International Journal for Innovation Education and Research

ONLINE ISSN: 2411-2933 PRINT - ISSN: 2411-3123

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The specifications for each converter module are the same, 48V/12V, 60W and 100 kHz of switching frequency. The designed modular curriculum has been applied to the Industrial Technology Research and Development Master (ITRDM) Program sponsored by the industry and government. And excellent acknowledgment from students is received for providing practical training and covering the wide range of magnetic components in power conversion applications.

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Published Date: 9/30/2017 **Page.67-81** **Vol 5 No 09 2017**

Link: http://ijier.net/index.php/ijier/article/view/795

Laboratory Course Modular Design for Learning Magnetic Components in Power Conversion Applications at Taipei Tech

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Abstract

The main theme of this paper is to present the laboratory course modular design for learning and hands-on magnetic components in power converters. The objective of the course is to give the students to model the converters, realize magnetic components and test the implemented converters via the hands-on work in order to improve practical skills of students under the insufficiency of regular course training. This designed course is based upon the modular concept of five modules in common use which include forward converter, flyback converter, push-pull converter, half-bridge converter and full-bridge converter. The controllers for these converter modules include voltage mode control and peak current mode control.
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1. Introduction

The Industrial Technology Research and Development Master (ITRDM) Program [1] is mainly sponsored by the government and companies. This program is aimed at providing graduate-level engineering workforce in high-tech industry and increasing the competitiveness of technology industry in Taiwan. The students received such sponsorship have the obligation to serve in the sponsored company for 2-4 years, depending upon the contract and content of sponsorship. Therefore, the final decision to accept the student to join this program is the sponsored company rather than the university. Under this circumstance, both hands-on skills and elementary knowledge trainings are important since the students assumingly receive job offer aiming at R & D as they join this program.

The power electronics industry is one of the most promising industries in Taiwan. As reported [2], Delta Electronics, Inc. was the first place of power supply market in the world and some of power supply manufacturers, such as AcBel Polytech Inc., Sunpower Technology Corp. and Lite-On Technology Corporation etc., are founded and locate in Taiwan. Therefore, the R & D workforce in power electronics is especially heavy in demand.

Taipei Tech. has established ITRDM program in power electronics since 2006. The related industry sponsors focus either power supply or motor drives industry. The course "Practice of Power Electronics System" is one of the optional courses for those who will join power supply industry. Therefore, the course is designed to help the students of ITRDM Program to fully appreciate the components of power conversion, converter design and hands-on experience.

It is well known that magnetic components are one of the most important elements in power converter applications. The magnetic components are used as energy storage, energy conversion and driver as shown in Fig. 1. Using DC/DC power converter as an example, the voltage level cannot be changed by transformer for not being able to produce time variant magnetic field without the assistance of switching components. By the switching devices, electrical energy of DC source is chopped and converted to time variant magnetic one and stored in the magnetic components on primary side and then transferred to the secondary side. The magnetic energy is finally converted to electrical energy to meet the desired voltage level by controlling the duty ratio of switching device.

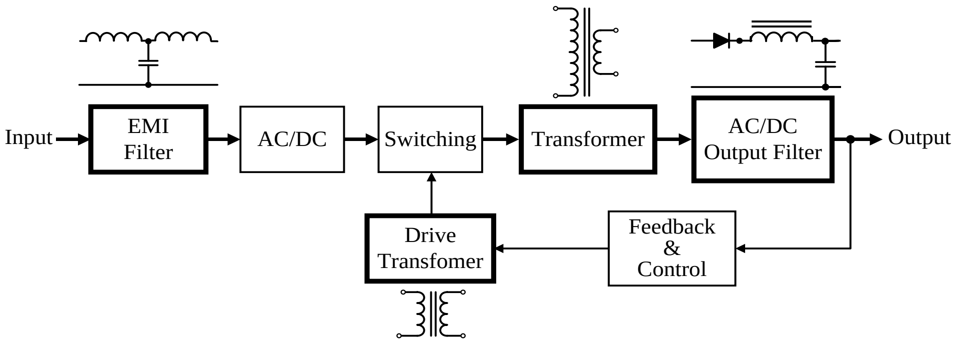


Fig. 1 Magnetic components in energy conversion system

The main theme of this paper is to present the laboratory course design for magnetic components learning and hands-on for ITRDM Program [3]. Recently, some reports have developed the software-based training program and tools, including new methodological approach to teaching power electronics converter experiments using LabVIEW [4], interactive rectifier educational tools using Java [5], graphic tool programmed in MATLAB for ac/dc and dc/dc switched-mode power supplies [6, 7] and e-learning platform for electrical circuit courses [8]. Some project-oriented programs have also been developed to enhance the students with hands-on experience in power electronics. These programs include project-oriented adjustable speed drive design course [9], project designed course for power electronics and motor drives using programmable intelligent computer (PIC) microcontroller and an H-bridge converter [10], and project task in power electronics based on a flyback test board [11]. Similar software-based tool and "learning-by-doing" course for control have been shown in [12-14], respectively.

