using an external gate driver. The students can measure the current and voltage waveforms for varying switching frequency and duty cycle. Needles to say that an ohmic load and a power supply with maximum current protection have to be available at this stage.

Reporting of measurement results can be practiced during the laboratory assignment. It will encourage students to document the complete set up and wiring of several experiments in order to be able to reproduce measurement results.

IV. KNOWLEDGE LEVEL AND INTERACTION

The theory and practical assignments have to be organized in parallel during the course. The student will gain knowledge during the lectures and during the assignments and should preferably have theoretical knowledge about a typical topic before entering the practical assignment. Figure 4. shows a typical gain in knowledge and the interaction between the lectures and the laboratory assignments for a power electronics course on switched mode power supplies.

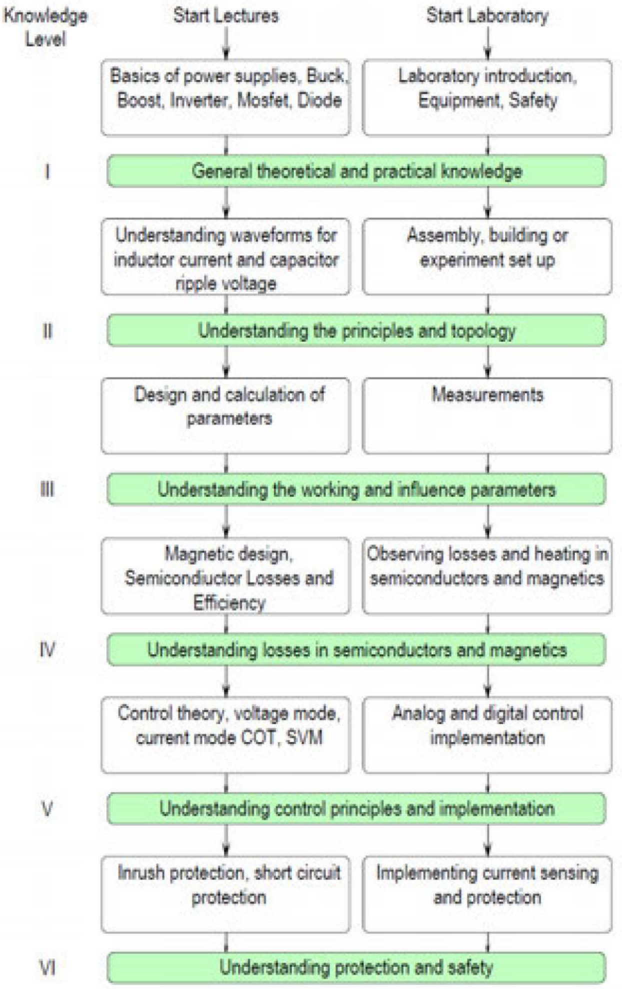

Figure 4. Knowledge level and interaction between theory and laboratory assignments for a typical power electronics course on switched mode power supplies.
(COT = Constant-On-Time, SVM = Space Vector Modulation)

The knowledge level in Figure 4. is displayed on the left side next to the achieved knowledge in the shaded box. Examination in the form of a written or oral examination or delivered measurement report can be used to follow the progress of each student individually. Continuing with the next knowledge level should be based on the fulfillment of the previous level. The lecture notes and tools are required in each stage. For example the design tool from Figure 1. is used during the knowledge level II and III for understanding the principle operation, but also for design and component values. Animation as shown in Figure 2. is typically used at knowledge level I where the basics of operation are explained. Specific design tools, for example for calculating the thermal impedance of heat sinks are again applied at knowledge level IV where the students observe the heating of components such as the losses in inductors as shown in Figure 3.

