IEEE Power Electronics Magazine, vol. 9, no. 4, pp. 45–53, 2022

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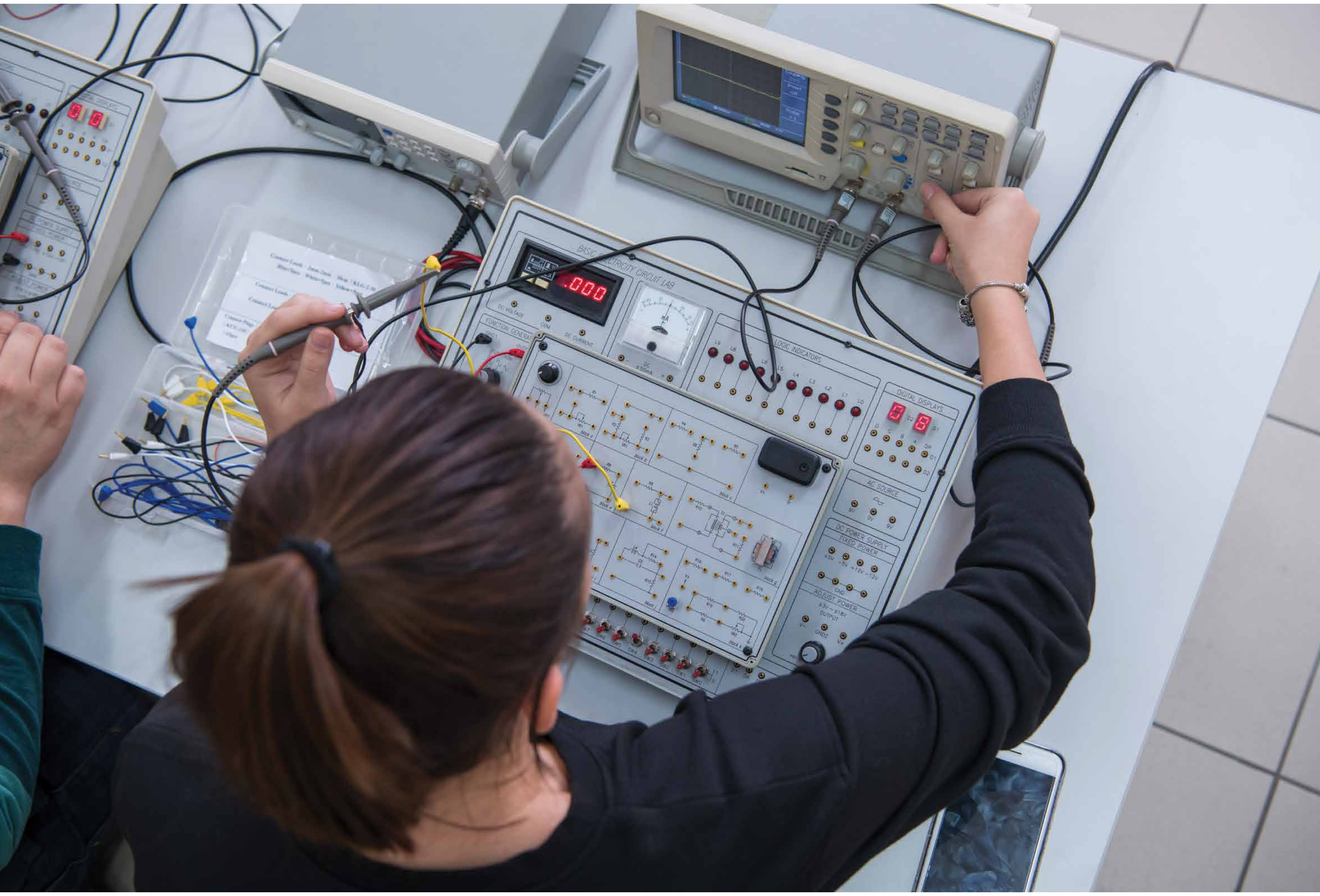

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Teaching Power Electronics: How to Achieve the Desired Learning Outcomes?

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Digital Object Identifier 10.1109/MPEL.2022.3216094
Date of publication: 6 January 2023

It is often said that teaching is an art as much as is science, and while it relies on tradition, it also draws from the innovations from various fields and inevitably evolves. There is no single best way to teach a certain topic, and clearly personal preferences of the teacher, background experience, availability of various teaching support equipment, number of students attending the course and desired learning outcomes will all come to play when defining an approach to develop a curriculum and practical method of delivery. This article does not aim to be scientific, completely correct, nor a universal way of doing the same thing, but rather aims to directly share experiences of how a Bachelor level Power Electronics (EE-365) course is organized by the Power Electronics Laboratory and taught at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland.

