

Teaching Magnetic Component Design in Power Electronics Course using Project Based Learning Approach

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Abstract

This paper presents the results and gained experiences from the Project Based Learning (PBL) of magnetic component design within a Power Electronics Course. PBL was applied during the laboratory exercises through a design-project task based on a boost converter test board. The students were asked to calculate the main boost converter's circuit parameters' capacitor C and inductor L, and then additionally required to design and build-up the inductor L, in order to meet the project's goals. The whole PBL process relied on ideas from the CDIO (Conceive, Design, Implement, Operate), where the students are encouraged to consider the whole system's process, in order to obtain hands-on experience. PBL is known to be a motivating and problem-centered teaching method that gives students the ability to transfer their acquired scientific knowledge into industrial practice. It has the potential to help students cope with demanding complexities in the field, and those problems they will face in their future careers.

Key Words: Electromagnetics, Inductor, Project based learning, Power electronics

I. INTRODUCTION

This paper presents the results gained after two years experience of using PBL teaching of electromagnetics, as realized from a student design-project task in power electronics, based on a boost converter test board layout. This test board was used during laboratory exercises as part of an advanced course in Power Electronics, offered as an optional subject to the third year students of a professionally-oriented undergraduate study program. During the second year of their curriculum, the students had participated in a basic course on Industrial Electronics that covered the basics of dc/dc, ac/dc, and dc/ac converters. The applied teaching methods in this course followed the strategy described in [1], which used theoretical lectures in conjunction with simulations and measurements in the laboratory. In this advanced course on Power Electronics, however, the converter's design and dynamical analysis are treated, amongst other themes, in combination with theoretical lectures using the PBL approach. One of the goals of the using PBL approach was to make power electronics more attractive to students, especially to those who originally preferred non-power related subjects.

In general, engineers have to deal with uncertainty, yet solving complex problems, and they need to be able to function

as effective members of teams requiring strong communication and problem-solving skills. However, it is commonly believed that today's engineering graduates lack these skills and have difficulty applying their fundamental knowledge to practical problems.

Recently, many authors have reported their experiences of using more learner-centered teaching approaches, such as problem-based or project-based learning (PBL), instead of using lecture-based teaching methods, when teaching undergraduate engineering [2]–[7]. Whilst in [2], problem based learning focuses on the dynamic modeling of higher-order switching converter, in [3] the learning process focuses on the system-level behavior model-simulation approach for basic switching converters, in order to enhance the students' learning outcomes. On the other hand, in [4]–[6], authors describe project-based learning approaches that involve design and construction practice. As discussed in [7], the PBL approach offers a number of advantages, amongst which are the ease of controlling the learning process, and the possibility of making rapid changes to the power electronics curriculum.

Although only limited research has been carried out on the beneficial effects of PBL regarding engineering students' learning, it is generally accepted that it enables future engineers to develop their problem-solving skills and, consequently, provides them with the abilities to participate as active and effective members of the global society. Some authors [4], [8] have reported that PBL students score slightly less on factual knowledge, but they retain more of the acquired knowledge, since this knowledge is grounded on context.

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The authors also argued that PBL students develop more conceptual knowledge; hence they are able to better recall their knowledge.

Teaching students through PBL is based on a philosophy that students learn fundamental laws and their applications most effectively through design practices, thus resulting in demonstrated success [8]. Through such practices, students learn that understanding the fundamentals and paying attention to details, are essential requirements for success in engineering. They also become familiar with the science/art of the iterative design process. A strong foundation, consisting of a deep understanding regarding the fundamentals of engineering, and the ability to deal with details, must be provided to students in order to prepare them for advanced courses as well as for the challenges of a highly- competitive industrial world.

From the student point of view, PBL is learner-centered and intrinsically motivating, encouraging collaboration and cooperative learning, that requires students to produce a product, presentation, or performance, by allowing students to make incremental and continual improvements to their product, presentation, or performance. It is designed so that students are actively engaged in ‘doing things’ rather than in ‘learning about’ something, and is challenging because it focuses on higher-order skills. Although some students prefer the traditional lectures [8] and feel themselves comfortable learning it because they find themselves more familiar with it, they also underline the importance of PBL in allowing them to apply concepts, and develop their problem solving abilities.

