DIDACTIC KIT FOR PRATICAL TESTING OF THE BASIC SWITCHED MODE POWER SUPPLY TOPOLOGIES

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Abstract

The DC/DC converters are widely used in regulated switch-mode DC power supplies and in DC motor drives. Their concepts are, in general, initially approached in disciplines like Power Electronics or Industrial Electronics, when the students have the first experience with high or medium frequency power switching. Thus, to overcome the natural difficulties in practicing this technology, the authors propose a didactic kit, equipped with basic structure for laboratory experiments related with Buck, Boost, and Buck-Boost converters.

***Keywords* –DC/DC converters, didactic kit**

I. INTRODUCTION

The DC/DC converters are widely used in regulated switch-mode DC power supplies, since the input of those converters is often obtained by rectifying the line voltage, which produces a natural undesirable fluctuation on the output voltage. In those applications, the converters are often used with an electrical isolation transformer [1].

An important application is in DC motor drive, in which one can use the converters to implement a closed loop speed control system including the four quadrant operation with or without regenerative braking. Here, the isolation transformer is almost never used [2].

Another important and actual use is related to renewable energy applications. Step-down converters can be used in battery charging devices from photovoltaic modules, and step-up converters are widely used in distributed generation and in the integration of renewable energy sources into the electrical grid [3].

The converters treated in this work are Buck (step-down), Boost (step-up), and Buck-Boost (step-down/step-up). Only the non-isolated converters are considered herein.

The main application of Buck converters is in regulated DC power supplies and DC motor speed control. In the case of Boost converters, an important application is in the regenerative braking of DC motors.

In general, the study of DC/DC converters is approached in disciplines like Power Electronics or Industrial Electronics for engineers, and starts with a presentation of the Buck, Boost and Buck-Boost converters. That happens for the relative simplicity of their topologies and the theory of electricity and magnetism involved. Therefore, the assembly and the tests of those topologies during laboratory classes are a challenge for the student, due to the difficulties using proto-boards and a high amount of noise. Aiming to reduce those difficulties, it is proposed in this paper a didactic kit, equipped with a satisfactory structure for the good functioning of the topologies mentioned before, for laboratory experiments. Similar teaching methodology has also been suggested in some recent papers [4]-[7]

This article is organized as follows. Section II presents the description of the proposed didactic Kit under the pedagogical and hardware point of view. In section III, the authors recommend suitable procedures to turn on each topology and suggest some experimentation. Mathematical model related to converters and static and dynamic transfer functions are presented in a nutshell in section IV. Brief experimental results are shown in section V. A conclusion is presented in Section VI with a summary of the achievements.

II. DIDACTIC KIT DESCRIPTION

The didactic kit proposed presents itself as a compact solution for a preliminary practice approach in the teaching of DC/DC converters in disciplines like Power Electronics and Industrial Electronics. A practical operational demonstration of classic converters like *Buck* (step-down)*, Boost* (step-up) *and Buck-Boost* (step-down/step-up) can be easily done.

The didactic kit platform consists basically of a command circuit for an electronic switch, the electronic switch itself and a matrix of components that are common for all topologies above-mentioned. Those components must be properly connected by the user, in such a way that the desired operation of each converter can be achieved. During demonstrations or investigations, it is only necessary to connect a primary power supply and do the manual adjustment of the desired output voltage. What follows are the technical and pedagogical aspects involved in the conception of the didactic kit.

A. Pedagogical Aspects

The conception of the kit was based on the idea that the user must do the suitable electronic connections for the goog functioning of the converter, object of the laboratorial practice. It is necessary a previous knowledge about the topology in question, at the same time that the student uses reliable and previously tested test bench, reducing the assembly time and avoiding the difficulties derived from noise, which is typically found when circuits are assembled in proto-boards.

The board layout was elaborated in such a way that the user can clearly distinguish the command circuit, the drive circuit and the power circuit. In addition, those circuits are in line, like one can see in simple electronic schemes presented in the didactic literature.

