Alenka HREN, Franc MIHALIČ, Miro MILANOVIČ
University of Maribor

Project based teaching of electromagnetics in power electronics course

***Abstract**. This paper presents the results and gained experience from the student design project task in power electronics, based on boost converter test board. In the project task the students are asked to calculate the main boost converter circuit parameters capacitor C and inductor L, additionally they are also required to design the inductor L in order to meet the project goals. The whole project design based on the ideas from the CDIO (Conceive, Design, Implement, Operate), where the students are encouraged to considered the whole system process to get the hands-on experience.*

***Streszczenie.** Artykuł przedstawia wyniki i zdobyte doświadczenie ze studenckich zadań projektowych w dziedzinie energoelektroniki, oparte na konwerterze wzmacniającym. W tym zadaniu studenci dostają polecenie obliczenia parametrów obwodu konwertera, pojemności C i indukcyjności L, a także wymaga się od nich, żeby zaprojektowali induktor. Cały projekt bazuje na idei czterech kolejnych czynności: koncepcja, projekt, implementacja, działanie. W takim cyklu projektu studenci zdobywają umiejętność patrzenia na system projektowy w sposób całościowy. (**Nauczanie projektowe elektromagnetyzmu w wykładzie energoelektroniki**)*

Keywords: teaching, design project, boost converter, inductor.
Słowa kluczowe: nauczanie, zadanie projektowe, konwerter wzmacniający, induktor

Introduction

This paper presents the results and gained experience from the student design project task in power electronics, based on boost converter test board layout. The test board is used in the advanced course of Power Electronics that is offered as an optional subject to the third year students of professionally oriented undergraduate study program. In the second year of the curriculum students participate in basic course of Industrial Electronics that covers basics in dc/dc, ac/dc and dc/ac converters. In advanced course of Power Electronics the converters design and dynamical analysis are treated among other themes. One of the main goals of the project based teaching was to make Power electronics more attractive to students, especially to those who originally preferred non power related subjects.

Teaching students through the design project task is based on philosophy that students learn fundamental laws and their applications most effectively through design practices which results in demonstrated success [1]. Through such practice students learn that understanding the fundamentals and attention to details are required to succeed in engineering. They also become familiar with the science/art of the iterative design process. A strong foundation consisting of a deep understanding of the fundamentals of engineering and ability to deal with details must be provided to students to prepare them for advances courses as well as for the challenges of the competitive industrial world.

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

The whole project design is based on the ideas from the CDIO (Conceive, Design, Implement, Operate), where students are encouraged to considered the whole system process to get the hands-on experience. According to the basic CDIO premise that hands-on experience is a vital foundation on which to base theory and science [2, 3], the engineering teaching should be arranged in following steps: Conceive – students formulate the given task into what needs to be performed to fulfilled 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.

Design project task specifications

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 details of the requirements. The following specifications were given to our students: using boost converter test board layout, shown in Fig. 1, build the converter with 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 ΔI_L = 0.2 A and f) maximum allowed output voltage ripple ΔV_o = 40 mV. Another requirement is that the converter has to operate in continuous conduction mode. In order to fulfill the given specifications students are required to calculate the necessary duty cycle and the main boost converter circuit (see Fig. 2) parameters as are the output capacitor C and the main inductor L. Additionally, they are also required to design and build the inductor L in order to meet the project goals. When students have opportunity to perform practical work with theoretical material they had been thought, their understanding of the subject increases.

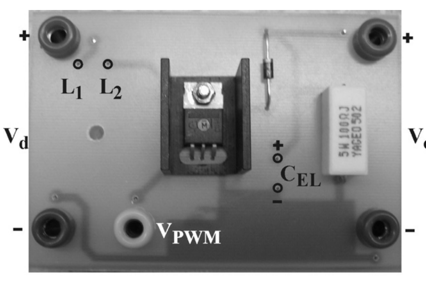

Fig.1. Boost converter test board layout

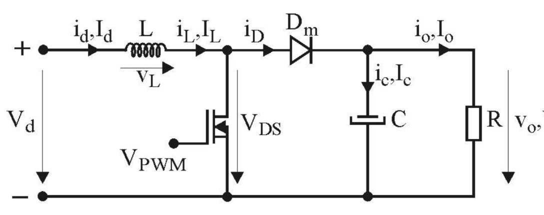

Fig.2. Boost converter circuit

In application of boost converter (shown in Fig. 2) where operation in continuous conduction mode is required, inductance value L is usually chosen such that inductor current ripple's peak magnitude has a prescribed fraction value of the full-load inductor current dc component. Based on calculated inductance value L, students have to design the inductor using procedure described in next sections.