Based on these reported observations, and by taking into account our experiences from previous years, we decided to apply certain traditional lectures in combination with a PBL-based design-project task, as a pedagogical method within a Power Electronics Course. The results from a comprehensively conducted survey at the end of the term, together with their final exam scores, confirmed the suitability and efficiency of our teaching approach. The higher costs associated with investing in material resources and facilities, can be seen as a main drawback of the proposed teaching approach.

The whole project design task is based on ideas from CDIO (Conceive, Design, Implement, Operate), where students are encouraged to consider the whole system’s process in order to obtain ‘hands-on’ experience. According to the basic CDIO premise that ‘hands-on’ experience is a vital foundation, based on theory and science [10], [11], engineering teaching should be arranged in the following steps: Conceive – students formulate the given task into what needs to be performed in order to fulfill the assignment, Design – students make adequate design/calculations, Implement – based on design, the derived construction is practically implemented, and Operate – the completed construction is analyzed and evaluated.

This paper is organized as follows. Section 2 introduces the design project’s task specifications and procedure using basic boost converter calculations and inductor-design procedure. Section 3 presents the magnetic component’s final design and a brief analysis of the results. Learning achievements using the PBL approach are evaluated in Section 4, and Section 5 concludes this paper.

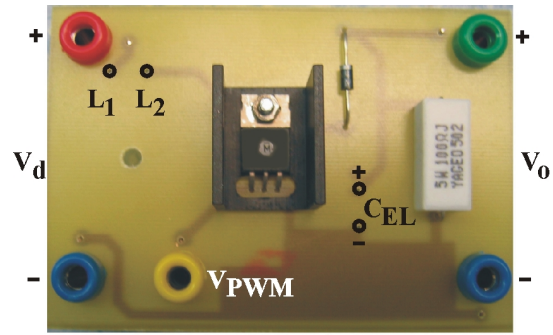


Fig. 1. Boost converter test board layout.

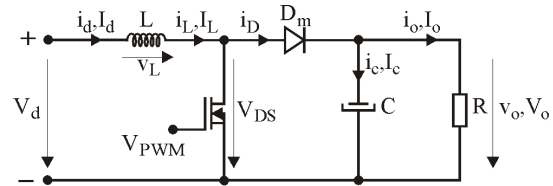


Fig. 2. Boost converter circuit.

II. DESIGN PROJECT TASK SPECIFICATIONS

The design-project task has to be selected very carefully, so that the students gain a meaningful experience. The design-project task can be considered as suitable if a) it is relevant to the course material, b) the design has been completely worked-out beforehand by the instructor, c) it can be performed by students within a relatively short period of time, and d) a prototype can be built.

The design requirements should be specified unambiguously, although they are seldom unambiguous in the professional world, where it is left to the engineer to work out the required details. The following specifications were given to our students: using a boost converter test board layout, as shown in Fig. 1, for building the converter using the following data: a) input voltage $V_d = 5$ V, b) output-voltage $V_o = 15$ V, c) switching-frequency $f_s = 25$ kHz, d) minimal load $R = 100$ Ω , e) maximum allowed inductor current ripple $\Delta I_L = 0.2$ A, and f) maximum allowed output voltage ripple $\Delta V_o = 40$ mV. An additional requirement was that the converter had to operate within continuous conduction mode. In order to fulfill the given specifications, the students were required to calculate the necessary duty cycle and the main boost converter circuit’s parameters, as were the output capacitor C , and the main inductor L (see Fig. 2). Additionally, they were also required to design and build the inductor L , in order to meet the project’s goals. When the students had the opportunity to perform practical work using the theoretical material they had been taught, their understanding of the subject increased.