Taking inspiration from prior teaching-inspired works published through the IEEE Power Electronics Society [1]–[4], educational material such as Power Management Lab Kit [5], online resources [6]–[8] and from our own experience throughout the recent years, we provide here a comprehensive description of the course, including details on expected learning outcomes, logistics, reports, and grading. The hope is that what follows will be useful to many colleagues and ideally inspire further developments and improvements along the presented lines.

Learning Objectives

The Power Electronics course is taught to Bachelor students at their sixth (last) semester, just before they need to choose their Master's program and specialization. As such, it covers basic converter topologies, modeling and operating principles, magnetic devices, semiconductors and thermal management, while the control of converters is just lightly treated. Students are generally of electrical engineering background and have already attended basic courses in electronics, signal processing, semiconductors, magnetics, etc. Nevertheless, they have limited practical laboratory experiences, mostly based on observations through advanced set-up laboratory exercises, and almost no "practical design" experience.

Upon the arrival of the lead author of this article to EPFL, back in 2014, the evaluation of the Power Electronics course was in the form of a written exam, and students were asked to solve converter design calculations on paper. It became clear after two-three years of teaching the course, that the format of the course needed changes in order to achieve learning objectives that could be best expressed as "*design of power electronic converters.*" Solely solving numerical problems relying on the understanding of operating principles of certain topologies was not sufficient, and various concepts could not be truly understood and appreciated by students. At the same time, the general feeling was that there was a lack of "*hands-on*" courses, and consequently the practical experience of students was limited and reserved only for semester projects in various laboratories. Thus, based on the belief that experience is the best teacher, the complete course was redesigned to be a project-based semester-long assignment during which students have to design and build a complete converter, from the technical design specifications to a fully tested and performing prototype.

Table 1. Example Flyback converter ratings*.

Flyback Converter Technical Requirements Specifications		Comment
Rated Power [W]	50	Identical for all project teams
Minimum Input Voltage [V]	30	
Nominal Input Voltage [V]	50	
Maximum Input Voltage [V]	60	
Minimum Power for CCM [W]	10	
Output Voltage [V]	5 9 12 15 24	Shuffled randomly between project teams
Switching Frequency [kHz]	200 220 … 500	Uniquely assigned to each project team over the range of switching frequencies
Maximum Output Voltage Ripple [%]	5	Identical for all project teams

**Power ratings and input voltage range is the same for all teams, while every team has a unique combination of the output voltage and switching frequency.*

Technical Requirement Specifications

Fortunately, there is a large number of converter topologies so that every year new projects can be given to students. While in the 2021–2022 academic year, the project assignment was to design a Flyback converter, the description provided hereafter is kept generic and whenever possible detached from the actual topology. It is important to stress that, being their first practical experience, students are not expected to "*design optimize*," but only to "*design*" converter fulfilling simplified technical requirement specifications.

A typical example is provided in Table 1. As can be seen, every project team has identical power ratings (kept low at 50 W for practical reasons, and with voltages being lower than 100 V), identical current and voltage ripple requirements, but different input/output voltage ranges and different predefined switching frequencies. At the same time, logic circuits, such as the PWM IC controller, gate driver IC, shunt amplifier, etc. are defined in advance and must be used for the design. This greatly simplifies the management of the course and care is taken that all designs can be served with selected devices. A portfolio of preselected MOSFETs and diodes, as well as various heatsinks are made available to students for their designs.

Course Logistics

The course is typically attended by around 40–50 students per year. To relieve the workload and to train some organizational and management skills, the students are randomly grouped into teams of two, creating project teams rather than having them do all the work individually. The purpose behind this random designation is to emulate, on a small scale, an engineering industrial reality, where one rarely ends up working with the best friend.

> ***The course is typically attended by around 40–50 students per year.***

Design specifications from Table 1 are also randomly allocated to each project team. Having different specifications assigned to each group prevents copying and incentivizes critical thinking. At the same time, students can see through comparison between their own and other groups' designs, how some parameters and/or requirements can have a huge impact on the final converter prototype (e.g., in size/weight, efficiency, etc.).

Four Teaching Assistants (TAs), typically Ph.D. students or postdocs from the Power Electronics Laboratory at EPFL, are allocated to support the course execution during the semester. In order to make this realistically possible, a semester before, those four TAs would go themselves through a design process of four different converter specifications, as if they are doing the course themselves and thus be completely ready to supervise the course. While this is an effort and a big burden, it is absolutely necessary and even beneficial for fresh Ph.D. students who may have had no opportunity to do any practical design earlier. At the same time, the TAs will get to know the main challenges and struggles of the specific design, with the aim to identify a systematic way to overcome them. This preparatory phase is also used to create structured project guidelines and reporting templates that are then used by students to report their progress and results throughout the semester, which is 14 weeks long. This is organized in four distinctive reports, as illustrated in Figure 1, where the overall course structure is shown.