Comparing to previous software-based work and project-oriented hands-on course, this paper will present the laboratory course modular design for magnetic components learning and hands-on [15, 16]. The design and applications of magnetic components include inductor, drive transformer, and transformer with and without center-tapped windings. The designed modular curriculum is based upon modular concept and the modules include forward converter module for inductor and transformer with center-tapped winding, flyback converter module for transformer with air-gap core acting as inductor and transformer, push-pull converter module for transformer with center-tapped winding, and full-bridge converter module for drive transformer.

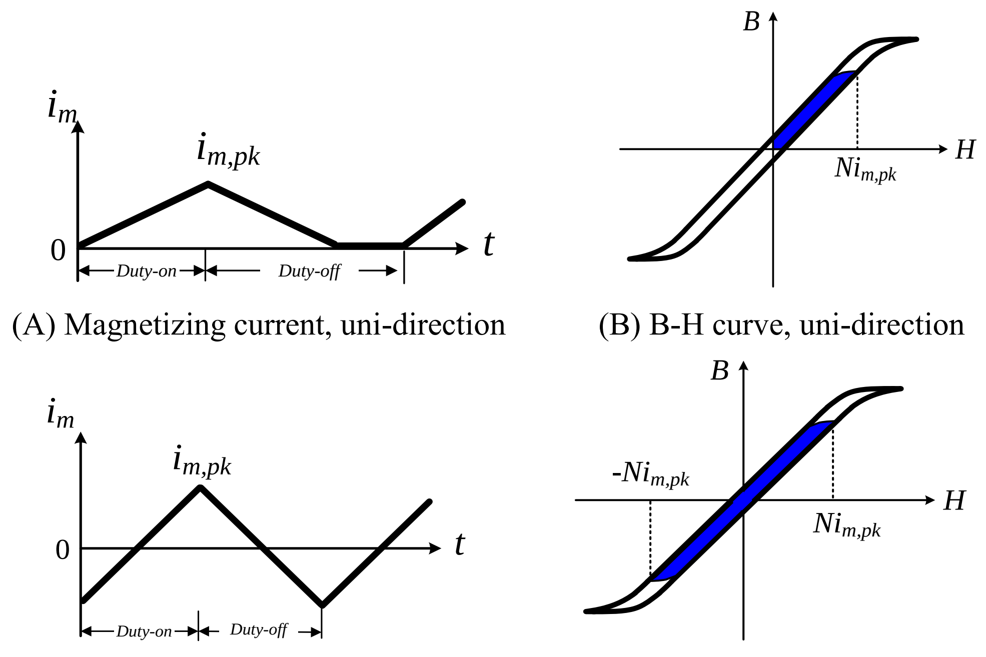
The specifications for all converter modules are the same, 48V/12V, 60W and 100 kHz of switching frequency. The designed modular curriculum has been applied to the ITRDM program sponsored by the government and companies. It will be shown that excellent acknowledgment is received for providing practical training and covering the wide range of practice of magnetic components in power conversion applications.

2. Designed Laboratory Modules for Magnetic Component Learning

2.1 Basics to the Magnetic Component for Power Conversion

As shown in Fig. 1, the magnetic components for power conversion include: transformer, driver and inductor. For transformer applications, one is called uni-directional excitation and the other is named bi-directional excitation as shown in Fig. 2. The former is applied to both forward and flyback converters, in which magnetizing current is provided only in one direction. The later one is used in push-pull, half-bridge and full-bridge converters in which magnetizing current is either I or III quadrant in B-H curve.

Moreover, the transformer for uni-directional excitation in flyback application also acts as an inductor. Its stored energy is released in the duty-off period other than duty-on duration. In contrast, the energy stored in the transformer of forward converter is pumped to the output side in the duty-on period.



(A) Magnetizing current, uni-direction (B) B-H curve, uni-direction

(C) Magnetizing current, bi-direction (D) B-H curve, bi-direction

Fig. 2 Magnetizing current and B-H curve of transformer, i_m = magnetizing current, $i_{m,pk}$ = peak value of i_m, N = number of turns of winding

2.2 Special Features of the Designed Laboratory Course

Table 1 summarizes the special features of the designed laboratory course related to the magnetic components for power conversion applications. As shown in Table 1, both transformer and inductor components are included for forward converter module. However, the transformer in this module is with third winding for de-magnetizing. For flyback converter module, the transformer is different from that for the other modules since it is used as both energy conversion and storage. Therefore, the design should be considered air-gap in order to avoid the flux saturation. Moreover, for push-pull converter module, the transformer has center-tapped windings on primary and secondary sides. In contrast, the half-bridge module transformer is with center-tapped winding on the secondary side only. For the full-bridge module, transformer, inductor as well as drive transformer are considered. Therefore, in the 18-week, 3-hour per week course, the students are motivated to learn how to design these magnetic components and their implementation. And these modules can cover the courses requirement of magnetic components for power conversion applications.

To provide a laboratory work while not invoking safety regulations, 48V/12V is specified for input and output voltage rating. Without requiring high power source and electronics load, the power rating for each module is 60W. However, to respect the students to fully appreciate the importance of layout, the switching frequency is 100 kHz. The specifications of each module are summarized as follows.