When applying of boost converter, as shown in Fig. 2, where the operation of a continuous conduction mode is required, the inductance’s value L is usually chosen, such that the inductor current’s ripple peak-magnitude is a prescribed fractional value of the full-load inductor current’s dc component. Based on the calculated inductance value L , students had to design the inductor using the procedure described in the following sections.

A. Design project task procedure

During the initial phase of the project, the students had to become familiar with the boost converter test-board's layout, and its circuit. At this stage it was important that the relevant fundamental laws were discussed in class, in order to prepare the students for the design project. When the initial phase had been completed, the design project task could be done over the following steps.

B. Basic boost converter calculations

The basic calculations were based on the assumption that the students were dealing with an ideal boost converter [11]. From the given converter input and output voltage specifications, the required duty cycle Δ_p could be calculated as:

$$\Delta_p = \frac{V_o - V_d}{V_o}. \quad (1)$$

And converter output power P_o , output current I_o and input current I_d as:

$$P_o = \frac{V_o^2}{R}, \quad (2)$$

$$I_o = \frac{V_o}{R}, \quad (3)$$

$$I_d = \frac{I_o}{1 - \Delta_p}. \quad (4)$$

Now the necessary inductance L and capacitance C can be calculated as:

$$L = \frac{V_d \Delta_p}{\Delta I_L f_s}, \quad (5)$$

$$C = \frac{V_o}{R} \frac{\Delta_p}{\Delta V_o f_s}. \quad (6)$$

According to the specification that the converter had to operate in continuous conduction mode, it was necessary to verify whether the following condition had been satisfied:

$$I_d \geq \frac{\Delta I_L}{2}. \quad (7)$$

If this condition hadn't been fulfilled, then the specification for the inductor current ripple ΔI_L should be corrected to a lower value that would consequently give a larger value for the inductance L . Finally, the rated peak-current through inductor could be calculated as:

$$I_{L,\max} = I_d + \frac{\Delta I_L}{2}. \quad (8)$$

When all the basic calculations were done, the students could start building-up the converter. The easier task is to choose an adequate capacitor, with a capacitance value of at least that calculated using (6), and the difficult one is to design the inductor with an inductance value of at least that given by (5).

C. Inductor design procedure

In power electronics circuits, inductive components such as inductors and transformers are basic elements. Since they can not be bought off the shelf as capacitors, they have to be dimensioned, designed, and built-up, and for that, a deep understanding of electromagnetic behavior is essential. Many students lacked a deeper understanding of the inductive components' physics, although they had successfully finished the introduction courses in basic electrical engineering.

In the case of inductor design, there are a large number of design parameters to be chosen including: air-gap length, conductor area, number of turns, all of the magnetic core dimensions, and the type of magnetic material with inductance factor A_L included.

The inductor design procedures described in literature make use of numerous monograms, and final result is achieved through several iterations. Therefore, the inductor's design presents a formidable optimization problem, and there is a general perception that it is a difficult task, requiring significant experience [12]–[14]. It is particularly difficult to teach inductor design to students at the undergraduate professional level, since they lack the ability to comprehend difficult physical concepts.

Due to the limited supply of magnetic cores, and to simplify the design procedure, the students were given a toroidal magnetic core L30 with the following specifications: inductance factor $A_L = 2000$ nH, saturated flux density $B_{sat} = 350$ mT, magnetic field strength $H = 250$ A/m, core cross-sectional area $A_c = 115$ mm² and the average length of the magnetic core's path $l_m = l_c = 45$ mm. All calculations for the inductor's design could now be performed, as follows.

Firstly, it was necessary to calculate the required number of turns, N based on inductance value L and inductance factor A_L . For a magnetic core without an air-gap, this could be done as:

$$N = \sqrt{\frac{L}{A_L}}. \quad (9)$$

During inductor operation, it is important that the core cannot be energized into saturation when the current increases, so the value of the saturation current I_{sat1} for the given core, has to be calculated (see Fig. 3). By applying Amper's Law, and taking into account the distribution of flux density B , depending on the magnetic field strength H (see Fig. 4), the saturation current was calculated as:

$$I_{sat1} = \frac{B_{sat} \cdot l_m}{N \cdot \mu} = \frac{l_m \cdot H}{N} \quad (10)$$

where l_m is the average length of magnetic core path and μ is the magnetic permeability of the ferromagnetic core.