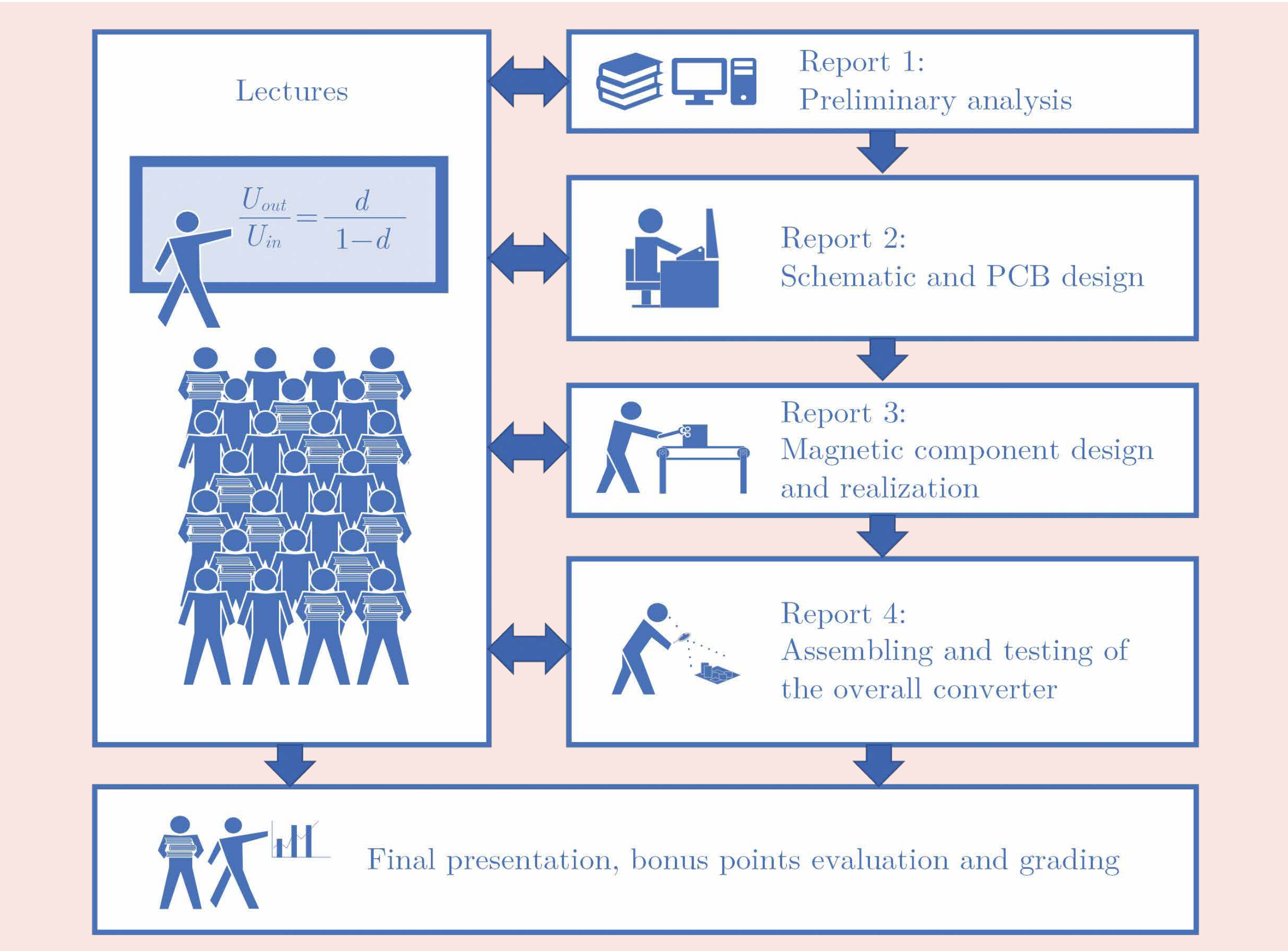

FIG 1 **General structure of the course and link between lectures and practical laboratory sessions.**

Report 1 covers the early phase of electrical circuit sizing according to specifications. The students get familiar with the assigned topology and learn how to simulate (through PLECS [9]) its basic operating principles, verify voltage and current stresses, calculate losses and select suitable semiconductor devices. They learn to analyze simulation results and compare them to analytical predictions. Then, theoretical loss calculations are performed and thermal design is finalized (e.g., selection of heatsink or printed circuit board (PCB) pad for cooling). Figure 2 illustrates some examples related to this part of work.

Report 2 represents the largest effort of the course, as the students learn how to design the schematic and the PCB of their converter. To be more specific, the electrical schematic is designed in ALTIUM [10], all components are sized and selected (e.g., correct ratings, footprints, etc.) both for power parts (e.g., semiconductors and passive components), sensing (e.g. shunt resistors, voltage dividers) and control IC surrounding circuitry (e.g., PWM IC, TL431, optocouplers, gate driver IC). The PCB design is then finalized and PCBs are ordered. Figure 3 shows an example schematic and PCB design. Some teams are more creative than others and count on the mystical powers of Pikachu.