- Input Voltage: 48 V
- Output Voltage: 12 V
- Output Current: 5 A
- Output Power: 60 W
- Switching Frequency: 100 kHz

Table 1 Special features of the designed laboratory course related to the magnetic components for power conversion applications, Tr. = transformer

	Forward	Flyback	Push-pull	Half-bridge	Full-bridge
Transformer	√	√	√	√	√
Inductor	√		√	√	√
Drive transformer					√
Special Features of magnetic components	Uni-direction Tr. with 3rd winding for de-magnetizing	Uni-direction Tr also acts as inductor	Bi-direction Tr. with center tapped windings	Bi-direction Tr. with center tapped winding on secondary	Bi-direction Tr. with center tapped winding on secondary

2.3 Forward Converter Module

Fig. 3 shows the circuit diagram of forward converter. This module is designed to help students to get familiar with the inductor and transformer design. The special feature of the designed transformer is with the third winding as shown in Fig. 3. As mentioned in the sub-section of Sec. II, the transformer for forward converter is uni-directional which is magnetized in the duty-on period. In order to provide a de-magnetizing mechanism to avoid the flux saturation, a third winding is required.

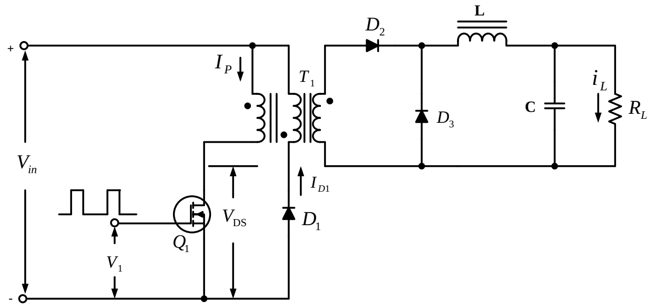


Fig. 3 Circuit of forward converter

2.4 Flyback Converter Module

The circuit of flyback converter is shown in Fig. 4. Obviously, the magnetized energy is stored in the exciting duty cycle and released in the remaining duty-off period. Therefore, the transformer also acts as an inductor. To provide a demagnetizing path to clamp the voltage spike, RCD clamping circuit [17] consisting of resistor, *R*, capacitor, *C*, and diode, *D* connected in parallel with the primary winding of transformer is used as shown in Fig. 4. Moreover, since the transformer acts as well as inductor which stores the energy, air-gap is required in its magnetizing path for avoiding saturation.

Therefore, this module is designed to facilitate the students to learn the design and implementation of a transformer with air gap. In short, the required magnetic component for this module is totally different from those in the other modules. Moreover, without causing too much leakage and loss in the air gap, the design of air gap is essential to the success of this module.

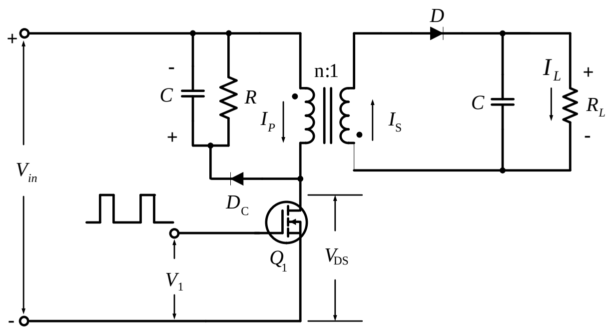


Fig. 4 Circuit of flyback converter

2.5 Push-pull Converter Module

This module is aimed at assisting the students to fully appreciate the design of transformer with center-tapped windings on both primary and secondary sides as shown in Fig. 5. Moreover, it will help students to understand the operation of bi-directional magnetic component. As compared with Fig. 3 and Fig. 4 for uni-directional magnetizing transformers, neither de-magnetizing winding nor clamping circuit is required for such bi-directional one. Another advantage for push-pull converter is its simplicity and excellence of driver circuits for two MOSFETs due to their common-ground features. By this module, the students will discover these special features as well as magnetic component design and implementation.

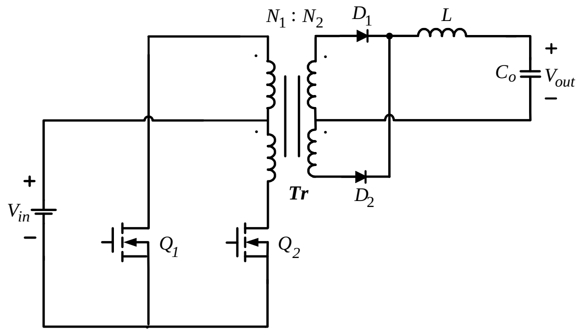


Fig. 5 Circuit of push-pull converter

2.6 Half-bridge Converter Module

Fig. 6 shows the circuit of half-bridge circuit which will give students the understanding of the transformer with only center-tapped winding on its secondary side. In this module, students will learn how to use the boot strap driver IC to drive the high-side and low-side MOSFET. Moreover, the voltage balance between two DC-link capacitors is also highlighted in this module. Without causing magnetic saturation due to the voltage un-balance of DC-link, a capacitor, C_B, is used to block the DC component as shown in Fig. 6.