V. Applications

The knowledge gained during the power electronics courses is important for other courses. Gained theoretical knowledge on inverter operation and modulation is of importance when starting a course on electric motor drives. Without prior knowledge on the operation of inverters a course on variable speed drives would need extra hours explaining the working of pulse width modulation and the control of currents through the motor windings. Assembled converters can be applied in other laboratory assignments, especially in electric motor control assignments or as interface to components such as solar panels and batteries. In this way the gained knowledge from the power electronics course as well as the laboratory assignments form a basis for other courses like mechatronics, electric drives, AC power systems and DC grid power systems like DC grid Droop Control and Solar Power applications.

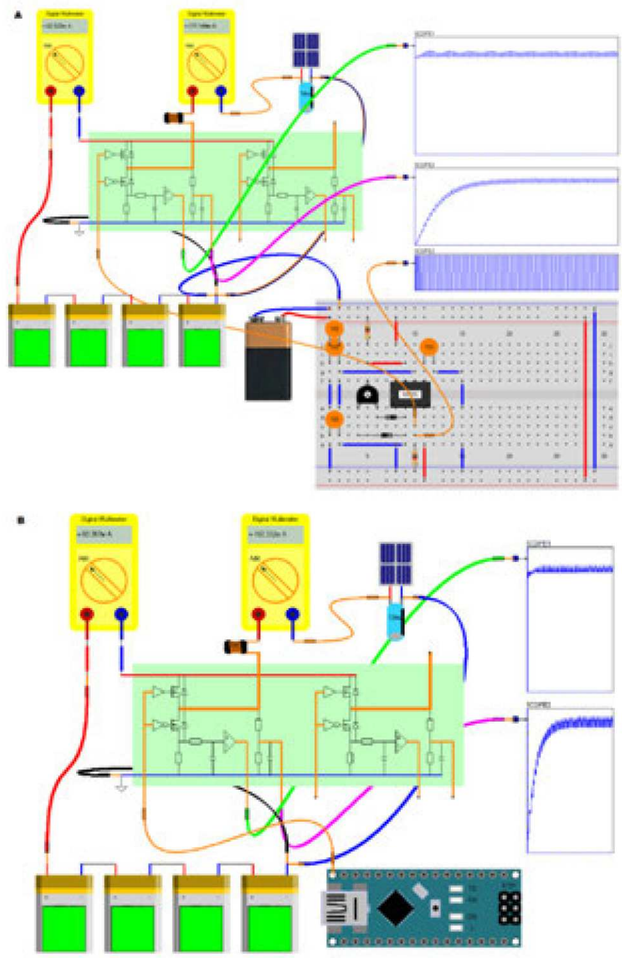

Figure 5. Charging Li-Ion batteries from a solar panel using and analog control(A) or digital control(B) and the Universal Four Leg inverter[10].

A typical application is the use of a boost converter to load a solar panel[10]. Figure 5 shows a set up where a pre-assembled inverter is used as a boost converter for loading a solar panel and charging 4 Li-Ion batteries.

VI. EXAMPLES

Typical examples during a power electronics course are DCDC and DCAC converters. There are many different types of possible examples that could be used during the course. At the power electronics courses at the THUAS there are two main converters that are assembled/measured during the practical laboratory assignments. The Boost converter is build during the lectures on DCDC converters and an inverter circuit is used in practical laboratory assignments to study the various modulation techniques used in DCAC applications[9] and DC grid droop control.

A. DCDC Boost Converter

After preliminary design, students have to assemble a boost on a PCB, see Figure 3. They start with a basic power circuit and the aim is to teach the students the influence of switching frequency and duty cycle in a Boost converter. A signal generator is used and controls the gate of the Mosfet in the boost converter. Students have to perform experiments for various switching frequencies and duty cycle and report current and voltage waveforms. During the oral lectures they have learned the basics of operation along with the waveforms. Using the design tool from Figure 1. and the animation and simulation from Figure 6. Here they are faced with the fact that from theory and during simulation it is easy to obtain the waveform for inductor current and voltage across the inductor. However, to achieve the same in a measurement, they have to improvise and measure the converter input current as well as the use of a differential probe for measuring the voltage across a component.

