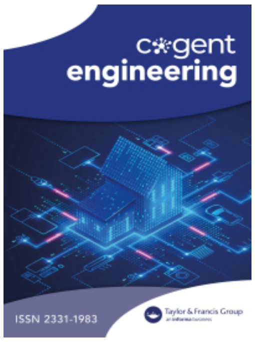

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A proposal to start training students in power electronics for experimental activities

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ABSTRACT
This article presents the proposition, application, and results of a graduate course focused on practical aspects of developing converters and applications in Power Electronics. The initial motivation behind the initiative was to mitigate the loss of laboratory experience resulting from the closure of laboratories or restrictions on shared access imposed by the COVID-19 pandemic, resulting in the breakdown of the synergistic experience that characterizes practical activities in the research environment. Over time, it was realized that the lack of practical experience in power electronics activities was related to structural issues in the training of engineers, and the pandemic worsened the situation. This signaled that the course could and should be offered regularly. Five themes were focused on topologies, power devices, passive devices, electromagnetic compatibility, thermal design, and electronic and control circuits. The activities included theoretical classes, laboratory classes, technical visits, and simulation exercises, ending with a final project. At the end of the course, an evaluation process with the students made it possible to verify a significant gain in knowledge in the different topics covered, especially in topics less emphasized in traditional courses, such as magnetics components design, printed circuit board development, thermal analysis, and EMC aspects.

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1. Introduction

The importance of practical experience for the training of professionals and academics in the field of Power Electronics has been discussed at length, mainly in terms of undergraduate education (Koleff et al., 2020; Pomilio, 2020; García et al., 2013). Everyone who researches and teaches in this field of knowledge knows the importance of practical experiences for consolidating learning. Numerous relevant phenomena are not modeled in simulators or analytical formulations and only manifest when dealing with operational prototypes. Thermal and electromagnetic compatibility phenomena, especially the latter, present great difficulty in measuring, modeling, and, therefore, numerical simulation under the typical operating conditions of a power electronic converter (Wunsch et al., 2021; Kato et al., 2009; Wilson, 2018).

Alongside technical issues, there is also the formal scenario of higher education. For historical, cultural, and economic reasons, it is not prudent to directly compare the conditions of access and retention of the Brazilian higher education system with those in more developed regions, such as Europe. On the other hand, it is undeniable that central countries' educational guidelines influence Brazil's path.

The approach, already fully accomplished in the European university structure (Moscovitz & Zahavi, 2020; Gaston, 2023), with a similar approach seen in North America, is to shorten training at the undergraduate level and facilitate the completion of the master's degree, which, in principle, could be completed after five years of entering higher education, the standard time for undergraduate Engineering courses in Brazil.

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Thus, changes in the curriculum guidelines for engineering education are compounded by the imperative to shorten course durations, resulting in curricula that closely approach the minimum hours limits (de Oliveira, 2019). As a result, we observe the removal of specific subjects or the reduction of content previously considered essential for the comprehensive education of engineers. Technological evolution can make some concepts obsolete, which partially justifies these changes. However, the pressure to reduce workload may overlap with a more in-depth discussion of the concepts essential to training.

It is also common for workload reductions to occur through the elimination and/or virtualization of teaching laboratory activities (Al-Nakhle, 2022; Mercado & Picardal, 2023). In this case, the issue of reducing class hours is combined with the minimization or elimination of financial investment in the creation, maintenance, and modernization of such laboratories.

Additionally, the deficit in engineering training results in pressure from companies and students to carry out internships early. Although the importance of this phase in professional training cannot be denied, so much so that it is mandatory, its completion in the preliminary stages of the professionalizing part of the course harms academic achievement, taking away precious study hours from students. Consequently, scientific initiation activities are also hampered, and there is a lower number of applicants.

If these aspects are structural, as they result from how Engineering courses have been structured in recent years, in 2020 and 2021, they all suffered the impacts of the restrictions imposed by the COVID-19 pandemic (Gusso et al., 2020). Teachers and students had to adapt to a complete distance learning structure, looking for improvised solutions and reformulating class, study, and assessment methods.

Although the academic impacts of these events are still being assessed, within the scope of this article, it is considered that there was significant, irrecoverable damage in practical teaching activities. Substantial losses in student training can be listed as the need for familiarity with laboratory equipment, the reduction in cooperative activities typical of laboratory classes, and the deficiency in the analysis of actual behavior in experiments compared to theoretical or simulation expectations. All these aspects are general in engineering training for any specialty. This article focuses on power electronics, which is deeply dependent on the experimental proficiency of students and researchers.

Concerning research activities, so many graduate projects had to be reprogrammed, minimizing or even eliminating experimental activities, replacing them with simulations of different types, as the counting of completion time, financing, and, mainly, exchanges did not follow the pandemic calendar.

With the normalization of face-to-face activities from 2022 onwards, it became evident during the admission selection processes that new graduate students, both master's and doctorate, had little or no bench experience. During the pandemic, there was a disruption in the typical dynamics of research laboratories, where students coexist in a very synergistic and motivating manner, engaging in intense exchanges of experiences and sharing information.

Trying to fill or minimize this gap in training new students became imperative. It was necessary to create conditions so that practical experiences that had not occurred could be concentrated in time and space with accelerated learning.

These objectives created a course of an eminently applied nature. It is not just a laboratory discipline but a set of initiatives that put students face to face with the challenges of the "real world" of power electronics.

Several authors have highlighted the importance of practical and laboratory experiences in regular PE courses. In this context, Project-Based (PB) methodologies have emerged as suitable approaches for PE courses, mainly at the undergraduate level (Chen & Lai, 2021; Shahnia & Yengejeh, 2019; Herrero-de Lucas et al., 2022; Zhang et al., 2016). The PB approach emphasizes teaching to solve specific real-world problems, such as developing a power converter or control strategy for a certain application (Herrero-de Lucas et al., 2022; Zhang et al., 2016). Under this approach, students engage in practical projects, applying theoretical knowledge to analyze and optimize specific power electronic systems.

Despite the consensus on the importance of practical activities in PE courses, the present proposal has two major differences from the PB approaches. First, the proposed course is intended for graduate students with a prior background in basic PE. Therefore, the laboratory activities are not aimed at validating basic PE concepts. Second, in the proposed methodology, the theoretical classes are not focused on basic PE concepts but rather on analyzing phenomena that arise in practical scenarios. Thus, the practical experiences are not considered as validating instances but, instead, as the source of the subjects studied.

Unlike other courses that focus on developing specific power converters, as presented in (Chen & Lai, 2021; Shahnia & Yengejeh, 2019), this course introduces students to the typical challenges of developing practical prototypes, regardless of the specific application. Thus, the main focus is studying these practical phenomena, their causes, consequences, and the corresponding treatments.

Even though it was initially designed in response to the impacts of the pandemic, it was found convenient to repeat the offering annually in order to expand, in a targeted manner, the practical knowledge necessary for the development of experimental projects.