Report 3 deals with the design of passive components for a given topology (e.g., inductors, coupled inductors, transformers). Some work stations are provided for manual assembly of the magnetic components and for the validation of their electrical parameters, saturation characteristics and temperature rise, as illustrated in Figure 4. Several winding iterations are common, and broken ferrite cores and coil formers are even more common. A universal footprint matching several core sizes is used during PCB design, to allow for passive component design, while we are waiting for PCBs to be manufactured and delivered.

Report 4 is essentially a commissioning and test report, during which the students assemble their PCBs and assess their functionalities. As project teams start to solder their PCBs, they also start collecting various measurement data to validate the correct operation of different sub-circuits. This way, they learn to split the overall testing into multiple small tasks, which makes it easier to debug eventual malfunctioning. The most exciting part is also the most frustrating as it involves debugging your own mistakes, realizing minor or big errors. Once converters start working, various electrical measurements are done to document converter performances. Operation at various input/output voltages as well loads is verified, control loop characteristic is measured using BODE 100 [11], control performances are measured using active loads, efficiency under different operating conditions as well as thermal performances. An example is provided in Figure 5.

In each stage of the course the students follow and compile technical reports, that provide them with a detailed step-by-step procedure to analyze, design and test their converter, moving progressively and systematically towards a functional prototype. Report templates, illustrated in Figure 6, are provided and prepared using Overleaf [12], greatly simplifying management of the process and leading to a uniform reporting from all teams.

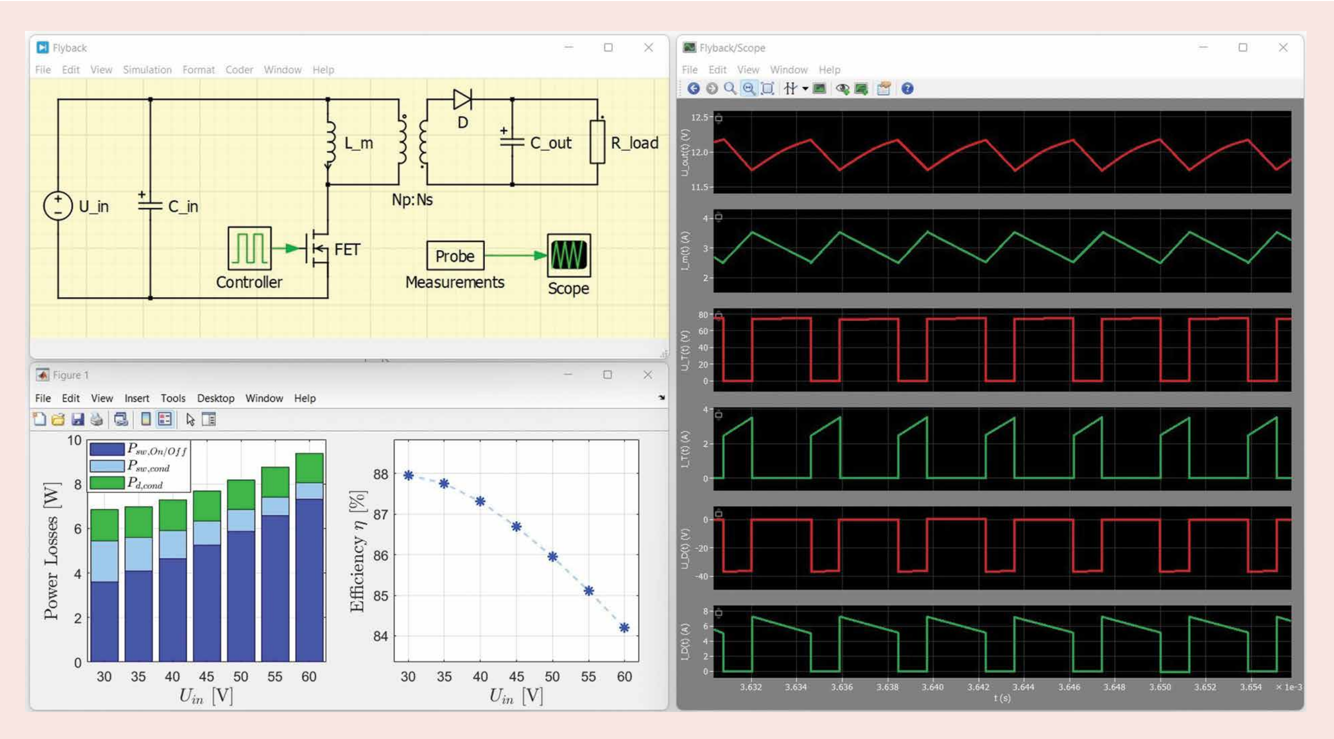

FIG 2 Example of the analysis and simulation activities performed during Report 1.