When the peak value of inductor current $I_{L,\max}$, denoted in (8), is close to the calculated value of the saturated current I_{sat1} , as expressed in (10), then it can be assumed that the core would be saturated when the boost converter is operating. Consequently, the amount of the energy stored in the inductor would be lower, which would result in a lower current and lower converter output power. The temperature in the core would increase, as well as core losses, which would result in a decrease in the converter efficiency.

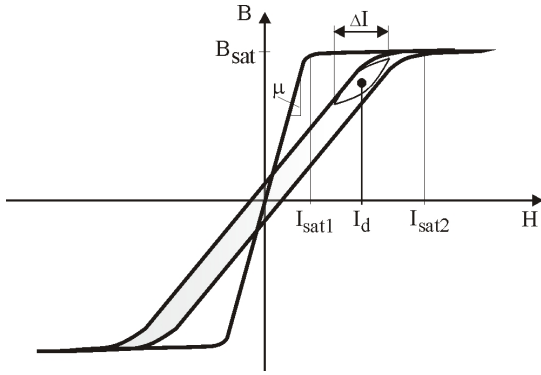


Fig. 3. Magnetic curve of the core with or without a air-gap.

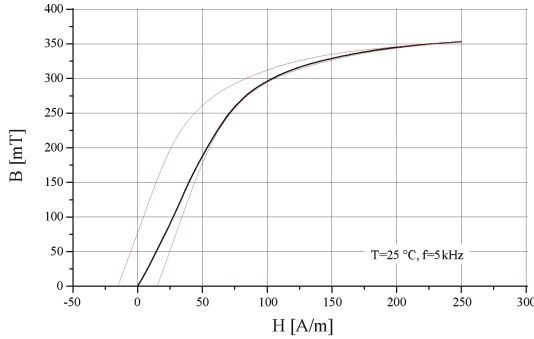


Fig. 4. Distribution of flux-density B , depending on the magnetic-field strength H .

So, a decision as to whether the core with the air-gap should be used or not, must be made. If the core with the air-gap is used (see Fig. 5), then the value of the saturated current would be higher (see Fig. 3), and can be calculated as:

$$I_{sat2} = \frac{B_{sat} \cdot A_c}{N} \left(\frac{l_c}{\mu \cdot A_c} + \frac{l_g}{\mu_0 \cdot A_c} \right) = \frac{B_{sat}}{N} \left(\frac{l_c H}{B_{sat}} + \frac{l_g}{\mu_0} \right) \quad (11)$$

where l_c is the average length of magnetic core path, l_g is the length of air-gap and μ_0 is the magnetic permeability in the air. As it is assumed that the core and air-gap have the same cross-sectional areas then, in practice the $\mu \gg \mu_0$, then the above equation can be simplified to:

$$I_{sat2} \cong \frac{B_{sat} \cdot l_g}{N \cdot \mu_0} \quad (12)$$

By choosing an appropriate length of air gap l_g , the value of the saturation current could be set higher than the peak value of the inductor current $I_{L,max}$, in order to prevent the inductor flux from going into the saturation region during the converter's operation. When the core with the air-gap is employed, the inductance is changed to the next value:

$$L = \frac{\mu_0 A_c N^2}{l_g} \quad (13)$$

So, finally, the necessary correction for the value of turns numbered N , has to be done based on (13), in order to fulfill the requirement for the boost converter inductance L value:

$$N = \sqrt{\frac{L l_g}{\mu_0 A_c}} \quad (14)$$

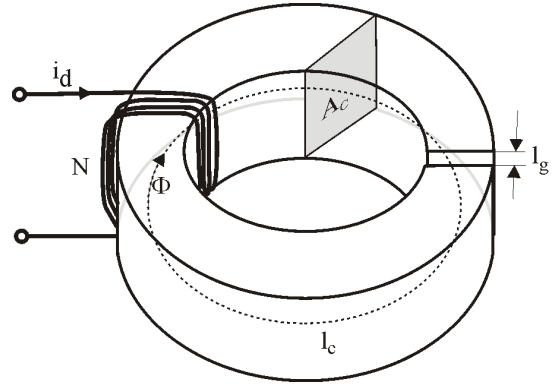


Fig. 5. Structure of the toroidal inductor with air-gap.