Next, this article presents the planning and execution of the discipline: "Topics in Power Electronics II: Conceptual and practical aspects of Power Electronic Converters design," as well as an evaluation of the results of this initiative based on the students' feedback.

2. The course structure

At the end of the course, the expectation is that students should be able to map the requirements of a particular application, select a topology and size of a power electronic converter in terms of electrical and thermal specifications, design and construct magnetic elements, and characterize them in the frequency domain. They are also expected to consider thermal and electromagnetic compatibility aspects when designing printed circuit boards and power assemblies and specify and select voltage and current sensing devices for designing signal conditioning circuits for sensor interfaces and the digital command and control system.

The course is conducted in person, comprising 15 weekly sessions, each lasting four hours, resulting in 60 hours. In weekly meetings, theoretical and laboratory classes alternate, and visits to research laboratories are carried out to learn about ongoing projects, check challenges for creating prototypes, and monitor tests. Intensive circuit simulation (based on PSPICE models) improves the modeling and includes parasitic behaviors and non-idealities. At the end of the course, participants individually define a project, with source and load specifications and general aspects of sizing of the power circuit, and develop an electronic signal conditioning system applicable to their specific case, presenting simulation results.

The course program consists of five units:

1. Introduction to power electronic converters and control techniques
   - Power switches: diodes and transistors;
   - Experiments and verification of non-idealities in diodes and transistors;
   - Reading and interpretation of characteristic sheets;
   - Principles of DC-DC Converters;
   - DC-DC converter selection criteria;
   - PWM modulation and hysteresis, static characteristic;
   - Principles of DC-AC Converters and control systems;
   - Sinusoidal and vector PWM modulation, static characteristic.
2. Thermal aspects
   - Estimation of losses from catalog data;
   - Thermal resistance and impedance;
   - Sizing of heat dissipation systems.
3. Passive Elements (capacitive and magnetic)
   - Types and characteristics of capacitors;
   - Ferromagnetic materials;
   - Sizing and construction of inductors and transformers;
   - Experimental characterization and verification of device non-idealities.
4. Principles of Electromagnetic Compatibility (EMC)
   - Causes and consequences of electromagnetic interference (EMI);
   - Practical aspects of creating printed circuit boards and power assemblies;
   - EMI filters;
   - Conducted and irradiated EMI compliance tests.
5. Electronic systems and circuits supporting power electronic converters
   - Power supplies and voltage regulation;
   - DSPs and peripherals;
   - Voltage and current sensors (characteristics and limitations);
   - Signal conditioning circuit (filters, regulators, amplifiers, and offset);
   - PWM circuit, voltage rise, and protections;
   - Relays and contactors;
   - Debugger and code recording;
   - Analog-digital conversion;
   - Communication interfaces.

A general overview of the course structure is depicted in Figure 1, where practical design activities

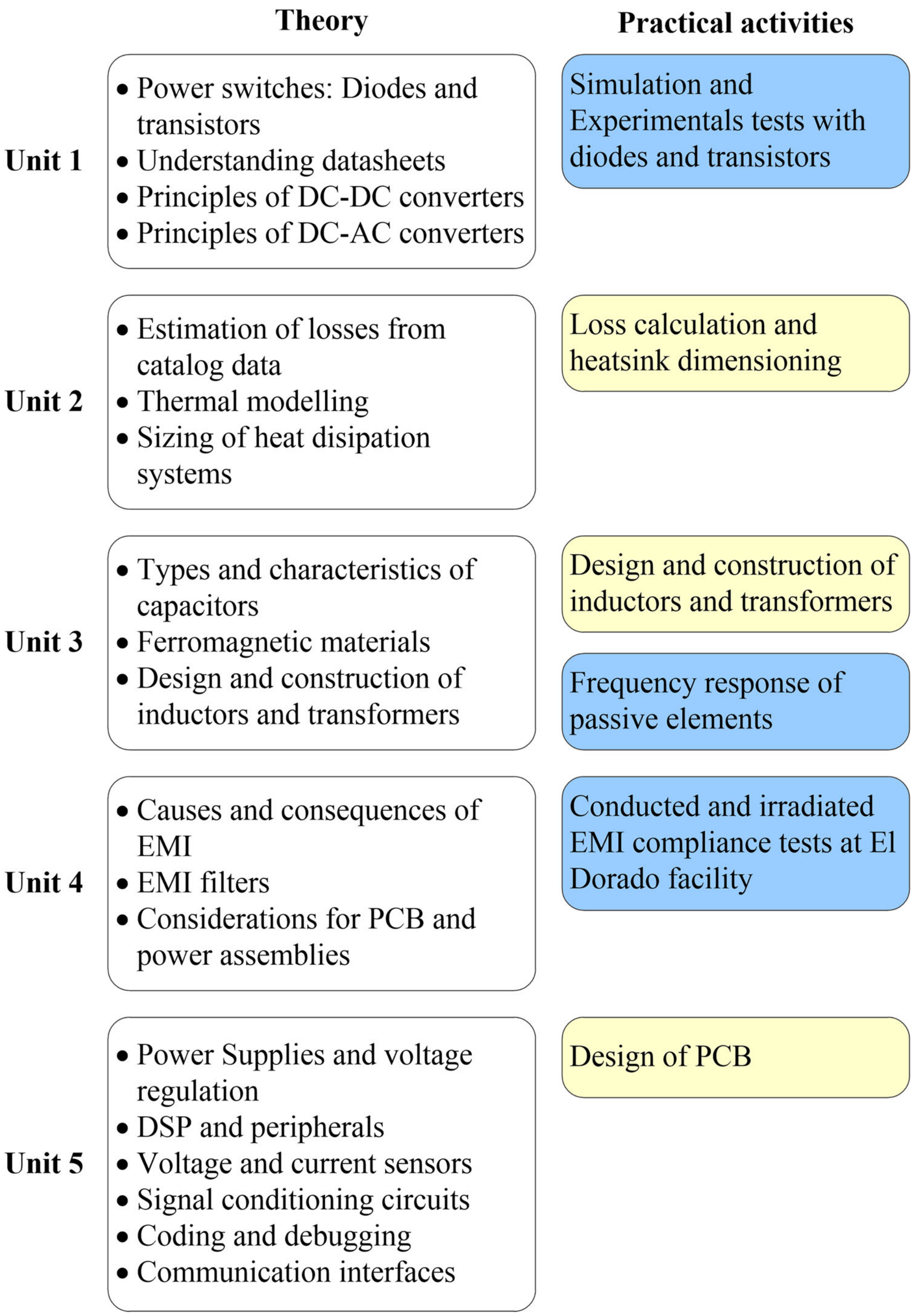

Figure 1. Overview of the course structure.

are highlighted in yellow, while experimental activities are in blue.

2.1. Practical activity: tests with diodes and transistors

The first practical activity in the teaching laboratory is testing semiconductor devices. The circuit for experimental tests is shown in Figure 2. Before the laboratory session, a simulation exercise is conducted to anticipate certain phenomena that will be experimentally verified, such as reverse recovery and junction capacitance of diodes. Regarding transistors, the simulation examines the impact of various drivers on switching performance.