Lectures are adjusted to introduce relevant concepts in time and support practical design considerations, while laboratory exercise sessions are completely devoted to required design steps.

Grading and Incentives

Following a project-based course during a semester full of other courses, is not an easy task for students. To ensure continuity and feedback on the work, all four reports are graded during the semester, and together with the final presentation at the end of the semester, they contribute to the final grade. In addition, several bonus categories are introduced allowing project teams to score extra half a grade in categories, as listed in Table 2.

These bonus categories reveal to be stimulating and engaging for students, who are productively motivated

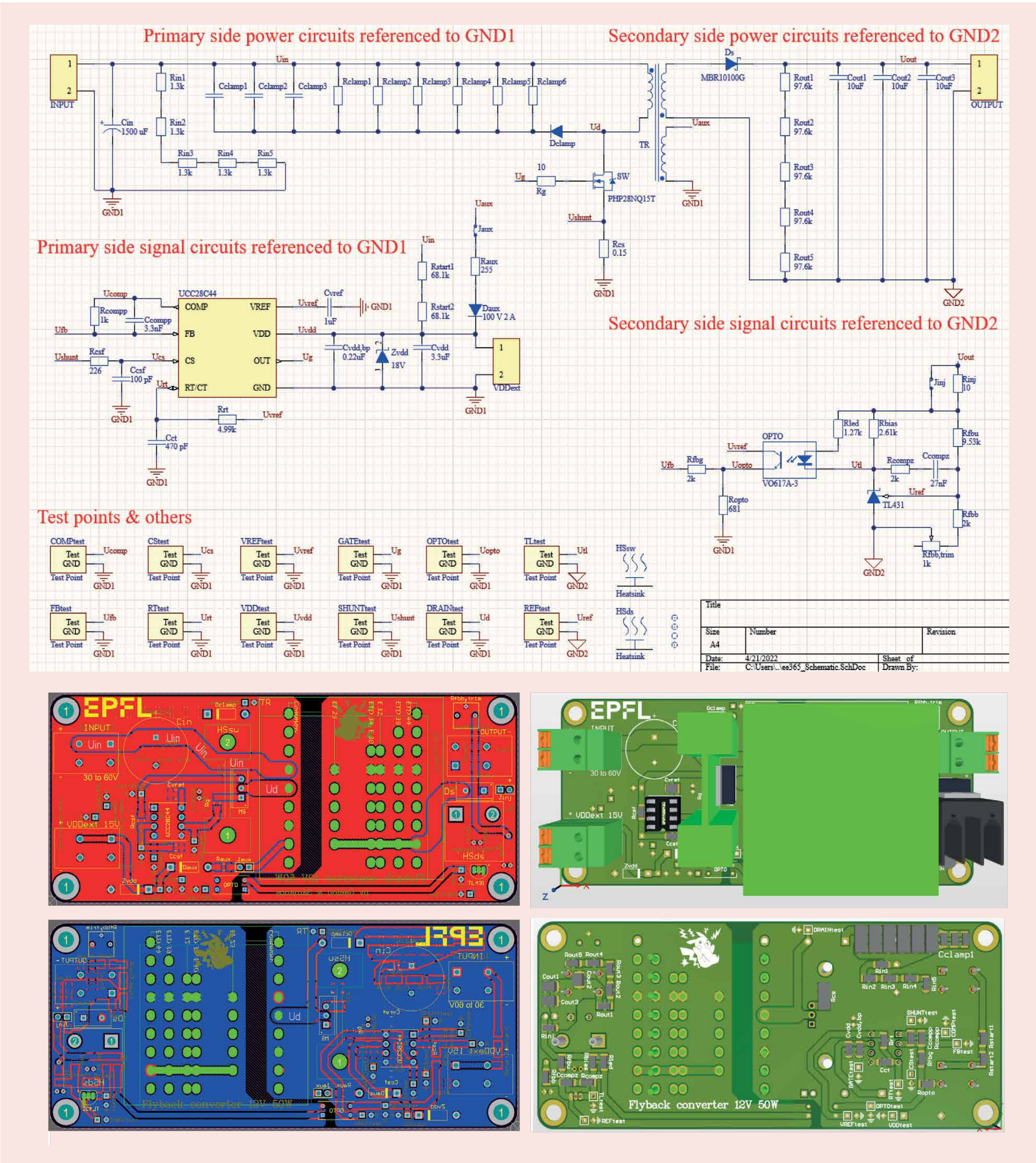

FIG 3 Example of the schematic and PCB design performed during Report 2.

FIG 4 Example of the manual assembly and testing of magnetic components performed during Report 3.