There are two ways to excite the command circuit of the electronic switch. Using a connector, which can receive an external pulse width modulation (PWM), or from a PWM generator circuit contained in the board itself. This way, the user can continuously change the duty cycle through the manual command of a potentiometer. The analog command voltage of the PWM generator, on board, can also be obtained through an external connector. From the connectors, the user can use analog or digital controllers to implement a closed loop system to regulate the output voltage, incorporating an interdisciplinary action to the kit.

B. Hardware Description

The board has an in line layout with 11x26 *cm* dimensions and accommodates, in sequence (bottom up – Figure 1), the following subsystems:

- PWM generator, implemented with a dedicated integrated circuit 3524. It provides a pulse width modulation signal with duty cycle continuously variable from 0 to 100%. The duty cycle can be commanded through connection 1 of the J2 jumper and by the adjustment of the P1 potentiometer. An external analog command signal can be obtained through the C1 connector. For that, the J2 jumper must be in position 2. A PWM signal generated by a microcontroller can also be applied directly to the command circuit of the electronic switch through connection 2 in the J3 jumper. Thus, the internal PWM generator is disabled. The switching frequency can also be selected between two possibilities by the J1 jumper, position 1 (5 kHz) or position 2 (16,45 kHz).
- Command circuit of the power switch implemented with non-isolated integrated circuit IR2111;
- Power circuit consisting of a MOSFET power transistor, N-channel IRF640 (18 A – 200 V), a super-fast diode MUR160 (1 A – 600 V), a resistor bank performed by four 22 Ω (5 W) resistors in series, a 1,515 mH inductor, and a 220 μF (35 V) electrolytic capacitor.

The schematic diagrams of the two first subsystems are shown in Figure 2. It is observed that the access to pin 6 of the IC 3524 is accomplished through the J1 jumper, in which the user changes the resistor associated with the RC time constant, responsible for setting the switching frequency. If the connection is done to the 20 kΩ resistor, the switching frequency is 5 kHz. Otherwise, it is 16,45 kHz. This resource allows the user to verify the effect of the switching frequency upon the operation temperature of the electronic switch.

It is important to note that during the power circuit, components sizing none of the restrictions relative to efficiency were taken in account, once the components can be used for the implementation of three different converters.

Snubber circuits were not used, favoring a simple approach and keeping the focus on the converters.