The main objective of the experiment is to identify and quantify device non-idealities. A square wave oscillator provides the signal for comparative tests of three different types of diodes (fast diode, Schottky diode, and slow diode) and three transistors (MOSFET, IGBT, and bipolar). Circuits are tested with resistive load and inductive load. The impact of

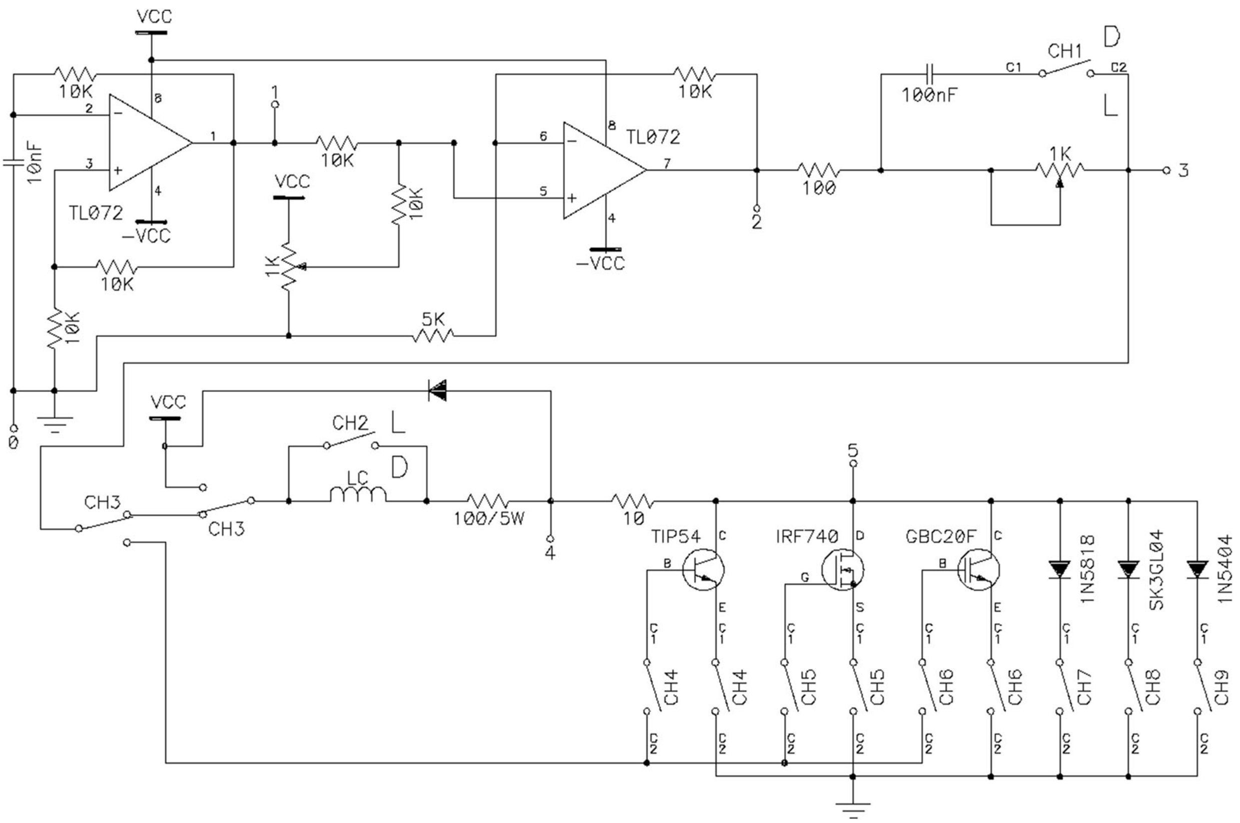

Figure 2. Circuit diagram for comparative tests of diodes and transistors.

different transistor control circuits (drivers) is verified by analyzing switching time delays and switching losses. For the diode, the reverse recovery behavior and the capacitive effects of the reverse-biased junction. Figure 3 shows some of the results observed, identifying non-idealities of the components.

2.2. Practical activity: Frequency response of passive elements

The main objective of these tests is to identify the non-idealities of passive elements: capacitors, inductors, wires, filters, and transformers (de Souza & Pomilio, 2018; de Souza et al., 2019).

The basic test obtains the behavior of the dipole impedance and establishes a linear circuit model to represent the device. It uses a function generator and an oscilloscope, allowing satisfactory results.

Checking the frequency response, which allows for obtaining the device's impedance, is done by observing the voltage and current (inverted) in the element under test, as shown in Figure 4, which illustrates the test of a capacitor. The internal resistance of the function generator is $R_i = 50\ \Omega$. The resistance over which the current is observed is chosen to have an adequate signal-to-noise ratio. In the case of testing, a $C_{test} = 20\ \mu F$, $R_{shunt} = 10\ \Omega$ was used. The function generator V_{sin} provides a sinusoidal output at no load, with 10 V peak to peak, without offset. It is suggested that average acquisition be used to reduce the influence of noise.

Scanning 4 to 5 decades, the regions of capacitive and inductive operation are easily identified, as well as the series resonance, making it possible to define an equivalent circuit with lumped parameters of the series CLR type. The same procedure is applied to an inductor and more complex arrangements, such as an LC filter and a transformer.

Since a Bode 100 network analyzer is also available, additional tests were carried out, confirming the results collected from the simplified tests but expanding the analysis range, making it possible to identify other non-ideal behaviors, such as the skin effect of conductors. The main features of this analyzer are a frequency range from 1 Hz to 50 MHz, adjustable output level from -30 dBm to 13 dBm, switchable channel input impedance (50 Ω/1 MΩ), highly sensitive inputs (superheterodyne receiver with 24-bit ADCs) and narrow-band receivers for highest noise rejection.

Figure 5 shows an inductor subjected to the impedance test and the corresponding model with