Design project task procedure

In the initial phase of the project students have to become familiar with the boost converter test board layout and its circuit. At this stage is important that the relevant fundamental laws are discussed in class to prepare students for the design project. When the initial phase is completed the design project task can be done in following steps.

Basic boost converter calculations

Basic calculations are based on assumption that students deal with the ideal boost converter [3]. From the given converter input and output voltage specifications the required duty cycle can be calculated as:

(1) $$\Delta_p = {(V_o - V_d)}/{V_o}$$

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

(2) $$P_o = {V_o^2}/{R}$$

(3) $$I_o = {V_o}/{R}$$

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

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

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

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

According to the specification that converter has to operate in continuous conduction mode it is necessary to verify if the following condition is satisfied:

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

If this wouldn't be fulfilled than the specification about inductor current ripple ΔI_L should be corrected to the lower value what would consequently give a larger value for the inductance L. Finally the rated peak current through inductor can be calculated as:

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

When all basic calculations are done students can start to build the converter. The easier task is to choose the adequate capacitor with the capacitance value at least as calculated by (6) and the difficult one is to design the inductor with the inductance value at least as given by (5).

Inductor design procedure

In power electronics circuits the inductive components like inductors and transformers are basic elements. Since they can not be bought on the shelves as capacitors they have to be dimensioned and designed and for that a deep understanding of electromagnetic behavior is essential. Many students lack deep understanding of the inductive components physic although they 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.

In literature described inductor design procedures make use of numerous monograms and final result is achieved through several iterations. Therefore, the inductor design presents a formidable optimization problem and there is a general perception that it is difficult task and that requires significant experiences [4, 5, 6]. It is particularly difficult to teach the inductor design to students at the undergraduate professional level, since they lack ability to comprehend difficult physical concepts.

Due to limited supply of magnetic cores and to simplify the design procedure students have been given a toroidal magnetic core *L30* with 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 average magnetic core path $l_m = l_c$ = 45 mm. All calculations for the inductor design can be now performed as follows.

First is necessary to calculate the required number of turns N based on inductance value L and factor A_L. This can be done as:

(9) $$N = \sqrt{{L}/{A_L}}$$

In inductor design is important that the core is not driven into saturation by increasing the current, so the value of saturation current I_{sat1} for the given core has to be calculated (see Fig. 3). By applying Amper's law and with taking into account the distribution of flux density B in dependence on the magnetic field strength H (see Fig. 4) the saturation current is calculated as:

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

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

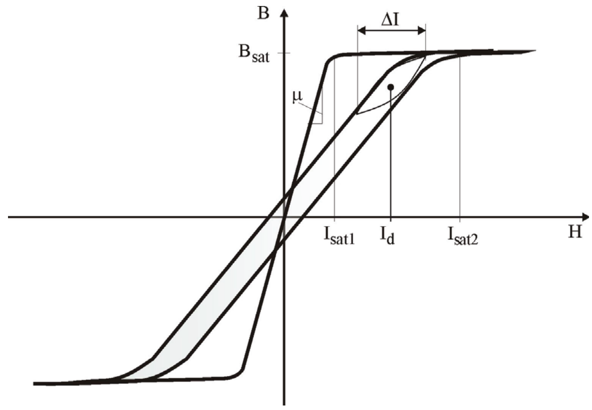

Fig.3. Magnetic curve of the core with- or without air gap

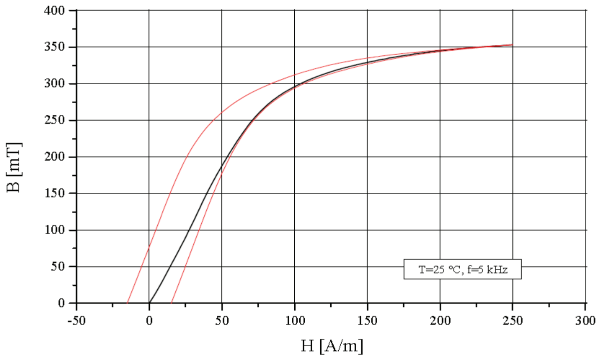

Fig.4. Distribution of flux density B in dependence on magnetic field strength H

When the peak value of inductor current $I_{L,\max}$ in (8) is close to the calculated value of saturated current I_{sat1} in (10) , then can be assumed that the core will be saturated during the operation of boost converter. Consequently the amount of the energy stored in the inductor will be lower what will result in lower current and lower converter output power. The temperature in the core will increase as well as core losses what will result in decreased efficiency of the converter. So decision whether the core with air gap should be used must be accepted. If the core with air gap is used (see Fig. 5) then the value of saturated current is higher (see Fig. 3) and can be calculated as:

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

where l_c is the average magnetic core path, l_g is the length of air gap and μ_0 is the vacuous magnetic permeability in the air gap. It is assumed that the core and air gap have the same cross-sectional areas. By usually adopted assumption that $\mu >> \mu_0$ the above equation can be simplified to:

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

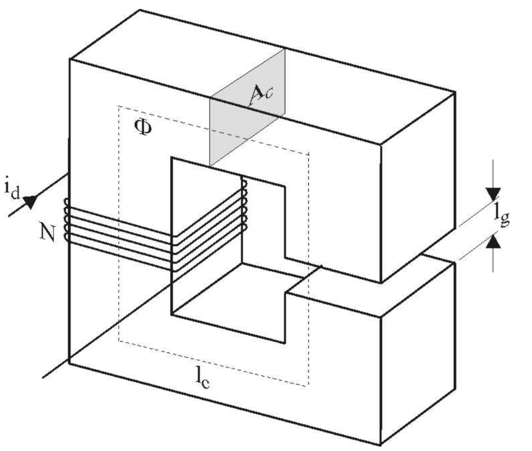

Fig.5. Structure of the inductor with air gap

By choosing the appropriate length of the air gap l_g the value of saturation current can be set higher than the peak value of inductor current $I_{L,\max}$ in order to prevent inductor to go into saturation during converter operation. When the core with the air gap is employed the inductance is changed to the next value:

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

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

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

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

When the above condition is fulfilled the selection of the diameter of copper wire the inductor will be wounded off, must be made. The selection is based on fact that the current density maximum value shouldn't be larger 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}:

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

so the copper wire diameter can be determined as:

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

The copper wire diameter from which the inductor will be wounded off should be the first largest one with respect to the calculated value (16).

From the required turns number N and copper wire diameter the dc winding resistance of the inductor can be calculated:

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

were l_{wire} is a length of the copper wire, d_{core} is a diameter of the toroidal coil former as can be seen in Fig. 6 and ρ is a copper specific electrical resistivity. It is desired to obtain the given inductance L with as small winding resistance R_L as possible, because the winding resistance R_L influences the copper losses and consequently the boost converter efficiency. From (17) is obviously that the value of winding resistance depends on the turns number N. When the core with air gap is employed the same inductance L is obtained with more turns compared to the core without air gap. As already stated more turns means more losses, so the decision about using core with air gap has to be carefully made. Resistance R_L also determines the maximum value of the boost converter output voltage that can be obtained by designed inductor L:

$$(18)\quad V_{o,\max} = \frac{V_d}{2\sqrt{\frac{R_L}{R}}}$$

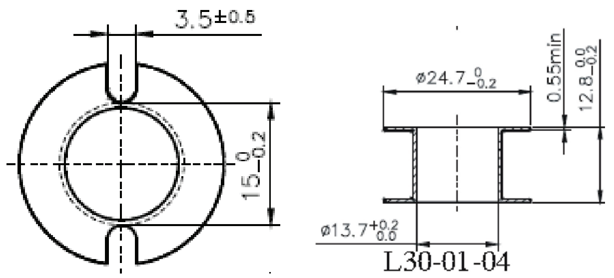

Fig.6. Dimensions of the toroidal coil former L30

After all the calculations are done and the copper wire is selected students can build the real inductor. The required turns are carefully wounded around the toroidal coil former (see Fig. 6) and the air gap is made by using a peace of paper of adequate thickness. The verification if the required inductance of the inductor L is obtained is done by measurement using LC-Q meter before the inductor is mounting on the boost converter test board (see Fig. 7 and 8). At this stage the resistance of the inductor R_L is also measured.

Analyses and Evaluation

When the built inductor L and the chosen capacitor C are mounted on the test board, students can perform final analyses and evaluation if the design project task goals are fully reached.