With the new value of turns numbered N , the value of the saturation current I_{sat2} is also changed according to (12), so once more verification as to whether this current is higher than the peak value of the inductor current $I_{L,max}$, has to be done.

When the above conditions are fulfilled, selecting the diameter of the inductor's copper wire must be done. This selection is based on fact that the maximum value for the current density shouldn't be greater than $J_{max} = 4 \text{ A/mm}^2$. The current density J_{max} depends on the converter input current I_d , and the cross-section of the copper wire S_{Cu} :

$$J_{max} \geq \frac{I_d}{S_{Cu}} \quad (15)$$

So the copper wire's diameter d_{Cu} can be determined as:

$$d_{Cu} \geq \sqrt{\frac{4I_d}{\pi J_{max}}} \quad (16)$$

The copper wire diameter from which the inductor will be wound-off should be the first largest ones, with respect to the calculated value in (16).

From the required turns number N and copper wire's diameter, the dc winding-resistance of the inductor, R_L , can be calculated:

$$R_L = \frac{\rho l_{wire}}{S_{Cu}} = \frac{4\rho N d_{core}}{d_{Cu}^2} \quad (17)$$

Where l_{wire} is the length of the copper wire, d_{core} is the diameter of the toroidal coil-bobbin, as can be shown in Fig. 6, and ρ is the copper's specific electrical resistivity. It is desirable to obtain the given inductance L with as small a winding-resistance R_L as possible, because the winding resistance R_L influences the copper losses and, consequently, the boost converter's efficiency. It should be obvious from (17), that the value of the winding-resistance depends on the turns number N . When the core with the air-gap is employed, the same inductance L is obtained with a more turns number, compared to the core without an air-gap. As already stated, more turns means more losses, so the decision about using a core with an air-gap has to be carefully made. The resistance R_L also reduces the output voltage transfer ratio of the real boost converter:

$$\frac{V_o}{V_d} = \frac{R(1 - \Delta_p)}{R_L + R(1 - \Delta_p)^2} \quad (18)$$

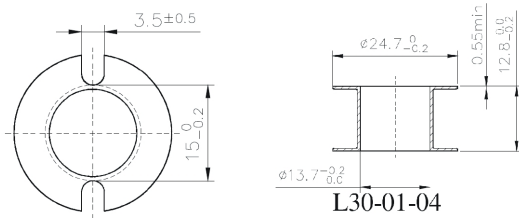


Fig. 6. Dimensions of the toroidal coil-bobbin for the L30.

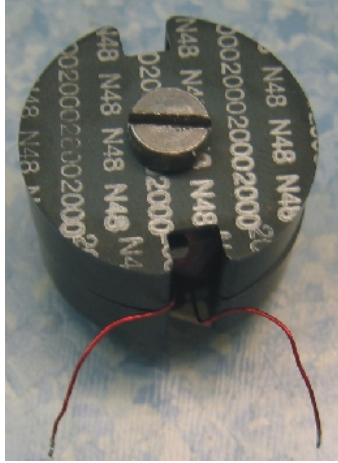


Fig. 7. Inductor built-up by students.

By calculating the derivative of (18) with respect to the duty ratio Δ_p , the maximum duty ratio could be found as:

$$\Delta_{p,\max} = 1 - \sqrt{\frac{R_L}{R}}. \quad (19)$$

From (19) and (18), the maximum value of the boost converter output voltage can be obtained as:

$$V_{o,\max} = \frac{V_d}{2\sqrt{\frac{R_L}{R}}}. \quad (20)$$

After all the calculations have been done and the copper wire has been selected, the students can build-up the real inductor. The required turns are carefully wound around the toroidal-coil bobbin (as shown in Fig. 6), and the air-gap is made by using a piece of paper of adequate thickness. The verification, if the required inductance of the inductor L has been obtained, is done by measurement using an LC-Q meter, before the inductor is mounted on the boost converter test-board (see Fig. 7 and 8). At this stage the resistance of the inductor R_L , should also be measured.