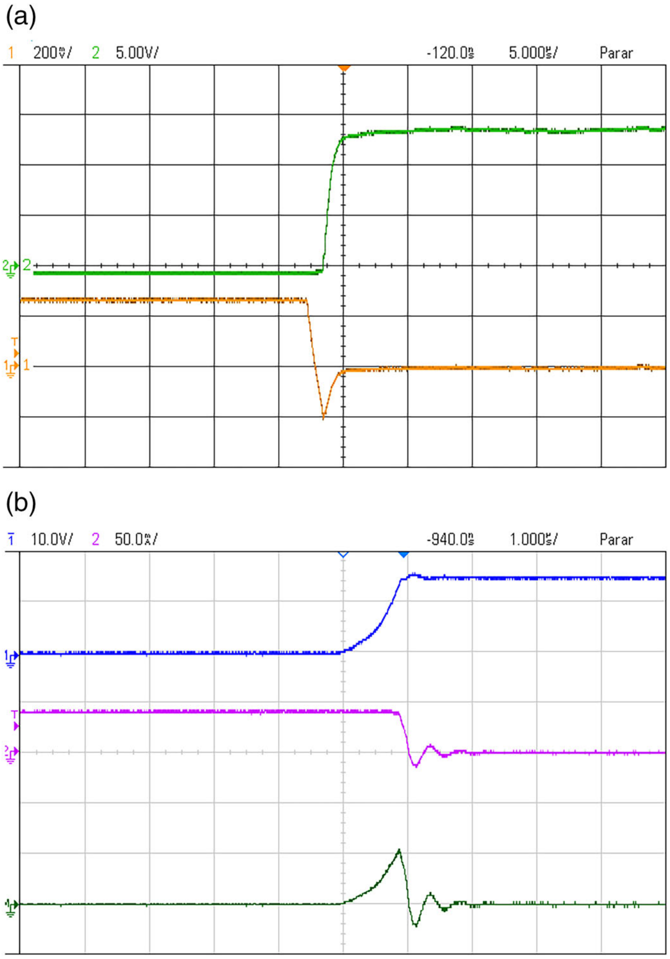

Figure 3. Results of the experimental verification of diode and MOSFET non-idealities.
a) Diode test: V_{ka} (top trace, 5 V/div.), I_a (bottom trace, 20 mA/div). Horiz.: 5 µs/div. b) Transistor test with inductive load: V_{ds} (top trace, 10 V/div.), I_d (center trace, 50 mA/div.), and power (bottom trace, 0,5 W/div.). Horiz.: 1 µs/div.

parasitic elements. For this model, the corresponding impedance is defined in (1). The test results are shown in Figure 6.

$$\boldsymbol{Z_L} = \frac{\boldsymbol{R_p L_s s + R_s R_p}}{\boldsymbol{C_p R_p L_s s^2 + (C_p R_p R_s + L_s)s + R_s + R_p}} \qquad (1)$$

A parallel resonance is expected from the equivalent circuit, observed at 542.9 kHz, showing inductive behavior at lower frequencies. Specific impedance measurements were carried out at four frequencies, as shown in Table 1.

The impedance value measured at 2 Hz corresponds to the series resistance value R_s (2). The value of the impedance at the resonance frequency allows for estimating the value of the parallel resistance R_p (3), which is associated with losses in the core at this frequency. The impedance at 7 kHz is determined by the inductance, obtaining a value of 2.84 mH (3), and the phase at 90°. For frequencies above resonance, the impedance assumes capacitive behavior, equivalent to 30.8 pF (4), representing the effect of inter-turn capacitances. Above 3 MHz, the multiple series and parallel resonances can be explained by the combinations of inter-turn

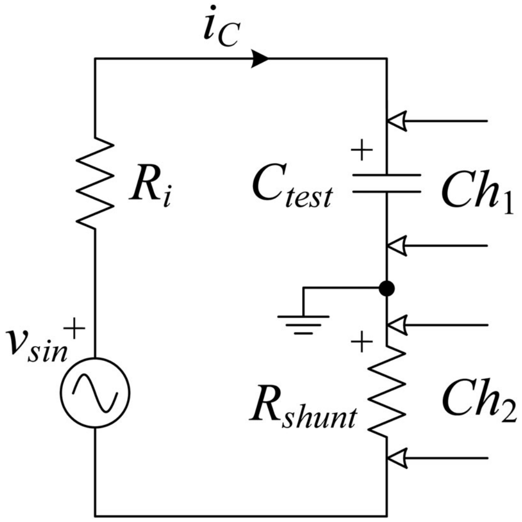

Figure 4. Capacitor frequency response test circuit.

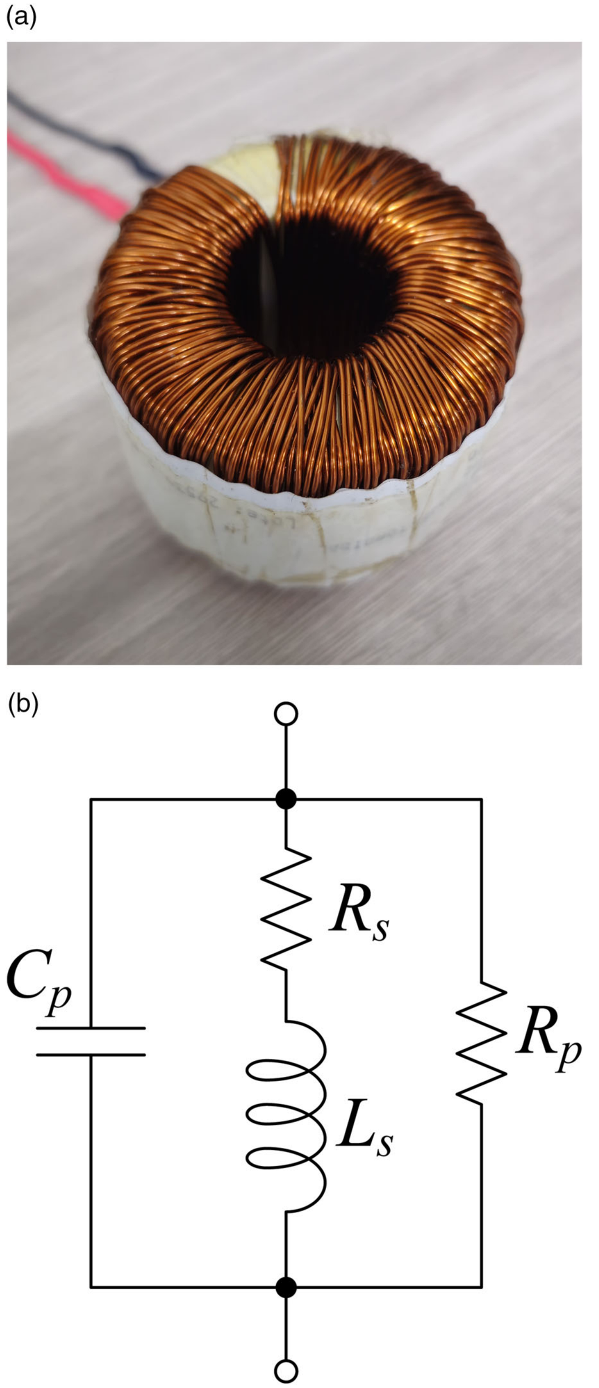

Figure 5. Inductor under test: (a) Component, (b) Equivalent circuit with lumped parameters and respective impedance expression.

capacitances with inductances in a behavior like a transmission line.