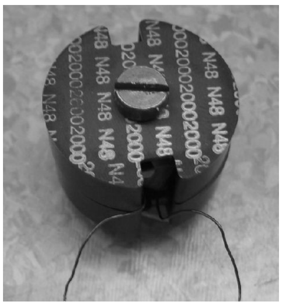

Fig. 7. Inductor built by student

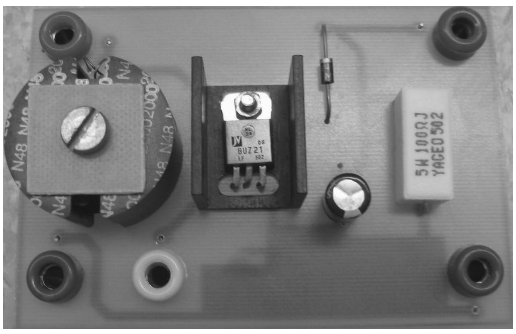

Fig. 8. Boost converter test board with mounted inductor and capacitor

In verification process students connect boost converter to 5 V voltage supply, they set the duty cycle to the value that gives 15 V voltage at converter output, so the converter operates in nominal operational conditions. Now they can measure the output voltage ripple ΔV_o as well as the ripple of the inductor current ΔI_L. The waveform of the inductor current ripple ΔI_L is shown in Fig. 9 together with the waveform of the transistor driving signal. The current was measured with the current probe that provides 100 mV output for each Amp measured. From Fig. 9 can be seen that project goal for the inductor current ripple ΔI_L = 0.2 A has been reached. The maximum output voltage $V_{o,\max}$ is also measured and compared with calculated value (18).

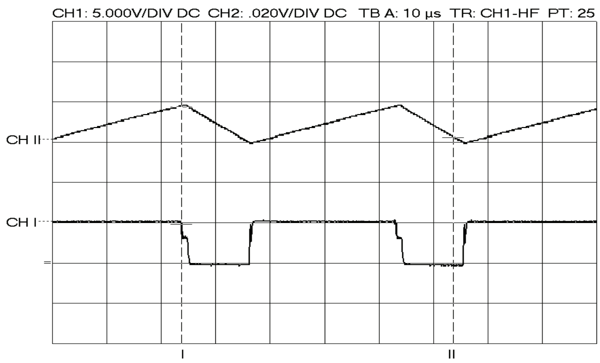

Fig. 9. Waveforms of the driving signal for transistor (CH I) and inductor current I_L (CH II).

Conclusion

This paper focuses on teaching students the fundamentals of electromagnetics through design of the inductor that is the part of the laboratory assignment on boost converter design. The whole project is prepared according to the CDIO principles and was well accepted by students. With respect to reported experiences in [3] and the fact that we worked with the students at the undergraduate professional level the detailed specification of the tasks in the Concieve (C) phase have been provided. The students work in group of three and were helped as much as it took for the best of them to carry out design successfully. With this teaching approach students were asked to apply the fundamental laws and work out details to complete design. In our opinion, students who gained a deep understanding of fundamental laws can self-educate themselves about any given subject. With working on the project design students also have gained the important experience that calculations are approximations of the real circuit behavior.

The project based teaching approach found high interest among all students and can be seen as a great success. Students enjoyed building their own boost converter and their rewarding experience will hopefully encourage students from next generations to enrol in Power electronics course.

REFERENCES

[1] Miri S. M., Fu R. J., "A Hands-On Practical Approach to Teaching Engineering Design", *IEEE Transaction on Education*, 36 (1993), No. 1, 131-136.
[2] CDIO, 2006 [Online]. Available: http:// www.cdio.org/index.html
[3] Max L., Thiringer T., Undeland T., Karlsson R., "Power Electronics Design Laboratory Exercise for Final-Year M.Sc. Students", *IEEE Transaction on Education*, 52 (2009), No. 4, 524-531.
[4] Mohan N., Underland T. M., Robinsson W., *Power Electronics, Devices, Converter, Application and Design,* John Willey and Sons. New York, Singapore, Toronto, Brisbane, 1989.
[5] Underland T. M., Lode J., Nilssen R., Robbins W. P., Mohan N., "A Single-Pass Design Method For High-Frequency Inductors", *IEEE Industry Applications Magazine*, September/October 1996, 44-51.
[6] Barmada S., Rizzo R., Sani L., "Didactic Consideration on Magnetic Circuits Excited by Permanent Magnets", *IEEE Transaction on Education*, 52 (2009), No. 4, 532-537.

Authors: Assist. Prof. Alenka Hren, Assoc. Prof. Franc Mihalič, Prof. Miro Milanovič, University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, SI-2000 Maribor, Slovenia, E-mail: alenka.hren@uni-mb.si, fero@uni-mb.si, milanovic@uni-mb.si.