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Original Article

Development of a Buck Converter Training Kit for Power Electronics Laboratory Experiments

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Abstract *- Technological advances in power electronics have not been accompanied by advances in power electronics training kits. Training kits are necessary for student competency to be achieved. This article proposes a buck converter training kit. This kit is innovatively designed to support in-depth and effective experimentation in the power electronics laboratory. This training kit is unique because it is equipped with a Graphical User Interface (GUI). The training kit is also developed using Visual Studio, offering interactive and intuitive control over experimental variables in real-time. The principle and characteristics of the buck converter can be easily understood by students due to the built-in measuring instruments. According to the experiment's results, this training kit can be used in a variety of conditions, and it is valid and effective enough to be used as a buck converter learning aid. This training kit is cost-effective, user-friendly, and designed for hands-on lab sessions that combine practical and theoretical knowledge.*

Keywords *- Buck converter, GUI, Power electronics, Training kit, Visual Studio.*

1. Introduction

Preparing students to confront real-world industry difficulties in vocational electrical engineering education depends on the integration of theory and practical application using training tools [1]. Studies done lately show that students' knowledge of ideas and technical abilities is much improved by learning experiences using practical training tools [2, 3]. Thus, the creation of a buck converter training kit for power electronics laboratory experiments with a Graphical User Interface (GUI) built on Visual Studio is an original contribution to vocational electrical engineering education. Enriching their learning experience, this GUI allows direct student engagement with experimental parameters and real-time input and output voltages and currents monitoring. Several studies have been reported with regard to buck converter training kits. An STM32 microcontroller is used in the digital control of the buck converter. This converter is used as a learning module in a training course [4]. Software has also been developed to investigate the functions and models of power converters. This research has an important contribution in the educational aspect and the development of digital tools for power converter learning and research [5].

The proposed buck converter is developed to integrate the findings from previous studies with new technologies by enhancing interactivity and responsiveness with the use of Visual Studio [6]. The interface allows students to directly observe the result of the changes in duty cycle settings on the output of the buck converter and to dynamically interact with different load scenarios, enabling them to appreciate the impacts of these variables on the converter's performance.

This training kit includes advanced technologies that let students connect to practical circumstances, especially in sectors that are quite dependent on the administration and optimization of power conversion systems [7]. The GUI now gives students access to power electronics concepts and their uses in energy conversion systems [8]. With this kit, students can directly apply theory to understand how power converters work in real industrial situations, thereby increasing their understanding of the devices. This device is designed with the intention of surpassing existing educational aids in teaching power electronics to promote greater user interaction and understanding of the subject [9]. Hopefully, this research will play a role in elevating the quality of electrical engineering education.

2. Design and Implementation

The training kit includes a buck converter circuit that can use digital measurement tools built into the kit to keep an eye on input and output voltages and currents. This makes the measurement process more efficient. The kit also has an LCD interface that shows important information like frequency and duty cycle values. The buck converter circuit is built on the basic ideas of power electronics. The kit comes with a controller chip that makes building on it even more possible, such as by connecting it to a PC through a GUI-based interface.

2.1. Buck Converter

A buck converter is a DC-DC converter that effectively reduces a larger input voltage to a lower output voltage. Its operation relies on the rapid switching of a power semiconductor device, typically a MOSFET, controlled by Pulse-Width Modulation (PWM) [10-12]. In general, buck converters are employed to reduce the voltage from a high-voltage source to meet the requirements of devices that necessitate a lower voltage level [13-15].

Buck converters have changed the way power supplies are designed in many electronic systems. Many industries use buck converters because they are flexible and work well [16]. Buck converters have been shown to be a reliable way to control voltage in everything from small electronic devices to big renewable energy systems.

Some of the things they can be used for are computer power supplies, battery chargers, and systems for electric vehicles [17-19]. The circuit diagram for the buck converter is shown in Figure 1.