$$\left|\boldsymbol{Z}_{\boldsymbol{L}(2\mathbf{Hz})}\right| = 224.54 \quad \mathrm{m}\Omega \approx \mathrm{R}_s \tag{2}$$

$$\left|\boldsymbol{Z}_{\boldsymbol{L}(542\mathbf{kHz})}\right| = 117 \ \mathbf{k}\Omega \approx \mathrm{R}_p \tag{3}$$

$$\left|\boldsymbol{Z}_{\boldsymbol{L}(7\mathbf{kHz})}\right| = 125\Omega \rightarrow L_s \approx 2.84 \ \mathrm{mH} \tag{4}$$

$$\left|\boldsymbol{Z}_{\boldsymbol{L}(2\mathbf{MHz})}\right| = 2.582 \ \boldsymbol{k}\Omega \rightarrow C_p \approx 30.84 \ \mathrm{pF} \tag{5}$$

2.3. Technical visit: standardized tests and electromagnetic interference

Electromagnetic compatibility was approached from practical power electronics situations, analyzing the layout of printed circuit boards (PCB) and the impacts of achieving compliance with EMC standards. The theoretical aspects of the phenomena, including their equations and spectral analyses, were worked on with power devices' characteristics and converter topologies. This approach facilitated an understanding of the relationship between EMC's physical phenomena, the operational aspects of the converters, and the conditions arising from layout and assemblies. Although it has specific EMC content, the analysis is based on the themes previously analyzed in the course: topologies, semiconductor issues, and potential solutions. The construction of magnetic devices, shielding alternatives, and PCB layout techniques were also presented and discussed (Orlandi et al., 2011; Rossetto et al., 2000). Figure 7 shows the layout of a half-bridge made with GaN devices that was used to discuss recommended procedures for making PCBs while minimizing EMC problems.

Furthermore, a visit is made to a certified laboratory (Eldorado Research Institute, Figure 8) to carry out both irradiated and conducted EMC tests using a converter developed in the research laboratory to compare with limits established in the standards (European Committee for Electrotechnical Standardization, 2021).

During visits to research laboratories, students had the opportunity to discuss details of prototype construction with researchers, emphasizing practical challenges and adopted solutions. During this technical visit, a grid-connected inverter (GCI) was tested for compliance with EMI standards, including CISPR 11 for radiated emissions limits and IEC 62920 for conducted emissions. Figure 9 shows the prototype (left) and results (right).

This experience made it possible to bring the generic analyses carried out in theoretical and practical classes closer to the objective questions of developing EMI-compatible prototypes.

2.4. Printed circuit board design

The course also covered electronic systems design, schematics elaboration, and printed circuit board (PCB) design for power electronics applications. In this activity, students learned the basis of control board design for high-performance microcontrollers

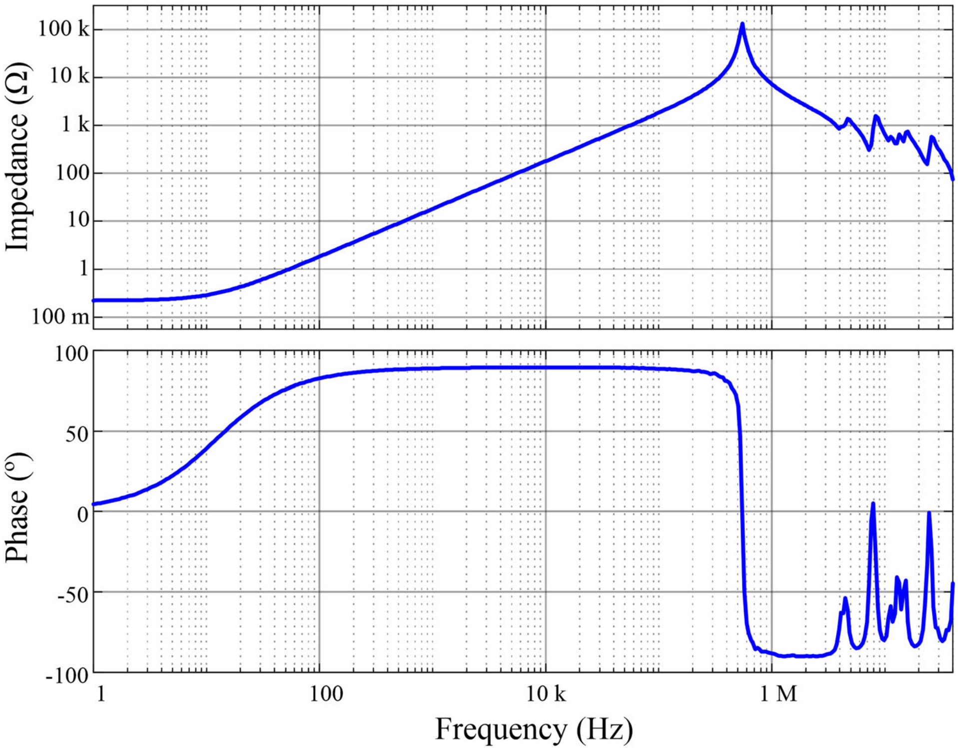

Figure 6. Measurement of module (in red) and phase (in blue) of the inductor impedance, measured with Bode 100.

Table 1. Inductor impedance measurements.

Frequency	Amplitude	Phase	R_s	R_p	L_s	C_p
2Hz	224.54mΩ	7.14°	221mΩ	–	–	–
7 kHz	125 Ω	89.5°	–	–	2.84mH	–
542 kHz	117.7kΩ	7°	–	130kΩ	–	–
2MHz	2,58 kΩ	−89.78°	–	–	–	30.8pF

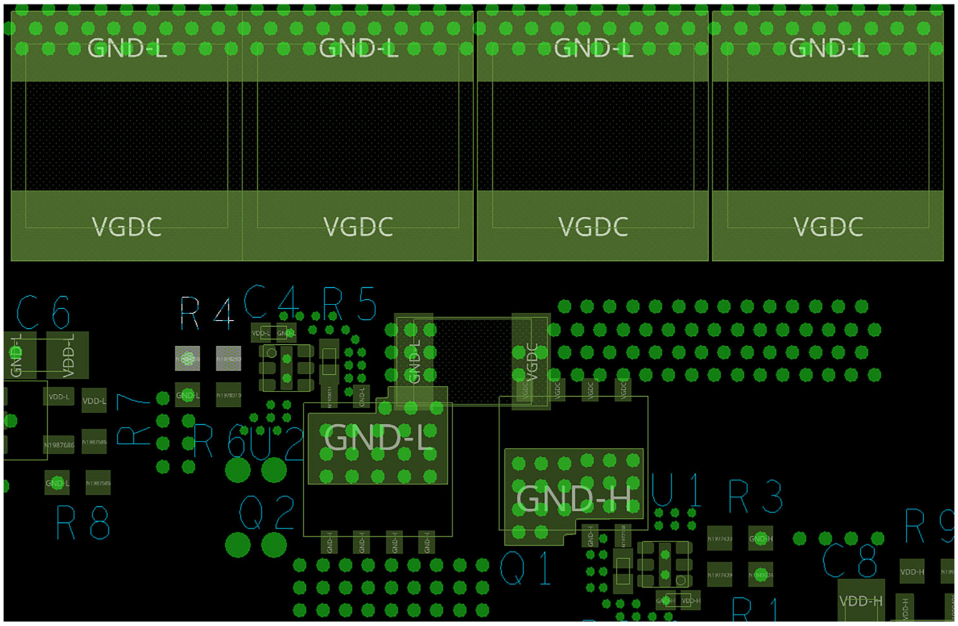

Figure 7. Half-bridge leg layout used for EMC studies.

and professional rules for designing PCBs (IPC, 2003). Students created anti-aliasing filters for conditioning signals obtained from current and voltage sensors as a final project. This was a changing experience for those who wanted to prototype their works.