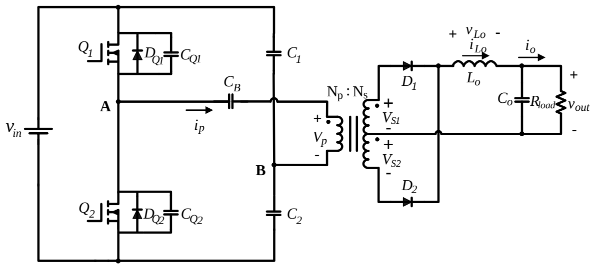


Fig.6 Circuit of half bridge converter

2.7 Full-bridge Converter Module

Fig. 7 shows the circuit of full-bridge converter. As shown in Fig. 7, the special feature of the transformer is the same as the half-bridge converter. Since full-bridge converter is applied to high power in general, its driver circuit consists of transformer driver rather than using boot strap driver in order to provide galvanic isolation between primary and secondary sides of transformer. Therefore, the objectives of this full-bridge converter module include introducing the transformer design used in driver circuits for both high-side and low-side MOSFETs. Fig. 8 shows the schematic diagram of drive transformer used in full-bridge converter.

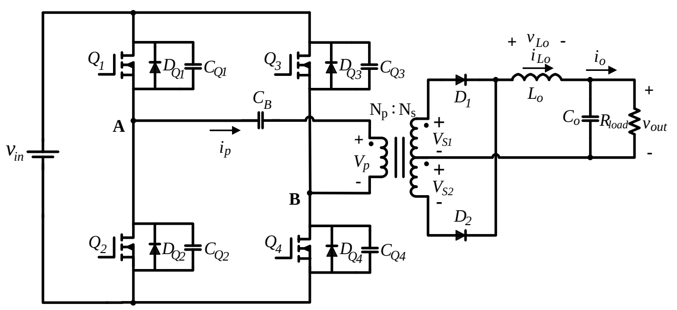


Fig. 7 Circuit of full-bridge converter

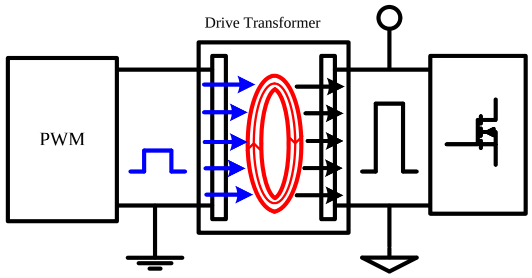
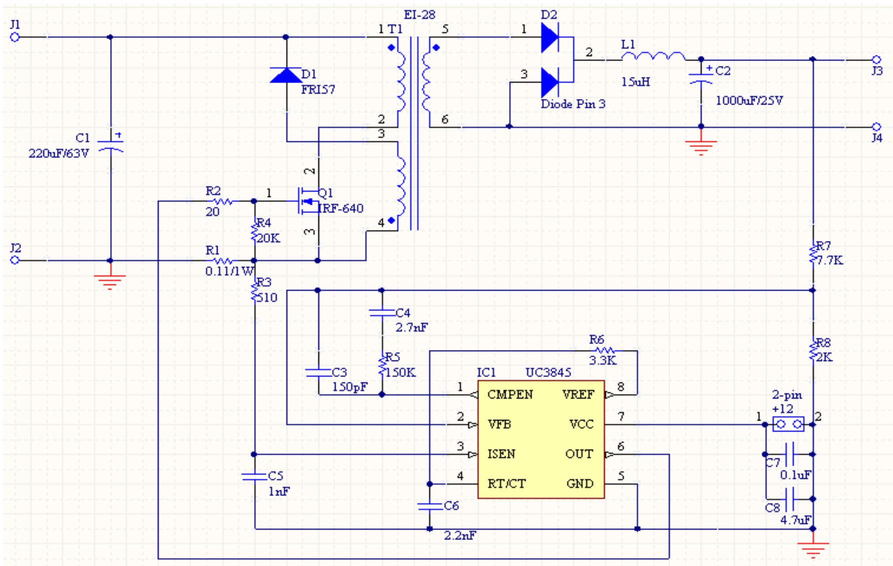


Fig. 8 Schematic diagram for drive transformer

3. Example of Design and Implementation

Fig. 9 shows the details of the circuit of the designed forward converter module. As shown in Fig. 9, the magnetic components include a transformer with the third winding and the output inductor. Moreover, UC 3845 [18] is used as the controller. And the output voltage is sensed by the voltage divider consisting of R_7 and R_8. The parameter of voltage controller is determined by the *RC* network, R_5, C_3 and C_4. The module details are introduced as follows.