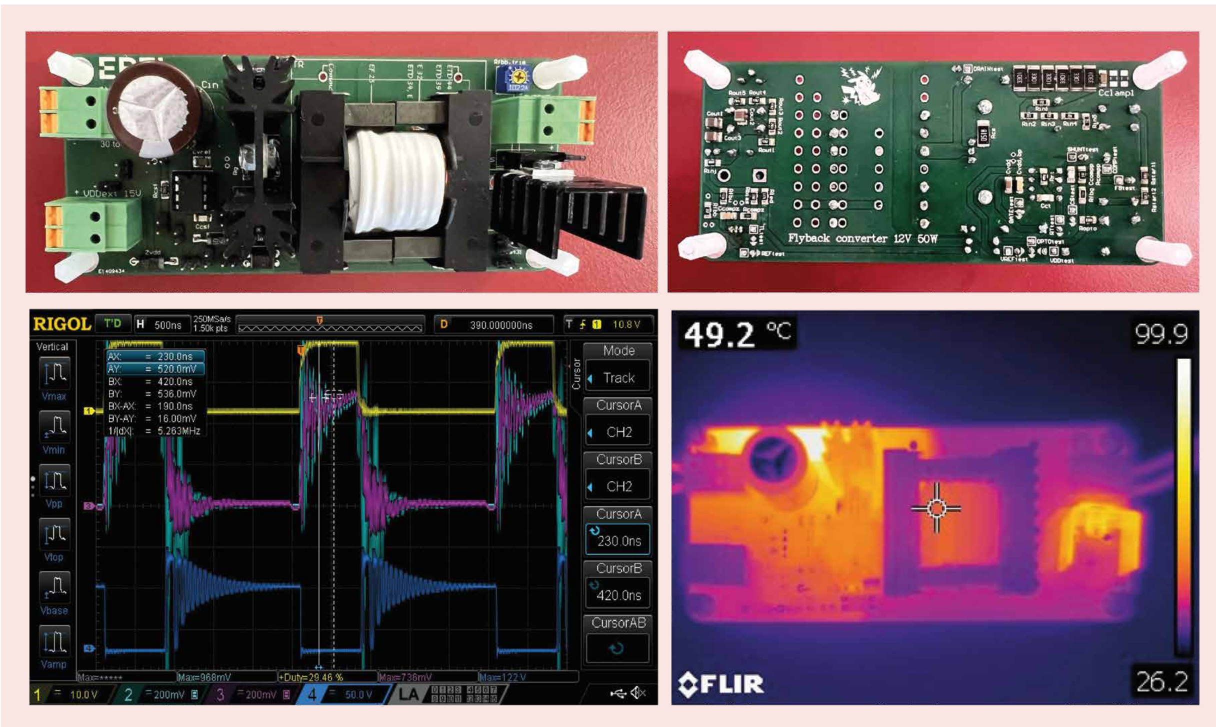

FIG 5 Example of an assembled PCB and of some test results performed during Report 4.

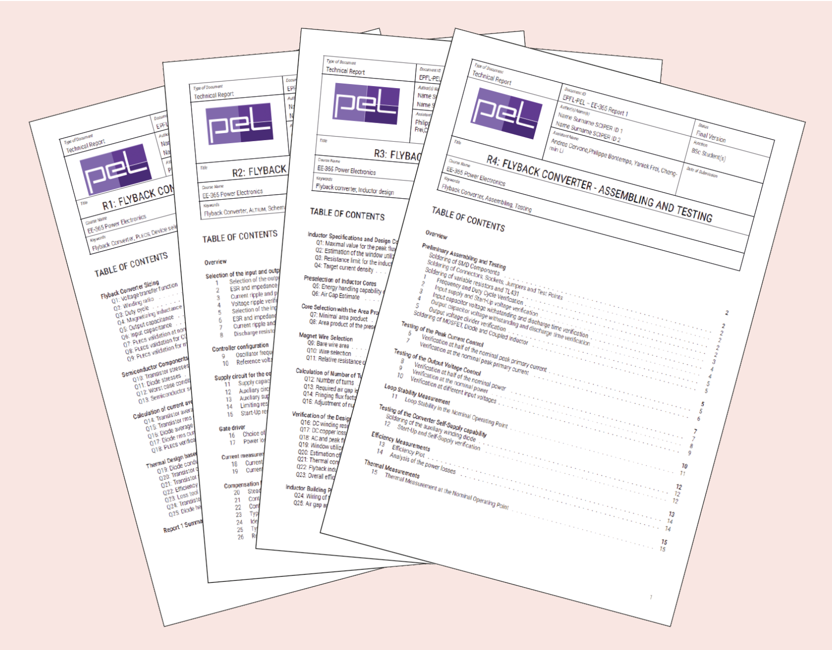

FIG 6 Example of the technical report templates provided to the students.

to challenge themselves to excel in a category of their choice.