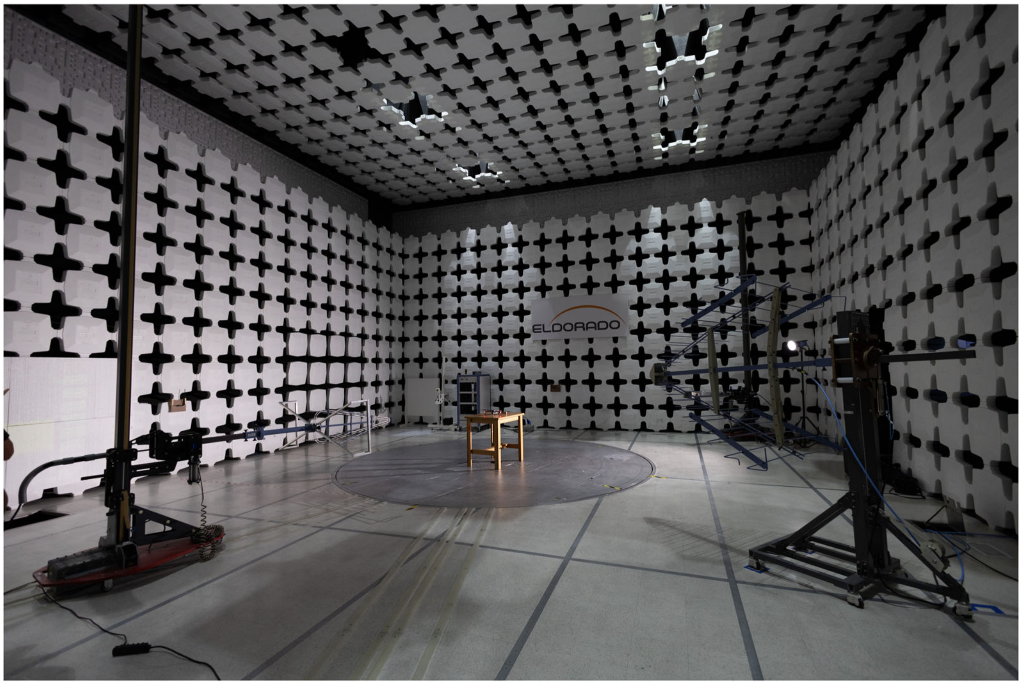

Figure 8. Anechoic chamber for EMI tests at Instituto de Pesquisas Eldorado.

After completing the course, students reported that these tutorials helped develop PCBs for their postgraduate projects. One student working with gate drivers could benefit from the EMI classes to improve the topology and layout for his master's prototype, while another doctorate student developed a voltage-sensing signal conditioning board for the grid-forming inverter used in his research, as shown in Figure 10.

3. Evaluation of results

The evaluation criteria comprised lists of exercises and reports of experimental practices conducted t as a team (40% of the grade) and a final individual project involving the development of an electronic board (60% of the grade). The approval grade is 5 out of 10. All ten students successfully passed.

The course was first introduced during the first semester of 2023. It is common practice to administer a questionnaire after a course to gather student evaluations. However, the approach taken in the current study differs in terms of the timing of the questionnaire administration. The questionnaire aimed to compare the students' self-assessed knowledge before the course with their knowledge after the course, consolidated through practical application since it was applied five months after the end of the course.

The purpose of this delayed timing was to allow students the opportunity to apply the knowledge gained during the course. Consequently, it aimed to enable a more accurate assessment of the potential benefits of the discipline based on practical application.

The results are summarized in Figure 11, which compares the students' initial perception of their knowledge of the topics with their perception after completing the course and the consequent application of expertise in their respective research projects. All ten students assigned themselves a level of knowledge on each topic between 1 and 10. The average of the answers and the relationship between the values before and after the subject were calculated. The questions covered the issues of converter topologies, semiconductor devices, thermal aspects, electromagnetic compatibility, passive devices, and auxiliary electronic circuits.

The highest confidence levels in one's knowledge were observed in the four most traditional topics, both at the initial and final levels. There was an average increase of around 40% for all these topics. The most notable improvements were observed in the issues of EMC and thermal design, which came from significantly less knowledge (students rated themselves, on average, close to three) and had a significant increase, between 70 and 80%, although with a final value lower than the other subjects. This behavior can be attributed to the minor or non-existent attention given to these two topics in power electronics disciplines.