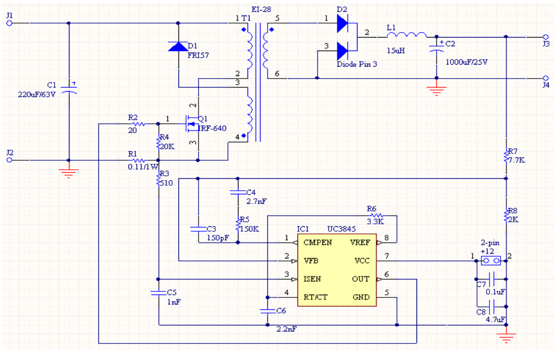


Fig. 9 Details of the circuit of the designed forward converter module

3.1 Design of Transformer

The design of transformer includes the turn number of primary, secondary and the third winding for demagnetizing. In order to reduce the skin effect, the number of wires for the windings should be considered. These data are derived based upon the specifications, core of transformer and dimension of wire. The details of the design are as follows.

Calculating the peak current of primary current:

$$I_{pri} = \frac{P_{out}}{\eta V_{in,\,\min}} = \frac{60}{0.8 \times 48} = 1.56 \text{ (A)}$$

where η = efficiency of forward converter = 0.8

Calculating the minimum voltage of secondary side:

$$V_{\sec,\,\min} = \frac{(V_o + V_f) \times T}{T_{on}} = \frac{(12+1) \times 10}{3} = 43.33 \text{ (V)}$$

where V_f = forward voltage drop of output diode, T_{on} = turn-on period, T = switching period

Turn number of primary winding:

$$N_p = \frac{V_s \times T_{on,\,\max} \times 10^8}{B_m \times A_e} = \frac{48 \times 4.5 \times 10^3}{86 \times 273} = 9.2 \;\rightarrow\; 10 \text{ Turns}$$

B_m= Designed maximum flux density for the selected core, TDK PC4 core [19], which is 70% of its saturated flux density

A_e= Effective cross area of the selected for the selected core, TDK PC4-EI28Z [19]

$T_{on,max}$ = maximum turn-on period,

Turn number of secondary winding:

$$N_s = \frac{(V_{\sec,\,\min} \times T_{on,\,\max}) \times 10^8}{B_m \times A_e} = \frac{43.33 \times 4.5 \times 10^3}{86 \times 273} = 8.3 \;\rightarrow\; 9 \text{ Turns}$$

Turn number of the third winding:

$$D_{\max} = \frac{1}{1 + \dfrac{N_p}{N_r}} \Rightarrow 0.45 = \frac{1}{1 + \dfrac{10}{N_r}}; \quad \therefore N_r = 8.18 \;\rightarrow\; 9 \text{ Turns}$$

Number of wires of windings:

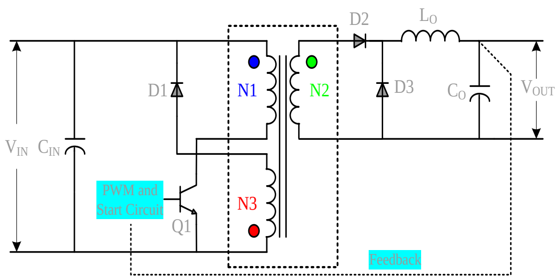
For the copper wire, the skin depth, δ, indicating at which the current attenuates to e^{-1} of that at the skin of conductor. The diameter of the wire should not be greater than 2δ to fully utilization of the conductor. The wire with diameter meeting this criterion is called Litz wire. The skin depth shrinks as the switching frequency increases. To carry large current, more twisted Litz wires connected in parallel are required. The number of wires is calculated as follows. First, the skin depth for copper wire with switching frequency = 100 kHz is calculated.

$$\delta = \frac{6.6}{\sqrt{f_{sw}}} = \frac{6.6}{\sqrt{100\times 10^3}} = 0.021\ (\text{cm}) = 0.21\ (\text{mm})$$

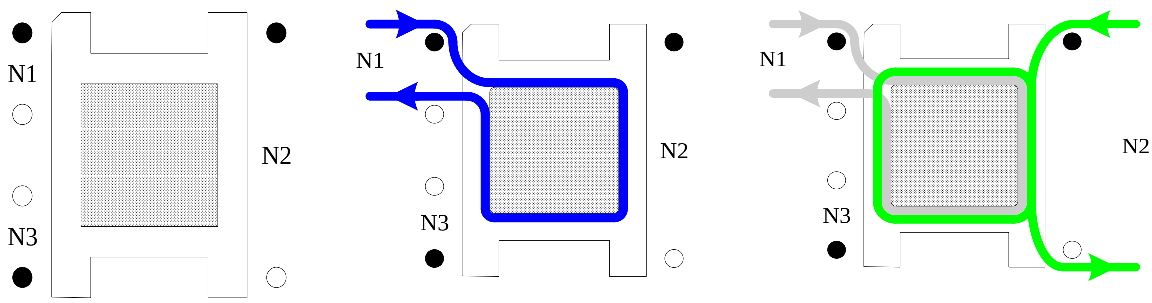
Therefore, the wire with diameter = 0.4 mm or 16 mil, and current density = 400 A/CM, is selected. The number of wire for primary winding, k_1, can therefore be derived as follows. Similarly, the number of wires for secondary side is 9.