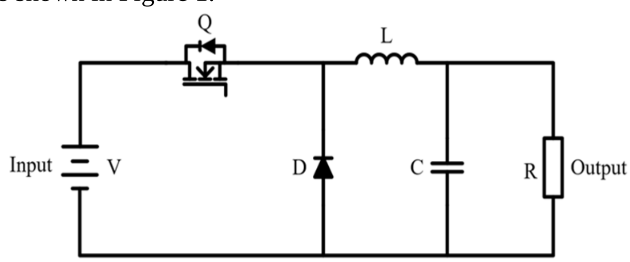

Fig. 1 Buck converter circuit

The mechanism of the Buck converter is inductive energy storage and switching control, enabling high efficiency (typically 80～95%) over a linear regulator. Converter operation is based on two main modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM), which depend on the current in the inductor.

A buck converter has a few important parts that work together to lower the voltage quickly. A PWM signal turns the high-side switch on and off quickly. Power flows from the input through an inductor to the output when it is on. When the MOSFET is off, a diode helps by letting current flow through it. When the switch is on, the inductor stores energy, and when it is off, the energy is released to keep the current steady [20, 21]. The capacitor smooths out the output voltage so that it does not change as much.

In general, the Buck converter has two main parts: the power section, which is responsible for voltage conversion and includes the switch and the output filter, and the control section, which manages the ON-OFF state of the switch [22].

The operation of the Buck converter can be described in two states: the ON state, when the switch is closed, and the OFF state, when the switch is open.

Figure 2 shows the buck converter circuit when it is ON. At time $t = 0$, the MOSFET is ON and the diode is OFF. Current flows from the source through the inductor, is filtered by the capacitor, goes to the load, and then goes back to the source.

The current charging period for the inductor is the name of this phase. During this time, the current starts at zero and slowly rises until it reaches its highest point.

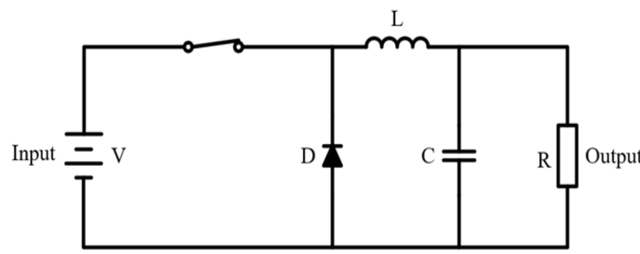

Fig. 2 Buck Converter Circuit in the ON Condition

In this ON state, the following equation can be derived.

$$V_{in} = V_L + V_o \tag{1}$$

$$V_L = V_{in} - V_o \tag{2}$$

$$L\frac{di}{dt} = (V_{in} - V_o) \tag{3}$$

$$Ldi = (V_{in} - V_o)\,.\,dt \tag{4}$$

Since the duration of time *dt* occurs while the switch is in the ON condition, then:

$$Ldi = (V_{in} - V)_o\,.\,t_{on} \tag{5}$$

$$di = \left(\frac{V_{in}-V_o}{L}\right)\,.\,t_{on} \tag{6}$$

When the MOSFET is turned off and the diode conducts at t=t_1, current passes via the inductor, capacitor, load, and diode.

The inductor current diminishes until the transistor is reactivated in the next cycle, during which the energy stored in the inductor is transmitted to the load. Figure 3 illustrates thSSSSPe OFF condition.

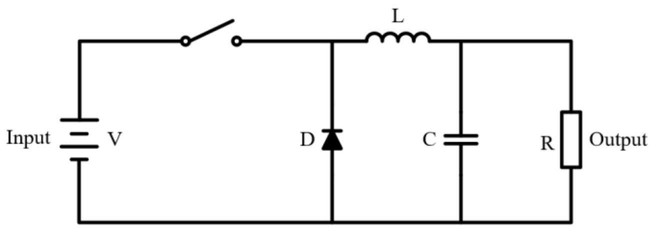

Fig. 3 Buck converter circuit in the OFF condition

In this OFF state, the following equation can be derived.