III. ANALYSIS AND EVALUATION

When the built inductor L , as shown in Fig. 7, and the chosen capacitor C have been mounted on the boost converter test-board, the students can perform the final analysis and evaluations, if the design-project's task goals have been fully reached.

During the verification process, the students should connect the built boost converter (as shown in Fig. 8) to a 5 V voltage supply, the duty cycle Δ_p should be adjusted to a value that produces 15 V voltage at the converter's output, so that the converter operates under nominal operational conditions. Now

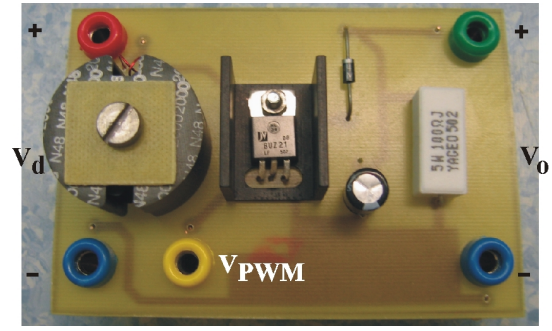
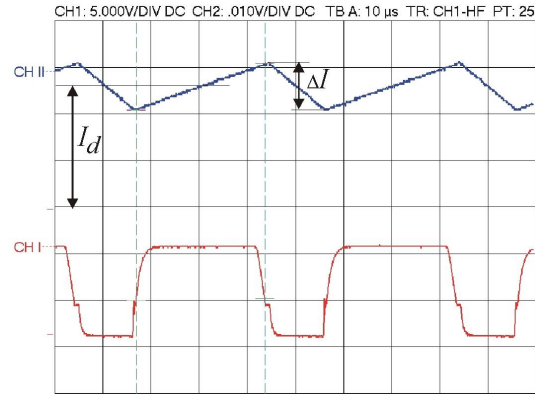


Fig. 8. Boost converter test-board with mounted inductor, and capacitor.

Fig. 9. Waveforms of the driving signal for transistor V_{PWM} (CH I) and inductor current I_L (CH II, 0.2 A/div).

they can measure the output voltage ripple ΔV_o as well as the ripple of the inductor current ΔI_L .

The waveforms of the inductor current's ripple ΔI_L and the transistor driving signal V_{PWM} are shown in Fig. 9. The current have been measured with a current-probe that provides 10 mV output for each 200 mA measured. It is evident, that the average input current is around $I_d = 0.5$ A, what is very close to the calculated value in the case of an ideal converter (expected current rate is $I_d = 0.45$ A). We should be able to see from Fig 9, that the project's goal for an inductor current ripple of $\Delta I_L = 0.2$ A, has been reached. The maximum output voltage $V_{o,\max}$ was also measured, compared with the calculated value in (20), and the reasons for the deviations argued about.

IV. ASSESSMENT OF LEARNING ACHIEVEMENTS

Although the PBL approach offers a number of advantages, as reported by several authors, we decided to assess the progress in study achievements within the same group of students. In our case, two similar topics were conducted in the class: the basic course on Industrial Electronics in the 4th semester, and an advanced course on Power Electronics in the 5th semester. In the first case, the students attended within a conventional teaching program: from lectures in the class, homework, mid-term exams, to assistant-guided lab exercises, and the final exam. In the second case, we applied a combination of traditional lectures with the PBL teaching approach within an advanced course on Power Electronics, with emphasis on ideas from the CDIO framework. A comprehensive survey was conducted of the class in the 5th semester using an anonymous questionnaire, and the results within a five