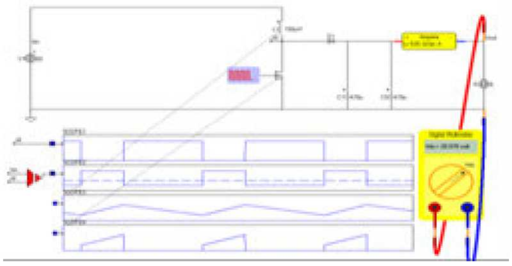

Figure 6. Understand the basic relation between the voltage across the inductor (V(Vin)-V(J8)) and the inductor current.

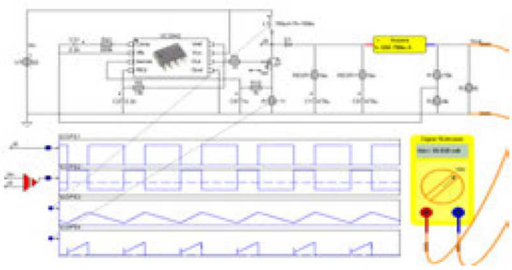

Figure 7. Closing the control loop using an industry-standard current-mode control IC.

From theory the current mode control can be implemented in a simulation and the students can start with designing the main components required to get a stable output voltage. Once they have built the Boost converter in the laboratory and start measuring, they have to explain the differences between the simulation results and the measurement results.

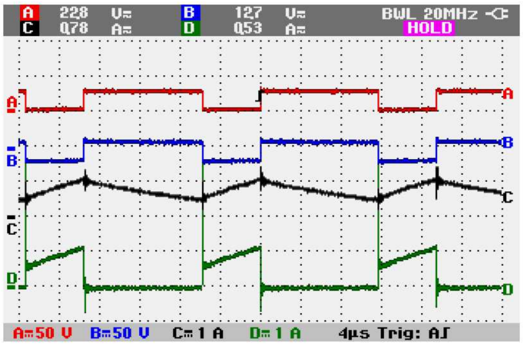

Figure 8. (A)Voltage over the Mosfet, (B)differential voltage across the inductor, (C)inductor current measured over shunt at the input, (D)current measured as voltage over the sense resistor R2.

From the result from Figure 8. the students have to explain the origin of the spikes on the current measurement. By adding parasitic components in the simulation they will step by step identify the most important parasitic components in the circuit, Figure 9.

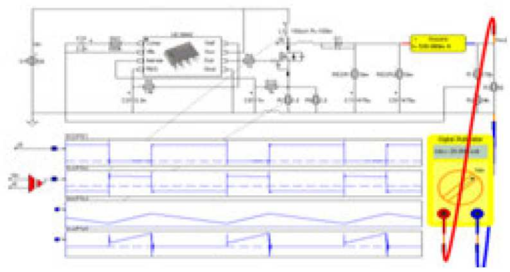

Figure 9: Parasitic components added to the simulation

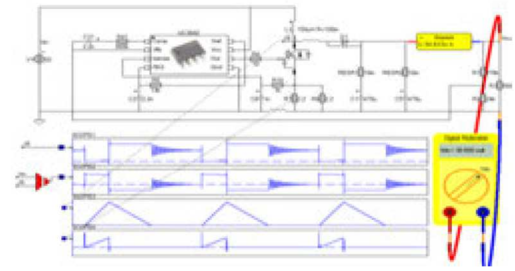

Figure 10. Ringing on the Mosfet's drain voltage because of parasitic loop inductance during discontinuous operation.

The ringing on the node where Mosfet, inductor and diode intersect is visible in the simulation. Measurements like in Figure 11. should confirm this.

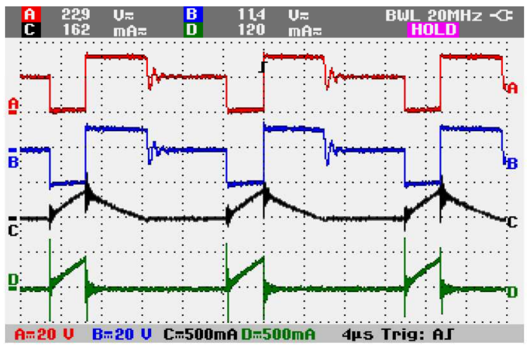

Figure 11. Discontinuous current causes ringing across the Mosfet. From top to bottom, voltage over the Mosfet, differential voltage across the inductor, inductor current measured over shunt at the input, current measured as voltage over the sense resistor R2.