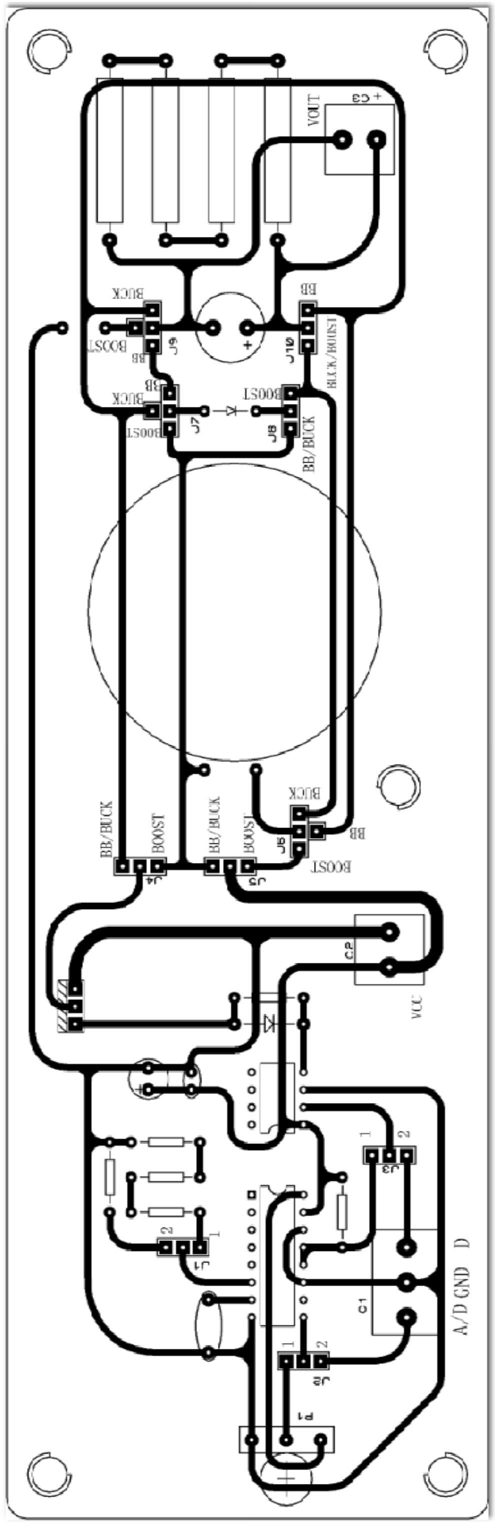

Fig. 1. Layout of the didactic kit.

III. RECOMMENDED PROCEDURES

Once defined the PWM source generator, the user must do the suitable connections at the components matrix, aiming the implementation among the three possible topologies.

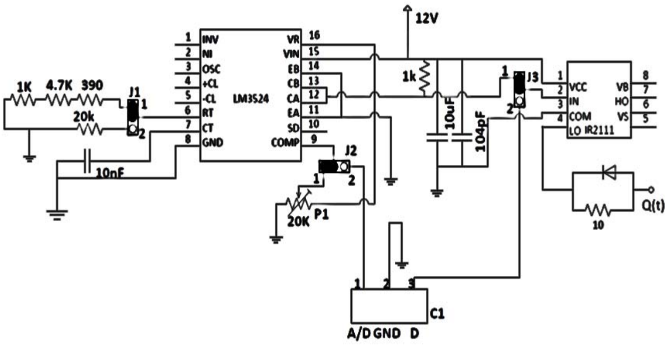

Fig. 2. Schematic diagrams of the PWM generator and electronic switch command subsystems.

Figures 3, 4, and 5 illustrate the schematic diagrams of the Buck, Boost, and Buck-Boost converters, respectively. In those figures, the components and the jumpers are disposed as in the electronic board. There are 7 jumpers, identified as J4 – J10, in which the user can easily recognize the BUCK, BOOST and BB intuitive labels. To implement the Buck converter, all the jumpers must be in the BUCK position. In the case of Boost, all the jumpers must be in the BOOST position. For the Buck-Boost, all the jumpers must be connected in BB position.

Once all the basic jumper connections have been made and the user has connected the power supply, the authors recommend the follow procedures:

- Verify the imposed duty cycle and the respective output voltage level of the chosen converter using an oscilloscope**;**
- Verify the gate circuit command signal and the drain-source voltage of the electronic power switch;
- Change the duty cycle and verify the critic operation point between continuous and discontinuous conduction;
- Change the switching frequency to verify the critic operation point between continuous and discontinuous conduction;
- Change the switching frequency to verify its influence over the electronic power switch temperature using an infrared thermometer.

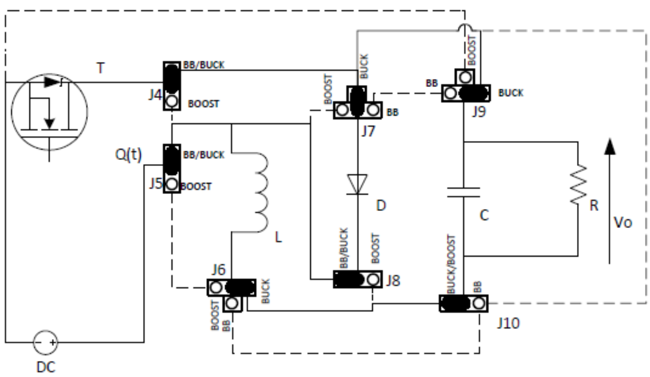

Fig. 3. Schematic diagram of the Buck converter implementation.

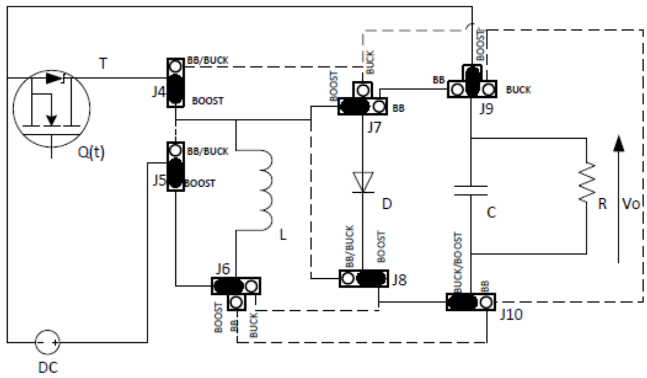

Fig.4. Schematic diagram of the Boost converter implementation.