Overall Impressions and Learnings

The course is demanding, and students are not shy to report that and complain all the time. While carefully structured and logically guided, many design steps are new to them and require revision of some previous courses on electronics, as we simply expect that they need to know some basics (e.g., low pass filter sizing, Op-Amp principles, etc.). They realize also that there is a big gap between "*knowing something in theory*" and "*having it done practically.*"

Motivated by incentives, very quickly it emerges that different project teams focus their efforts towards certain of the previously mentioned bonus categories. With switching frequency not being a parameter that they can change in their specifications, they also develop an understanding of why other teams have smaller or bigger passive components. Extreme range of switching frequencies also impacts their semiconductor losses, and range of input/output voltage impacts their PCB routing and filtering needs.

As the control is performed by the PWM IC, and feedback circuitry contains a TL-431 and, in case of an isolated topology—an optocoupler, everyone learns to read various datasheets or application notes. Being a new source of information for students, there is typically a struggle in the beginning, as the language of this course is not that of the textbooks, but rather of expert engineering level. Datasheets for semiconductors are widely different from those for magnetic core materials, aiding further to the challenges.

While everyone is designing the same converter topology, with the same set of ICs but different electrical parameters, ultimately everyone is having the same

Table 2. Bonus categories allowing to score extra points towards the final grade.

Category	Remarks
The best efficiency	Experimentally evaluated at rated operating conditions.
The best power density	Overall enclosing volume of final solution is measured.
The coolest design	Thermal performances are measured after 15 minutes of continuous operation.
The most stable control	Phase margin and Gain margin are measured using BODE 100.
The smallest leakage inductance	In case of Flyback coupled inductors, this was judged important due to clamp circuit losses.
The best matching magnetizing inductance	Considering specifications and measured results.
The cheapest design	Based on the Bill of Material of each design.
The best-looking PCB	Somewhat artistic category.
The best reports	Based on the overall look and feel and clarity of reports.
The best final presentation	Based on the final presentation project by project team.