$$V_L = V_o \tag{7}$$

$$L\frac{di}{dt} = V_o \tag{8}$$

$$Ldi = V_o dt \tag{9}$$

Since the duration of time dt occurs while the switch is in the OFF condition, then:

$$Ldi = V_o \ . \ t_{off} \tag{10}$$

$$di = \left(\frac{V_o}{L}\right) \ . \ t_{off} \tag{11}$$

By integrating Equations (6) and (11), the relationship between the input and output voltages can be expressed as follows:

$$V_o = V_{in} \times D \tag{12}$$

In this context, V_O denotes the output voltage produced by the buck converter circuit, V_{in} represents the DC input voltage applied to the converter, and D is the duty cycle, a modulation factor that controls the pulse width and is utilized for scaling the output voltage [23-25].

2.2. Graphical User Interface (GUI)

The GUI is an interactive visual design system for computer software. The GUI itself displays objects from a design that can convey the information needed and present the work of the user [26]. This system enables users to interact with devices using input tools such as a mouse, touchpad, and keyboard [27]. GUI is a type of user interface used to enable communication between humans and devices such as laptops, computers, smartphones, and tablets [28].

The GUI consists of several elements in the form of images. These elements can be seen as icons, windows, and menus. The computer can also execute commands such as opening, moving and deleting files. The GUI system works through mouse commands and can be executed through keyboard shortcuts [29]. The purpose of the GUI itself is to provide convenience for users without the need to understand the code input to process the command. Developers can also change the appearance of the interface as flexibly as possible without changing the existing functions [30].

Some of the most popular tools for making GUIs are JavaFX, SwiftUI, wxWidgets, and Visual Studio. Visual Studio is an IDE that makes it easier to make GUIs. With Visual Studio's Windows Forms Designer, users can build the GUI visually and write code to handle events like button presses and text input, as well as add extra features like file access, network communication, and database integration.

3. Hardware Design

The buck converter training kit's open-frame, hands-on design makes learning more real by letting you experience things in real life. Figure 4 shows a Buck Converter control system that runs and gets power from an Arduino UNO-based platform. A 220 VAC power source starts the system. An AC to DC step-down converter changes this to 12 VDC. After that, this 12 VDC supply is split into two levels: 9 VDC for the Arduino UNO and 5 VDC for the gate driver and other sensors.

Arduino Uno is the master controller for all. Arduino Uno reads signals coming from several inputs, decodes them, and sends out processed signals as output signals to be carried out by the buck converter. A potentiometer is connected to the Arduino and is used as a manual controller for the PWM duty cycle setting. This adjusted PWM affects the output voltage regulation of the buck converter. In this system, the Arduino is also equipped with an LCD display to show measurement results for voltage, current, and duty cycle. To enhance the system, a PC is used to monitor the parameters of the buck converter and to control its operation via serial communication. A GUI developed using Visual Studio software is used as the interface between the PC and the buck converter.