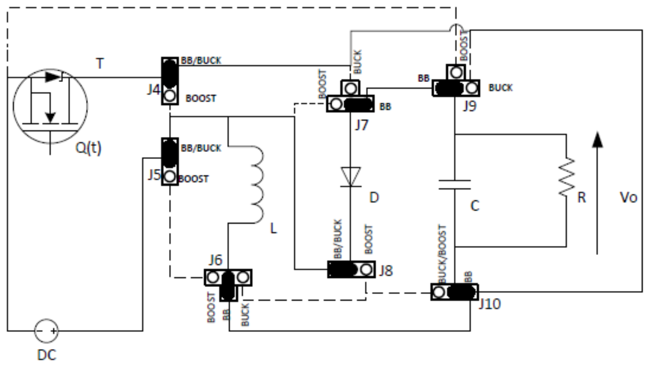

Fig.5. Schematic diagram of the Buck-Boost converter implementation.

IV. MATHEMATICAL MODEL

For each possible topology, the user must know the steady state relation between the converter output voltage V_o and the input voltage V_s. All of them depend on the duty cycle $D = T_{ON}/T$, in which T_{ON} is the turned on time of the electronic power switch and $T = 1/f_s$ is the operation period (the inverse of switching frequency). In the Buck converter, this relation is represented by (1) as follows:

$$V_0 = DV_s. \tag{1}$$

Note that, as $0 \le D \le 1$, the maximum value achieved by the output voltage is equal to input voltage, what characterizes the Buck as a step-down voltage converter.

The Boost is a step-up voltage converter, what can be seen in (2) as follows:

$$V_0 = \frac{1}{1-D} V_s. \tag{2}$$

In the case of the Buck-Boost converter, when the duty cycle set is lower than 0.5, the converter works like a step-down voltage converter. Otherwise, it works like a step-up voltage converter, (3) illustrates this peculiarity:

$$V_0 = -\left(\frac{D}{1-D}\right)V_s. \quad (3)$$

It is important to note that the minus signal in equation 3 indicates that the output voltage, referenced to the negative pole of the power supply, is inverted [8].

The didactic kit can also be applied in practices involving control systems, but the equations presented before are not appropriate in those cases. Thus, based on the low signals model [1] and on the principle of the superposition, the equations shown ahead represent the influence of low variations of input voltage $\widetilde{v_{in}}(s)$ and of the duty cycle $\tilde{d}(s)$ upon the transitory behavior of the converters output voltage $\widetilde{v_o}(s)$. For the Buck converter, the dynamic model is presented in (4) as follows

$$\widetilde{v_o}(s) = \frac{(1+rCs)/LC}{\left(s^2+\left(\frac{1}{RC}+\frac{r}{L}\right)s+\frac{1}{LC}\right)}\left[V_{in}\tilde{d}(s)+D\widetilde{v_{in}}(s)\right]. \quad (4)$$

The dynamic behaviors presented by Boost and Buck-Boost converters are modeled in (5) and (6), respectively. One can realize that the structures are similar to the Buck converter, but an additional zero in the positive (right) semi-plane side in S-plane in $\widetilde{v_o}(s)/\tilde{d}(s)$ transfer function is added. This way, the converters are characterized as no minimal phase systems.