$$k_1 = \frac{400\times 1.56}{\frac{\pi}{4}\times 16^2} = 3.10 \ \rightarrow\ 3$$

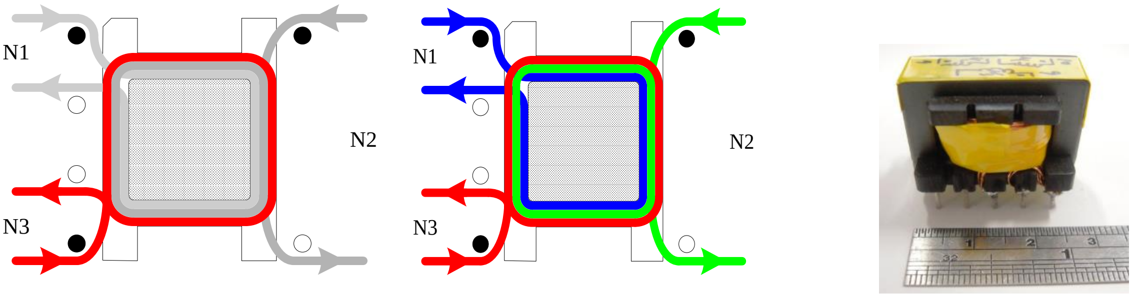
To facilitate the students to fully appreciate the implementation of the transformer, Fig. 10 shows the circuit, transformer implementation process and the photo of implemented transformer. To follow the above-mentioned design stages and this detailed process; see Fig. 10 (A) to Fig. 10 (G), the students can easily implement the transformer as illustrated in Fig. 10 (F).



(A) Circuit of forward converter



(B) Bobbin and core, (C) Primary winding, (D) Secondary winding



(E) Third winding, (F) Completion of transformer, (G) Photo of transformer

Fig. 10 Illustration of transformer implementation, forward converter

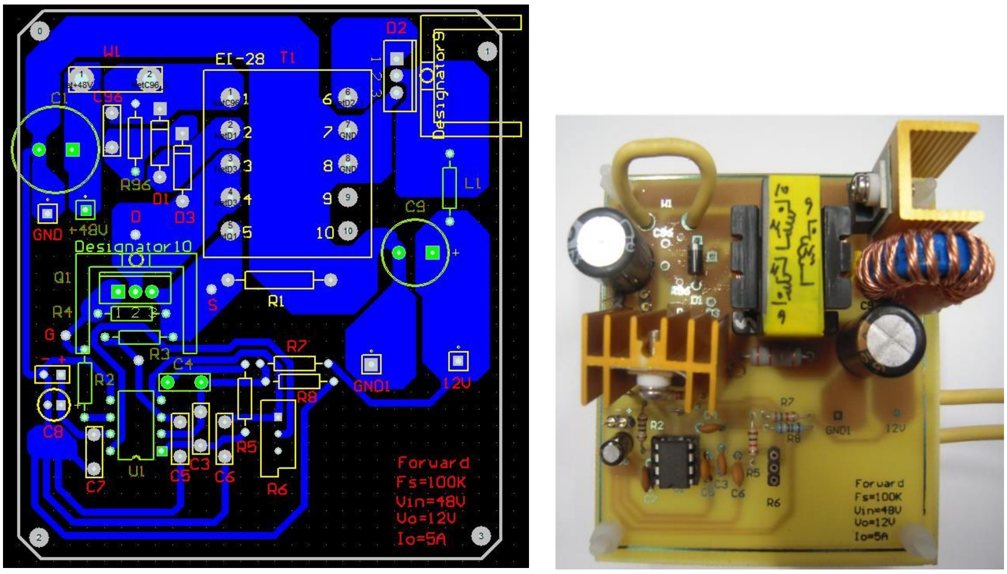
3.2 Design of Inductor

The core for inductor design and implementation is MS-080060-2, MPP core, ARNOLD. By the datasheet [20], the inductance factor, *mH* for 1000 turns, A_L = 32 mH/N^2. Therefore, for the inductor current = 5A and inductance = 15 μH, the number of turns is 22 and the number of wire is 10. Fig. 11 shows the implemented inductor which is designed and made by the student taking this course.