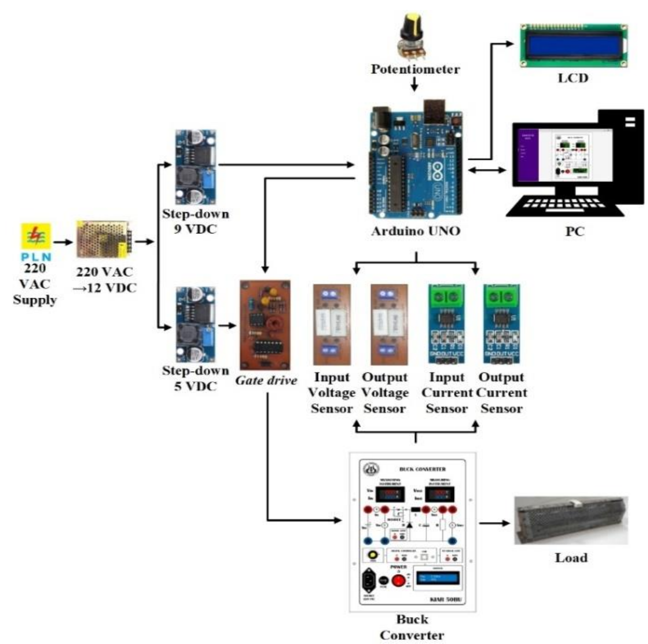

Fig. 4 The Configuration System of Buck Converter

Four sensors are included in the system: input voltage sensor, output voltage sensor, input current sensor, and output current sensor. These sensors measure electrical parameters at the input and output sides of the Buck Converter, providing critical data to the Arduino for real-time monitoring and potential feedback control. The gate driver acts as a signal amplifier, converting the low-power PWM signal from the Arduino into a suitable control signal for switching devices within the Buck Converter.

4. Results and Discussion

The buck-converter training kit was fabricated on a single-layer FR-4 (100 mm × 70 mm) PCB and mounted in a 210 mm × 297 mm × 100 mm acrylic enclosure with an integrated LCD, potentiometer, fuse, switch, digital voltage and current measurement and banana-plug terminals. The Arduino Uno is employed to interface the buck converter training kit with a Personal Computer. The buck converter testing is conducted by supplying an input voltage of 24 VDC to the power circuit. The buck converter is engaged with 1.8 mH of inductor, and 4.7 μF of capacitor, the IRF460 is employed as MOSFET, and MUR460 as diode. The duty cycle is set between 10% and 90% using a potentiometer. The designed buck converter training kit is shown in Figure 5; meanwhile, Table 1 contrasts the principal design targets with the experimentally measured values.

Table 1. Compares major design targets to experimental values

Parameter	Design Target	Measured (mean ± SD, n = 5)	Unit
Input voltage range	12 – 24	12, 15, 18, 24	V
Output voltage range	0 – 20	0 – 19.6 ± 0.04	V
Max. output current	3.0	2.95 ± 0.03	A
Switching frequency	31.25	31.4 ± 0.1	kHz
Peak efficiency @ I_o = 1 A	≥ 90	92.1 ± 0.4	%
Output ripple @ I_o = 1 A	≤ 1.0	0.78 ± 0.02	% V_{out}

Fig. 5 The buck converter training kit

Electrical performance was evaluated under nine duties (10%, 20 %, 30%, 40%, 50 %, 60%, 70%, 80 % and 90%) and two loads (R = 100 Ω and R = 32.8 Ω). Tables 2 and 3 show the steady-state results with various duty cycles. Meanwhile, the testing of the entire buck converter training kit can be seen in Figure 6.

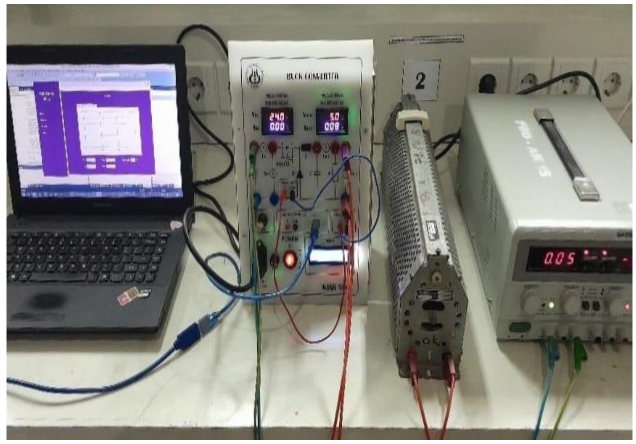

Fig. 6 Overall testing of the buck converter training kit

Table 2. Steady-state results with various duty cycles for 100Ω load

Duty cycle (%)	V_{out} ± 0.05 (V)	I_{out} (A)	P_{in} (W)	P_{out} (W)	η (%)
10	2.38	0.024	0.077	0.057	74
20	4.78	0.048	0.278	0.229	83
30	7.21	0.072	0.589	0.519	88
40	9.63	0.096	1.013	0.924	91
50	12.2	0.120	1.565	1.464	94
60	14.41	0.144	2.304	2.075	90
70	16.78	0.168	3.282	2.819	86
80	19.15	0.192	4.389	3.677	84
90	21.57	0.216	5.690	4.659	82