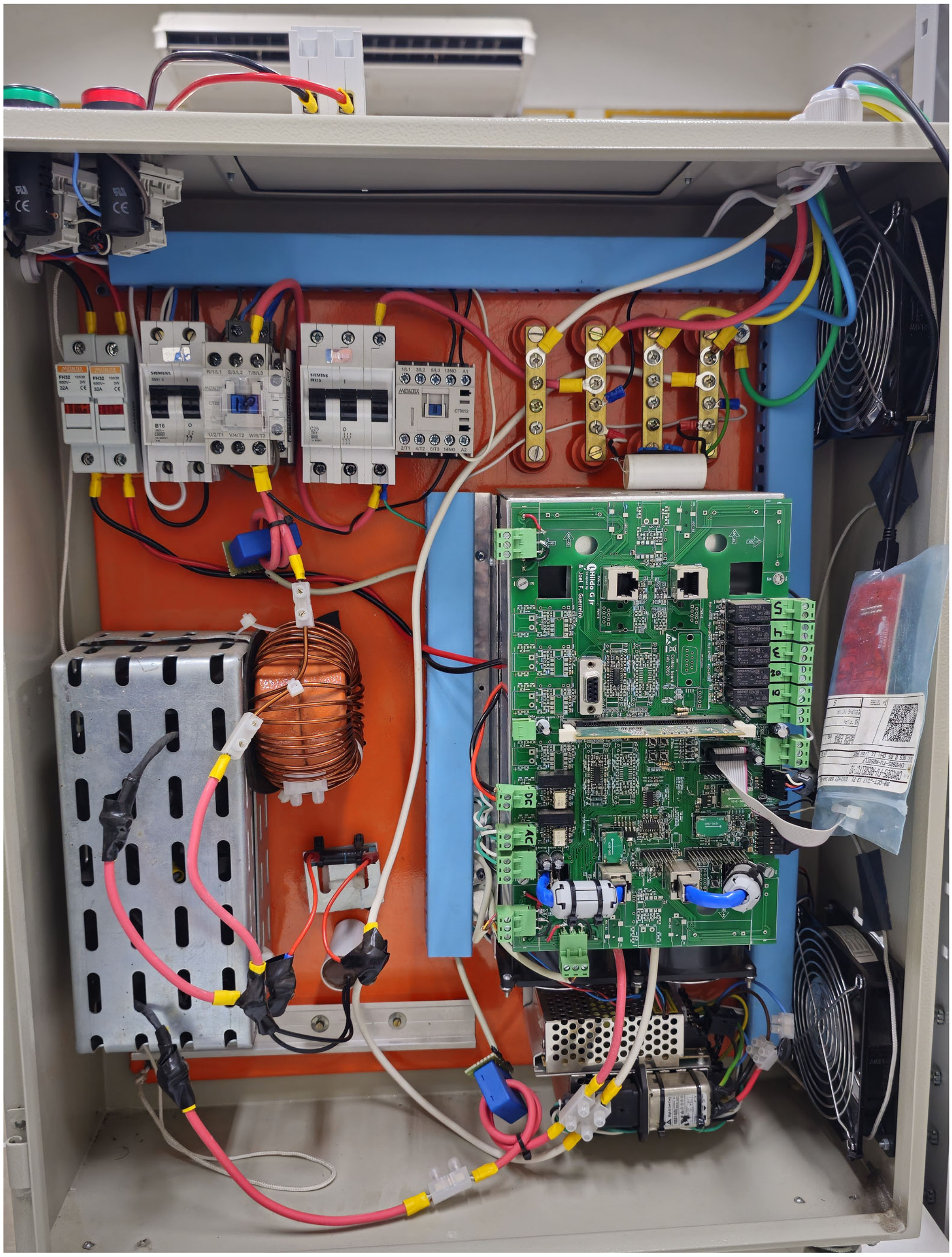

Figure 9. Power electronics converter subjected to to EMI tests at anechoic chamber and results.

Half of the students reported that, after the course, they felt very motivated to develop hardware for power electronic converters. The other half indicated a moderate degree of motivation. No student negatively evaluated the methodology or the learning process.

4. Conclusions

The proposed course aimed first to cover graduate students' absence or reduced practical experience resulting from the closure or restricted access to laboratories due to the COVID-19 pandemic. One year later, the instructors realized that offering the course regularly would be highly beneficial.

The motivation was to emphasize the non-idealities of active and passive components, as well as the functioning of the circuits so that students would be more attentive to such behaviors in the future implementation of their experiments required for validating research projects. The methodology applied included introductory theoretical classes,

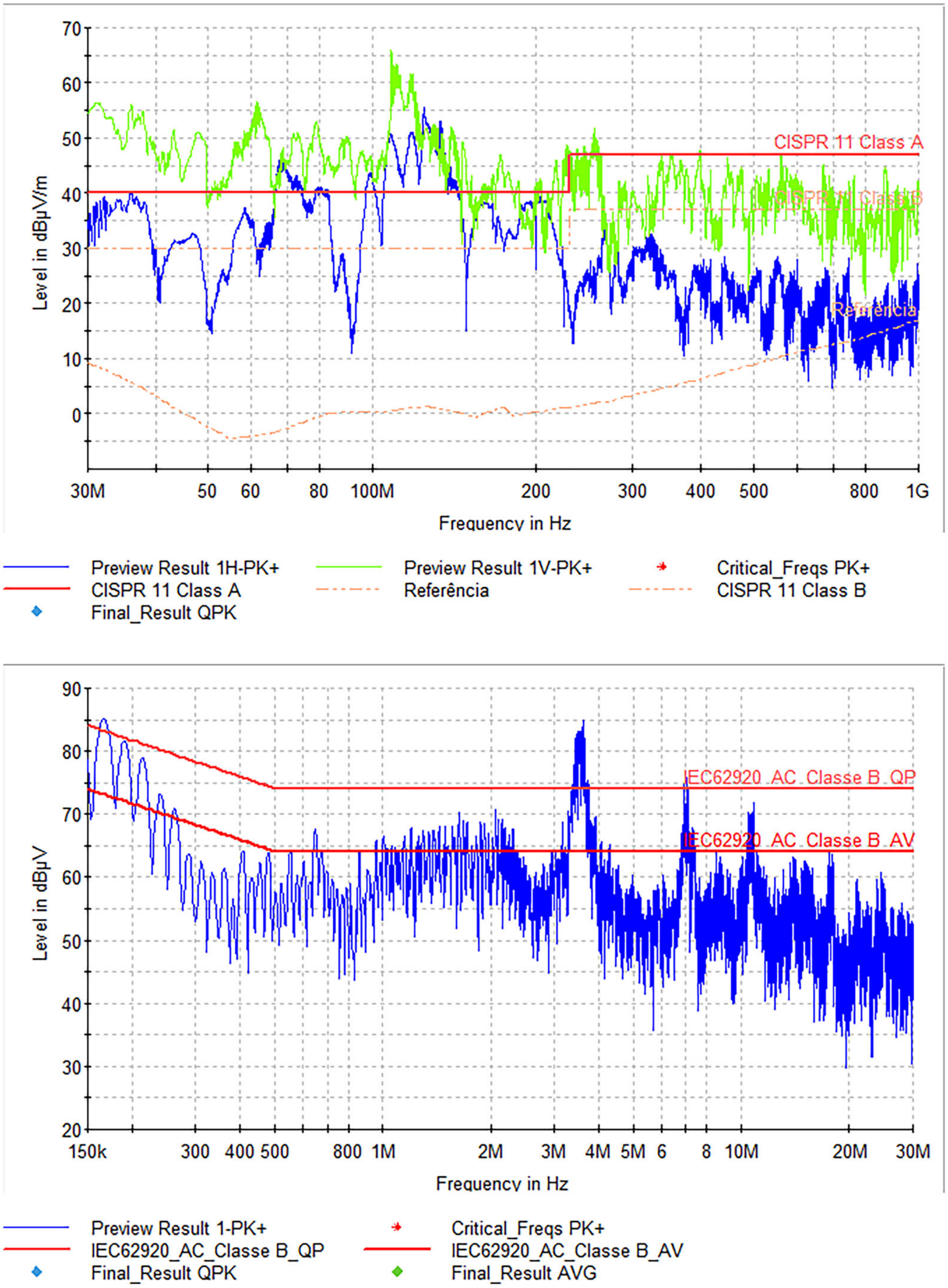

Figure 9. Continued

hands-on team activities, circuit simulations including non-idealities, technical visits to test environments, and a final project.

According to the students' evaluations, conducted five months after completing the course, there was a perceived significant knowledge gain across all covered topics. Half of the participants indicated a great motivation to carry out experimental activities, and 60% stated that they were already doing practical activities linked to their projects intensely or moderately.

The students' supervisors noted greater student motivation for the experimental activities, which began to be carried out with greater confidence and effectiveness. This improvement was a clear differentiator compared to more traditional courses.