B. DCAC inverter

The DCAC converter is already pre-assembled, as the PCB contains many SMD components that require too much time from the students. Also the goal of he laboratory assignments is to get a basic understanding on the working of the inverter and the modulation principles.

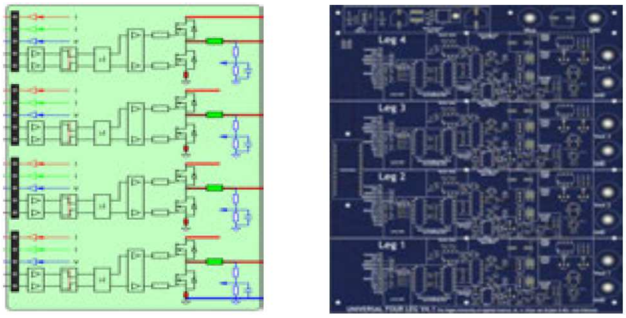

Figure 12. CASPOC Simulation model and hardware of the Universal Four Leg (U4L).

The students will use a pre-assembled Universal Four Leg[10]. In Figure 12 we see the simulation model of the U4L with the PCB of the hardware of the U4L. An additional analog control will be added for three phase modulation that can be connected to the U4L, as shown in Figure 13. The students will have to solder this analog circuit first before they can test it in combination with the U4L. This circuit can be used to modulate the input of three legs of the U4L for controlling an inductive load like a three phase motor.

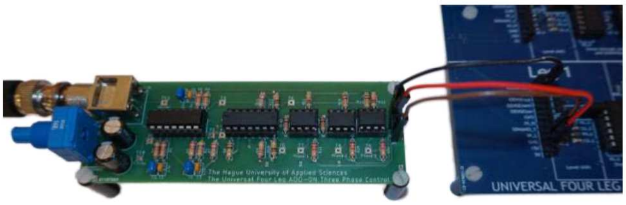

Figure 13. On the left the hardware for three phase modulation with one phase connected to Leg 1 of the U4L to control an inductive load.

The students can feed in their own triangular high frequency carrier wave and measure the output frequency of the three phase oscillator. The output signals of this circuit combined with the U4L can be seen in Figure 14. The three phase output signal should confirm the simulated results.

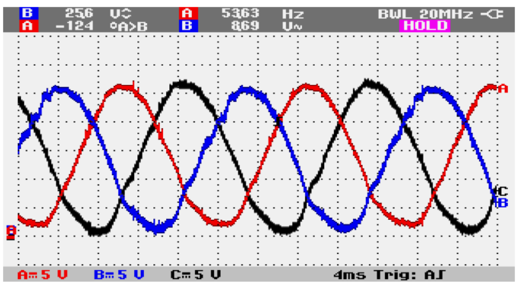

Figure 14. Three phase output currents in an inductive load created using the Universal Four Leg with analog control.

C. DC Grid Droop Control

The U4L is also used to study DC Grid Droop Control. The outputs of the U4L can regulate a bidirectional current flow, depending on the DC voltage level on their output terminal. Using the U4L students can model DC Grid prosumers like batteries, solar MPP controllers, non-linear loads and grid connections[11].

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Thanks to Casper Grootes for providing the three phase analog control circuit and output current measurements.

VII. CONLUSION

Combining oral lectures including written lecture notes, design tools, simulation and animations tools with laboratory assignments enriches power electronics courses. The structure and knowledge levels in the course contents are given which are helpful in the progress of the students and allow intermediate examination and or passing of laboratory assignments. Dedicated educational trainers like the U4L enrich the laboratory assignments and can be applied to other courses like mechatronics and electric drives as well.

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