Table 3. Steady-state results with various duty cycles for a 32.8Ω load

Duty cycle (%)	V_{out} ± 0.05 (V)	I_{out} (A)	P_{in} (W)	P_{out} (W)	η (%)
10	2.43	0.073	0.225	0.177	79
20	4.81	0.146	0.836	0.702	84
30	7.19	0.220	1.796	1.582	88
40	9.58	0.293	3.122	2.807	90
50	11.95	0.366	4.824	4.374	91
60	14.36	0.439	7.024	6.304	90
70	16.83	0.512	9.778	8.617	88
80	19.22	0.585	13.069	11.24	86
90	21.61	0.659	16.934	14.22	84

The twin tables capture how the buck-converter training kit behaves across nine duty-cycle settings (10 % → 90 %) under two extreme but pedagogically useful loads: a light load of 100 Ω and a heavy load of 10 Ω.

The converter behaves just like a textbook buck stage: as the duty cycle—and therefore V_{out} increases, the output current raises in exact proportion to the load resistance (Ohm's law). With the light load (100 Ω), the current is small, so at very low duty (V_{out} ≈ 2.4 V), almost all the input power is wasted in the control electronics; efficiency starts at only ≈ 74 %. Once the output reaches about 10 V–12 V, real power flows and those fixed losses become a small fraction of the total, so efficiency peaks at around 94 %. Beyond that point, the switching devices heat up and magnetic losses grow; by the time V_{out} hits 21 V, efficiency has slipped to ≈ 82 %.

With the heavier load (32.8 Ω), the story is similar but shifted upward. Higher current means the control-circuit losses matter less from the start, so efficiency already begins at about 79 % and peaks near 91 % around V_{out} ≈ 12 V. Because conduction losses now loom larger, the drop after the peak is milder; efficiency stays above 84 % even at the highest voltage.

The monitoring data from the buck converter circuit will be displayed on the Visual Studio software. In Visual Studio, a page has been designed to display the monitoring data of the buck converter, including V_{in}, I_{in}, V_{out}, and I_{out}. Figure 7 shows the display page showing a duty cycle value of 20% at a load of 32.8 Ω, with an input voltage of 24.00 VDC, output voltage of 4.82 VDC, and a frequency of 31.4 KHz.

The kit is most efficient in the middle of its range (roughly 30 %–60 % duty). Light-load performance could be improved with a low-power "burst" mode, while heavy-load efficiency would benefit from lower-resistance switches or thicker copper traces to cut conduction loss.

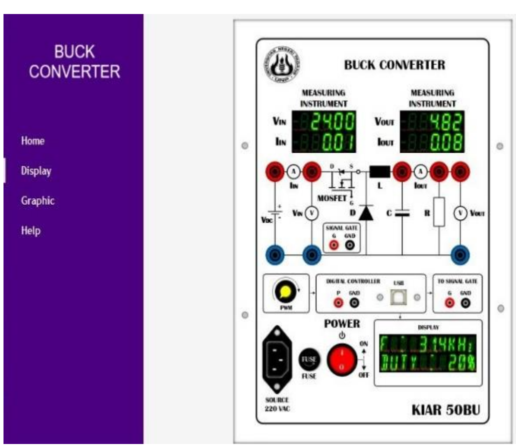

Fig. 7 Display page in the GUI for measurement

As shown in Figure 8, the output voltage of the buck converter is influenced by the duty cycle. The output voltage increases as the duty cycle becomes larger. This observation is in line with the theory of Pulse Width Modulation (PWM), which states that a higher duty cycle results in a higher output voltage produced by the buck converter. These results indicate that using the PWM method is an effective approach for regulating the output voltage of a buck converter.