After the first edition, the potential of the course became clear to help overcome the gap in

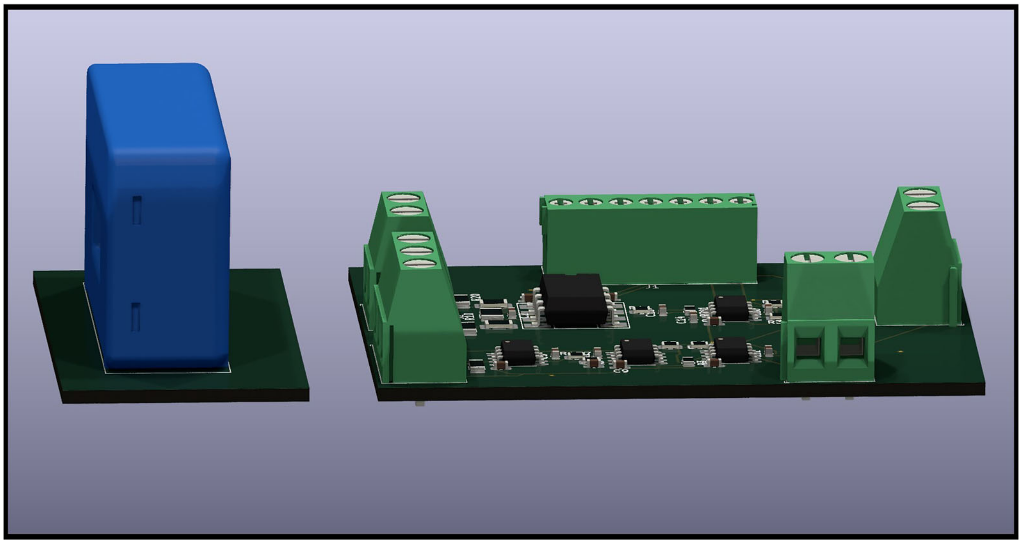

Figure 10. PCB design elaborated by a student.

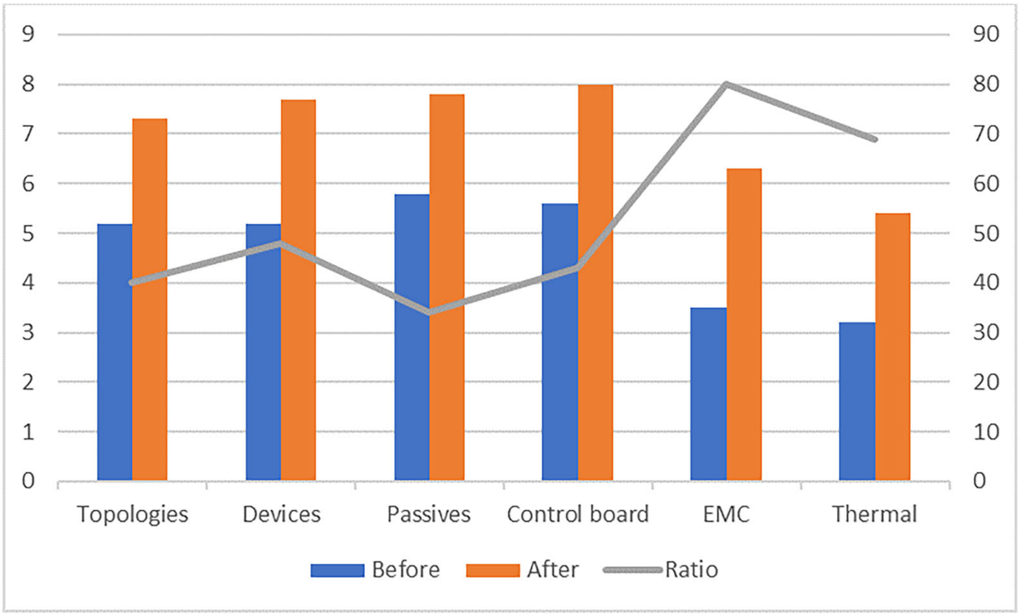

Figure 11. Perception of knowledge on the topics before and after the subject (scale 0-10, on the left) and relative variation (scale % on the right).

experimental practice with which some doctoral and master's students begin their studies. For this reason, it is being offered again in 2024, becoming a regular course in the master's and doctoral programs.

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Authors contributions

J. A. Pomilio and J. F. Guerreiro proposed and implemented the course and wrote the article. G. Spiazzi was responsible for the EMC part, including the respective classes and reviewing the article. J. C. U. Pena was responsible for testing passive devices and respective classes and reviewing the article. The authors agree to be accountable for all aspects of the work.

Disclosure statement

No potential conflict of interest was reported by the authors.

About the authors

José Antenor Pomilio was born in Jundiaí, Brazil, in 1960. He received his B.S., M.S., and Ph.D. in electrical engineering from the University of Campinas, Campinas, Brazil, in 1983, 1986, and 1991, respectively. From 1988 to 1991, he was the Head of the Power Electronics Group, Brazilian Synchrotron Light Laboratory. He was a visiting professor at the University of Padova in 1993 and 2015 and at the Third University of Rome in 2003 in Italy. He is a Professor at the School of Electrical and Computer Engineering, University of Campinas, where he has been teaching since 1984. His main interests are power electronics and power quality. Dr. Pomilio was the President of the Brazilian Power Electronics Society from 2000 to 2002 and a member of the Administrative Committee of the IEEE Power Electronics Society from 1997 to 2002. He is a member of SOBRAEP, SBA, SBQEE, ABENGE, and IEEE.

Joel Filipe Guerreiro, born on May 28, 1988, in Belém (Brazil). He received his B.S. in electrical engineering (2011) from the Federal University of Pará (Brazil), master's (2015), and doctorate in Electrical Engineering (2010) from the State University of Campinas (UNICAMP). He is a project leader at Eldorado Research Institute and a researcher at the School of Electrical and Computer Engineering (UNICAMP). His areas of interest are power electronics, modeling, and control of power converters, microgrids, wide-bandgap semiconductors, and electric vehicle powertrains.

Giorgio Spiazzi received the Graduate degree (cum laude) in electronic engineering and the Ph.D. degree in industrial electronics and informatics from the University of Padova, Padova, Italy, in 1988 and 1993, respectively. He is a Full Professor at the Department of Information Engineering (DEI), University of Padova. His main research interests include dc–dc converters for renewable energy sources, high-power factor rectifiers, soft-switching techniques, solid-state lamp ballasts, and electromagnetic compatibility in power electronics.

José Carlos U. Peña, born on March 1st, 1984, in Lima (Peru), is an electrical engineer (2010) with the National University of Engineering (Peru), a master (2012), and a doctor in Electrical Engineering (2016) from the São Paulo State University (UNESP). He is a researcher at the School of Electrical and Computer Engineering, University of Campinas. His areas of interest are power electronics, modeling and control of power converters, microgrids, and power quality. Dr. Peña is a member of the SOBRAEP and IEEE.

Data availability statement

The data supporting this study's findings are available from the corresponding author, J. A. Pomilio, upon reasonable request.

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