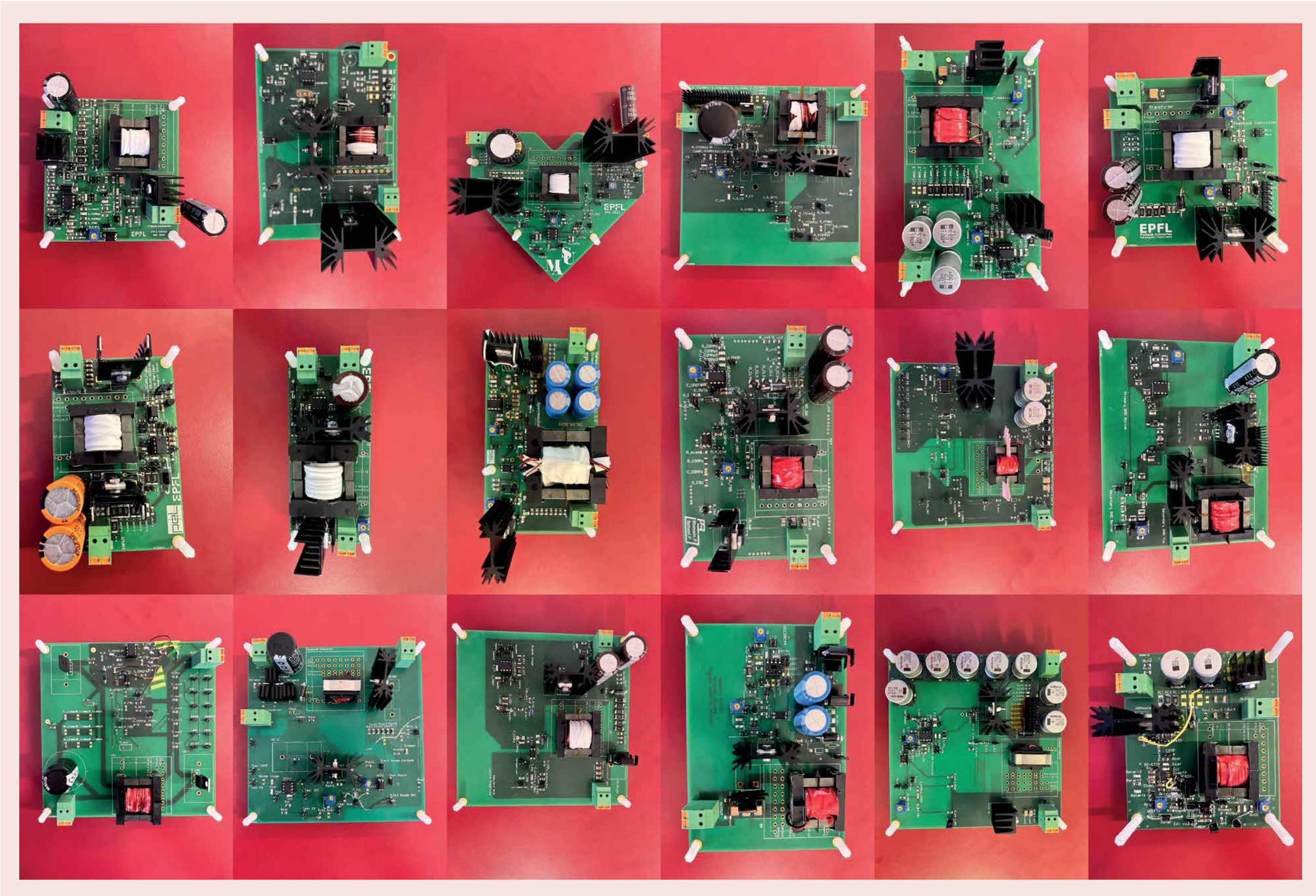

FIG 7 Flyback converters realized by the students in the academic year 2021/2022.

electrical schematic. Clearly, there are differences in values, number of parallel or series connected resistors or capacitors, as specifications are different for every team. This also helps them clarifying the difference between basic circuit diagrams, shown in text books to catch the working principle of a power converter, and schematic diagrams, used for real design and implementations. While we review the schematic for everyone, the PCB design is not reviewed. Instead, an ALTIUM PCB training session is organized and all the needed best practices are presented, terminology is clarified, examples are provided, etc. Irrespectively, mistakes are always made by some teams and patched later during soldering and testing. This is nothing unusual or penalized, as identifying and correcting mistakes is by itself a fundamental aspect of the learning process. Most of the troubles during soldering or debugging are due to a lack of practical experience and while we can predict and prevent many erroneous attempts, many ICs die in the process. Thus, we avoid using SMD components for sensitive parts, but rather utilize through-hole ICs with sockets on the PCB. Clearly not a 21st century technology, but very suitable for the objectives of the course.

There is a great deal of satisfaction achieved at the end of the course, seeing students being very proud of making something working for the first time.

On the soft skills side, students learn to work in a team, even if that team is very small. The success of the project depends on the team performing efficiently, as both team members are receiving the same grade, irrespectively from actual contributions, which may or may not be observed during interactions with them. They also learn, immediately and quickly after scoring not as expected on the Report 1, how to write technical reports. Initial tendency to write essays, repeat material from lecture slides, express opinions and not facts, and describe steps of a process rather than results in a clear and concise manner is rectified.

With every week of the course, project teams are one step closer to the working converter, and the overall mood and motivation changes significantly. Complaining about the workload is replaced by desire to get the PCB working and processing power.

When the light at the end of the tunnel comes within reach, the motivation is boosted, and the last few weeks of the semester and week or two after the semester ends, Power Electronics Laboratory is full of students coming to finalize their designs and collect their measurement results.

Finally, Figure 7 provides an overview of many realized Flyback converters from 2021–2022 academic year. Eighteen out of 20 teams have managed to get their converters working with an acceptable level of performance, considering the novice design team behind doing it for the first time ever.

Conclusion

There are clearly many ways how power electronics can be taught, and this article summarizes details and practices we deploy. There is a great deal of satisfaction achieved at the end of the course, seeing students being very proud of making something working for the first time. Even if the final result does not work as expected, they are most of the time able to explain what mistakes were made and what is the cause of a strange behavior or lack of performances. They also get to keep their converter after the end of the course, as a trophy of some sort. Ultimately, we are managing to achieve our learning objective and, at the same, the complexity and beauty of power electronics designs get revealed, hopefully motivating many to join into the community and dedicate careers to it.

Acknowledgment

The authors would like to acknowledge all EPFL Bachelor students who have successfully designed their converter prototypes during the Power Electronics course (EE-365): Delphine Lucie Allimann, Mathias Antonio Arnold, Johanna Laure Diane Crucke, Oulaya Darbi, Nicolas Antonin Devaux, Benjamin Duc, Matthieu Julien Duret, Evan Cyril El Khoury, Ismael Tobias Frei, Santiago Gallego Restrepo, Eva Paloma Garcia Bermejo, Loïc Ginesi, Michael Ha, Luc Iain Harrison, Anis Hassan, Charlotte Arielle Florence Heibig, Mathilda Myriam Aïda Souad Henoud, Victor Marc Joseph Jean Henry, Sam Guy Houliston, Severin Leander Julen, Louis-Léandre Mackaya, Micah Yo Maheo, Cecilia Stella Männik, Gaël Metras, Asbjørn Nisi, Romain Alain Jacques Peseux, Nearchos Potamitis, Ariane Coline Priou, Ludovic Pujol, Clement Weihao Samanos, Lucile Anne Siegfried, Pablo Suárez Reyero, Seyedehfatemeh Taghishokrgozar, Konstantinos Tolanoudis, Sinan Ulcay, Matthis Valentin Lucas Valazza, and Valentin Antoine Roger Vuillon.

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