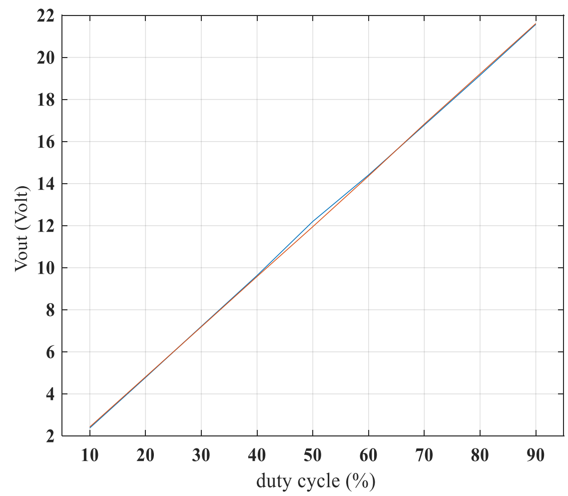

Fig. 8 Comparison of efficiency versus duty cycle

Figure 9 shows a typical "hill" efficiency profile for both load circumstances. At low duty (10%), fixed losses—micro-controller and gate-driver bias—become dominant, producing 74% for light 100 Ω loads and 79% for heavy 32.8 Ω loads. Output power at 50% duty rose quicker than losses, therefore reaching maximal efficiency of 94% (100 Ω) and 91% (32.8 Ω). After peak, increased switching, core, and MOSFET I²R losses happen with more drop at 100 Ω to 82% at 90% duty; 32.8 Ω keeps 84%.

At low duty, larger loads reduce the effect of fixed loss; at high duty, they raise conduction loss and flatten the curve. While burst-mode or adaptive-frequency control increases efficiency under light loads and very low duty, the 40–60% duty range provides the greatest energy performance for both loads.

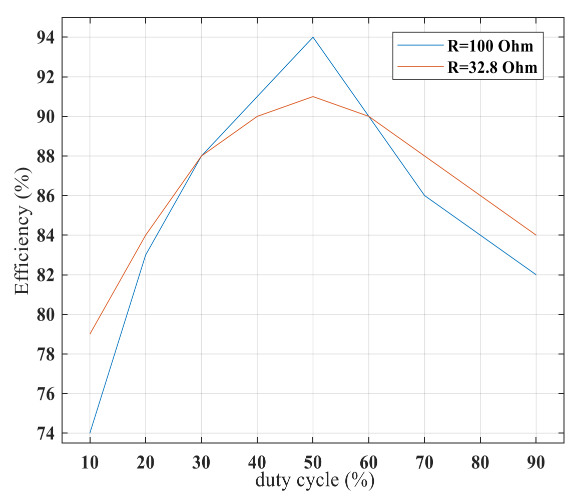

Fig. 9 Comparison of efficiency versus duty cycle

To assess educational value, the prototype was deployed in a third-year Power Electronics course (N = 28). Students completed a three-hour practical encompassing duty-cycle control, efficiency mapping, and CCM/DCM identification. Table 4 summarises anonymous questionnaire results (1 = poor, 5 = excellent).

Table 4. Questionnaire results

No.	Criterion	Mean Score
1.	Ease of setup	4.6
2.	Clarity of onboard measurements	4.4
3.	Perceived learning gain	4.5
4.	Hardware robustness	4.3

5. Conclusion

This buck converter training kit includes a GUI made in Visual Studio. It makes it easier for students to control and monitor experiments linked via Arduino UNO, which contributes an unprecedented pedagogical aid focusing on interaction and unhindered experimentation in learning environments. Opposed to the existing systems that revolve around simulation and closed-platform tools, this training kit supports hands-on control, incorporating open-source hardware and GUI design, where educators and students can modify or personalize the system to meet defined learning goals. This technique addresses the shortcomings of excessively adaptable teaching kits alongside frameworks and contemporary technology in vocational and undergraduate engineering education.

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