Fig. 11 Photo of inductor, made by student

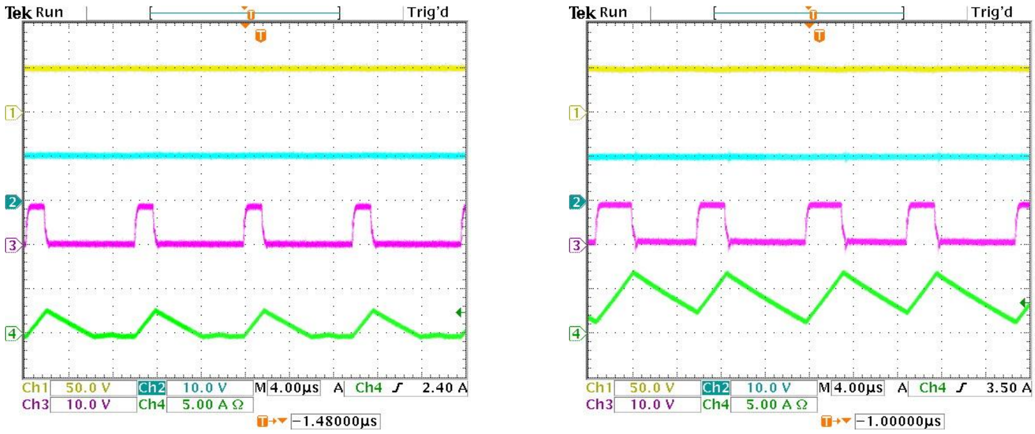
3.3 Assessment of Design and Implementation

Fig. 12 shows the layout and photo of the implemented forward converter; both are made by the student taking this course. For the switching frequency = 100 kHz, layout is important to the success of the implementation. To help the students to further confirm the design and implementation [21, 22], some test results are required as illustrated in Fig. 13. As shown in Fig.13 (A) and Fig. 13 (B), the output voltage can be well regulated at 12 V. Moreover, the duty; see Ch 2 in Fig. 13, increases and the inductor current goes to continuous conduction mode from discrete conduction mode as the load increases. These results are measured by the students from their implemented module for confirmation. Another measurement related to efficiency as shown in Fig. 14 is required to help students to understand the importance of converter design and implementation.



(A). Layout, (B). Photo

Fig. 12 Results, forward converter module made by students



(A) Output = 1A, 20% load, (B) Output = 5A, 100% load

Fig. 13 Measured results, forward converter, output voltage and inductor current, Ch 1 = input voltage, Ch 2= output voltage, Ch 3 = Vgs of MOSFET, Ch 4 = Inductor current

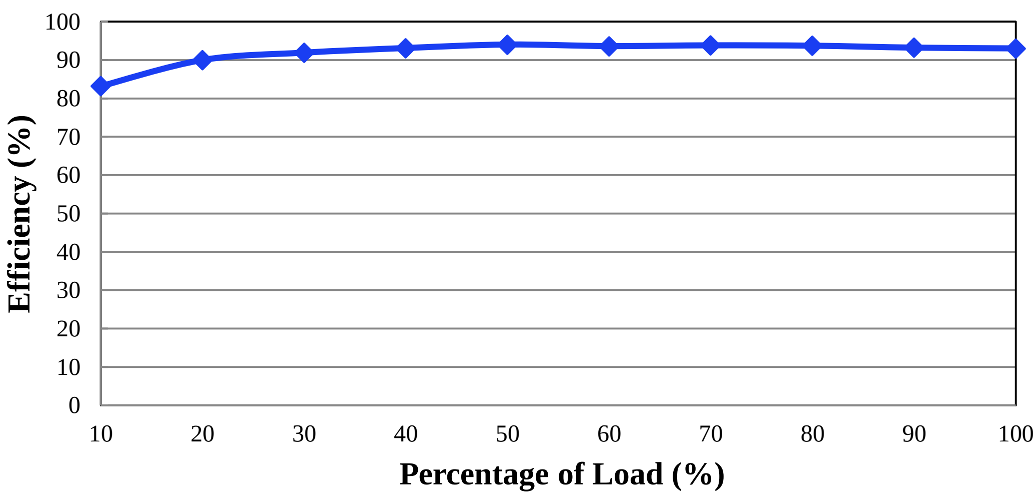
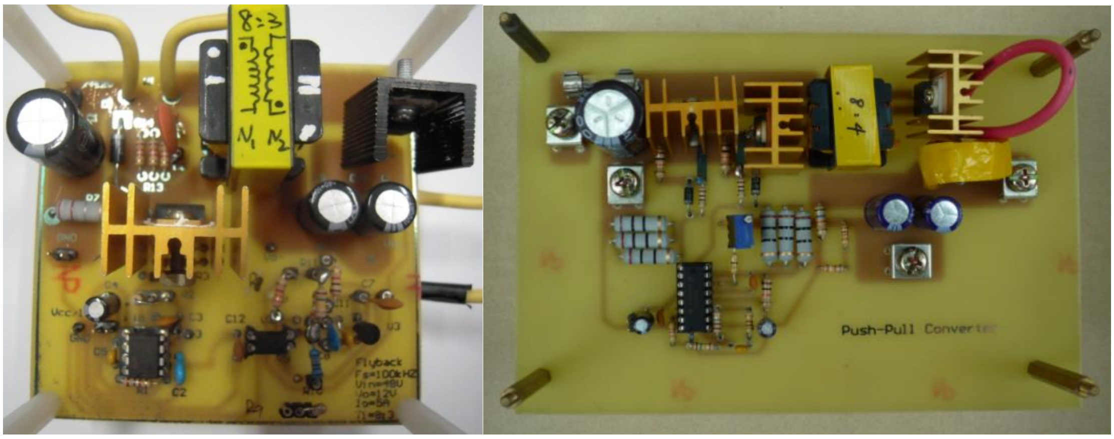