TABLE I
QUESTIONNAIRE AND RESULTS

Question	1	2	3	4	5	Avg.
1. How much of the study up to now has helped you to consider being an engineer?	1	1	12	7	2	3.35
2. Do you think that the PBL has helped you to better engineering thought?	0	1	5	14	3	3.83
3. How much did the PBL encourage and qualify you for cooperation?	0	1	7	13	2	3.70
4. How much did the PBL encourage and qualify you for project work?	0	1	8	12	2	3.65
5. Please evaluate the benefits of the PBL against the conventional.	0	1	5	13	4	3.87
6. Provide your evaluation of PBL on this course.	0	2	6	11	4	3.74

1: very bad (certainly not), 2: poor (I don't know), 3: good (probably), 4: very good (very probably), 5: excellent (definitely yes)

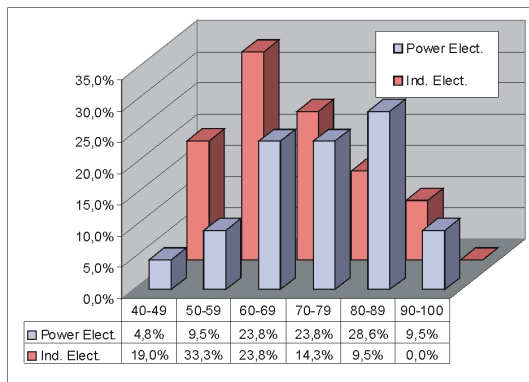


Fig. 10. Comparison of final exam scores with two different teaching approaches.

point scale, are shown in Table I. It is also important to note, that there were more additional questions in this set, where students could express and write down their proposals, new ideas, legitimate critiques, and also possible recommendations.

The percentage comparison of the final grades between the courses in the 4th and 5th semesters is shown in Fig. 10. According to the evaluation results - by using the PBL method in the 5th semester, the students had obtained 10 - 20 % higher final grades, as a result of better scores in their final exams. This can be seen as a significant improvement with respect to other authors' observations [4], [8]. At the same time, the lower grades had been reduced by similar percentages, as against the 4th semester as well.

The opinions and suggestions that came from the student feedback are very positive with regard to the practical assistance of the laboratory staff. The majority of students felt that the final hands-on layout of the inductor enhanced their understanding of the theoretical background of the electromagnetic theory, and made the course more interesting.

It is also well-known that students who learn the techniques through discussions, quiz, and seek answers to problems, show more interest in the course than those who learn the

theory via the traditional instruction approach. The average scores of the mid-term and final examinations also confirm these conclusions. At the end of course, it was found, that majority of the students could now digest those important and difficult topics within their lecture notes, and what the teacher explained during the lectures. A comparison with other universities using conventional education, states that the final yield is much higher using the PBL approach. It is also an encouraging fact that, with this learning approach, we succeeded in also keeping a similar amount of students during the new study semester.

V. CONCLUSIONS

This paper focused on teaching students the fundamentals of electromagnetics using the PBL approach, when asked to design an inductor as part of a laboratory assignment on boost converter design. The whole project was prepared according to the CDIO principles, and was well-accepted by students. With respect to the reported experiences in [11], and the fact that we had already worked with these students at the undergraduate professional level, the detailed specification of the tasks during the Conceive (C) phase had already been provided. The students worked in groups of three, and were helped as far as it took for the best of them to carry out their designs successfully. With this teaching approach, the students were asked to apply fundamental laws, and work-out the details to complete design. In our opinion, those students who gained a deep understanding of the fundamental laws can now educate themselves about any given subject. By working on this project design, the students also gained the important experience that calculations are approximations of a real circuit's behavior.

Although the results of this comprehensive survey, and the comparisons of the final exams scores covering two semesters, confirm that the PBL approach upgrades student performance, we found it very important that the basic concepts were taught before PBL was used.

The PBL approach stimulated high-interest amongst all the students and could be seen as a great success. The students enjoyed building their own boost converters, and their rewarding experience will hopefully encourage the students from the next generation to enroll in Power Electronics courses.

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