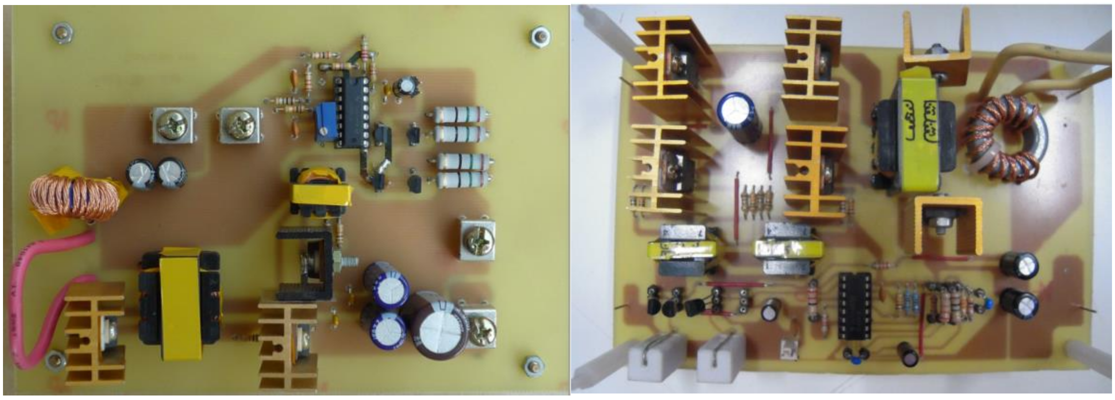
Fig. 14 Measured results, efficiency *vs.* load current

4. Course Implementation and Feedback

The other modules are designed and implemented based upon the same concept and development process. The students can follow the designed course to learn the magnetic components design and implementation. Similar training for layout, implementation and test are given to students to help them appreciating the special features of the required magnetic components applied to flyback converter, push-pull converter, half-bridge converter and full-bridge converter. Fig. 15 shows the photos of these converters realized by the students joined this course.



(A) Flyback converter, (B) Push-pull converter,



(C) Half-bridge converter, (D) Full-bridge converte

Fig. 15 Photos of implemented board, made by students

A survey is conducted which contains eight statements regarding the course [23-25]. Students are asked to rate these statements. Survey statements and associated responses from students are given in Table 2. The overall average is 4.61 points out of five. According to the survey, students showed really positive reaction to this course. The majority of the students are quite satisfied with this course, 4.87 points. Moreover, it is said that this course provides students better comprehension about the magnetic component design of power converters after taking this course. Another important point in this feedback is that this course helped students to learn the magnetic component implementation of power converters, 4.87 points, higher than the average. The feedback indicates that this designed course receives excellent acknowledgment for providing practical training and covering the wide range of magnetic components in power conversion applications.

Table 2 Feedback, Average points = 4.61 out of 5

The Designed Power Electronics Laboratory Course	Strongly Agree (5 points)	Agree (4 points)	Neutral (3 points)	Disagree (2 points)	Strongly Disagree (1 point)	**Average Points**
I become familiar with the layout of power converters after taking this course.	12	4				4.75
I have better comprehension about the magnetic component design of power converters after taking this course.	9	7				4.56
This course helps me to learn the magnetic component implementation of power converters.	14	2				4.87
I have better comprehension about the controller design of power converters after taking this course.	6	7	3			4.18
This course helps me to learn the controller implementation of power converters.	8	6	2			4.37
This course makes significant contributions to my hands-on test capability of power converters.	13	2	1			4.75
This course promotes my professional skill in power converter.	10	5	1			4.56
In general, I am quite satisfied with this course.	14	2				4.87

5. Conclusions

The contributions of this paper include the presentation and assessment of a laboratory course modular design for magnetic components used in power conversion applications. Five modules are designed to help students to fully appreciate the theory, hands-on work of layout, magnetic components design and implementation, and integration test. These magnetic components include inductor, transformer for power conversion and drive transformer. Transformers for power conversion include uni-direction and bi-directional applications with/without third windings and center-tapped winding(s).

The feedback from the Industrial Technology Research and Development Master Program students indicates that this designed course receives excellent acknowledgment for providing practical training and covering the wide range of magnetic components in power conversion applications. The designed course indeed facilitates the students to learn magnetic components design and implementation for power conversion applications.

6. Acknowledgement

The Industrial Technology Research and Development Master Program is organized and supported by the Ministry of Educations and Ministry of Economy Affairs, Taiwan. The industrial sponsorship for the power electronics course at Taipei Tech. is kindly offered by AcBel Polytech Inc., Allis Electric Co., Ltd., Chicony Power Technology Co., Ltd., Delta Electronics, Inc., Jaguar Precision Industry Co. Ltd., Leader Electronics Inc., Lite-On Technology Corporation, Rhymebus Corp., Sunpower Technology Corp. and TECO Electric and Machinery Co. Ltd., etc. since 2006. The authors also appreciate those students who joined this course and gave feedback for further improvement.

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