$$\widetilde{v_o}(s) = \frac{(1+rCs)/L_eC}{\left(s^2+\left(\frac{1}{RC}+\frac{r}{L_e}\right)s+\frac{1}{L_eC}\right)}x$$
$$\left[\frac{V_{in}}{(1-D)^2}\left(1-\frac{L_e}{R}s\right)\tilde{d}(s)+\frac{1}{(1-D)}\widetilde{v_{in}}(s)\right] \quad (5)$$

$$\widetilde{v_o}(s) = \frac{(1+rCs)/L_eC}{\left(s^2+\left(\frac{1}{RC}+\frac{r}{L_e}\right)s+\frac{1}{L_eC}\right)}x$$
$$\left[\frac{V_{in}}{(1-D)^2}\left(1-\frac{DL_e}{R}s\right)\tilde{d}(s)+\frac{D}{(1-D)}\widetilde{v_{in}}(s)\right] \quad (6)$$

These transfer functions were developed assuming that the converters work with continuous inductor current. Thus, the control systems designer must know the limit conditions between continuous and discontinuous operation of each converter. For the Buck converter, one can guarantee a continuous current condition if the relation presented in (7) is observed, which involves inductance, load resistance, duty cycle, and switching frequency [9].

$$L_{min} = \frac{(1-D)R}{2f} \quad (7)$$

The relations for Boost and Buck-Boost converters are presented in (8) and (9), respectively [5]. It can be verified that, depending on the imposed duty cycle and the switching frequency by the user, the three topologies can operate under continuous or discontinuous current conduction, what didactically is interesting.

$$L_{min} = \frac{D(1-D)^2R}{2f} \quad (8)$$

$$L_{min} = \frac{(1-D)^2R}{2f} \quad (9)$$

V. RESULTS AND DISCUSSION

Some results achieved through a data acquisition device are presented in this section.

Figure 6 presents the voltage signal applied to the gate terminal (V_G) of the power transistor and its drain-source voltage signal (V_DS). It is important to point out that in this figure, the voltage reference for V_G is 0 V and for V_DS is 15V. One can realize that the power transistor is operating properly.

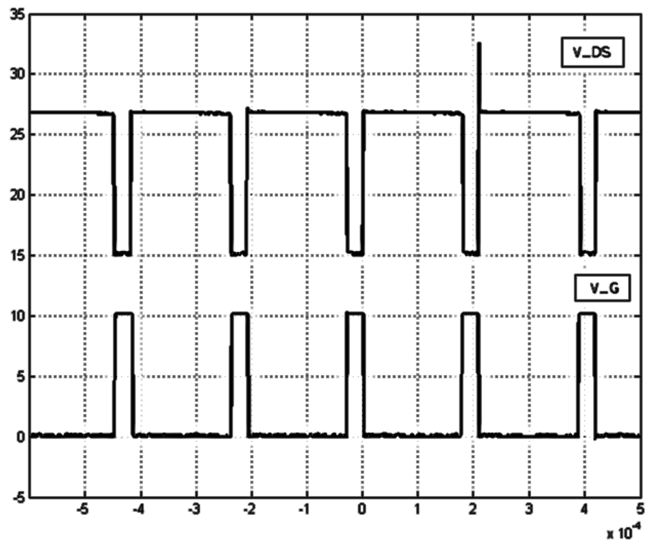

Fig. 6. Gate voltage signal (V_G) and Drain-Source voltage signal (V_DS) on power switch.

As it can be seen in Figure 7, the output voltage of the proposed kit is susceptible to variations of the input voltage. In this figure, it is illustrated the behavior of the Buck output voltage due to the variation of its input voltage. To overcome this limitation, the student can develop a closed loop system to control the output voltage despite some input voltage variation. This is highly recommended due to the interdisciplinary character of our proposal.

The authors have designed an analog controller as an application example. Figure 9 illustrates a simplified version of the proposed controller, which is implemented with four 741 operational amplifiers. They are used as an error amplifier, a single proportional controller, and a single integral controller. The closed loop system can be implemented with a proportional controller or, if we connect the two controllers together, with a PI controller. Thus, it is necessary another operational amplifier to sum the outputs of the single controllers. In this application, the proportional gain and the integral gain are, respectively, $K_P = 11.4$ and $K_I = 20$. In Figure 8, one can see the PI controller effect over the output voltage control system of the Buck converter. In spite of the considerable input voltage variation, from 9V to 16V, the output voltage is practically maintained constant.

The Figure 10 shows a picture of the proposed didactic kit.

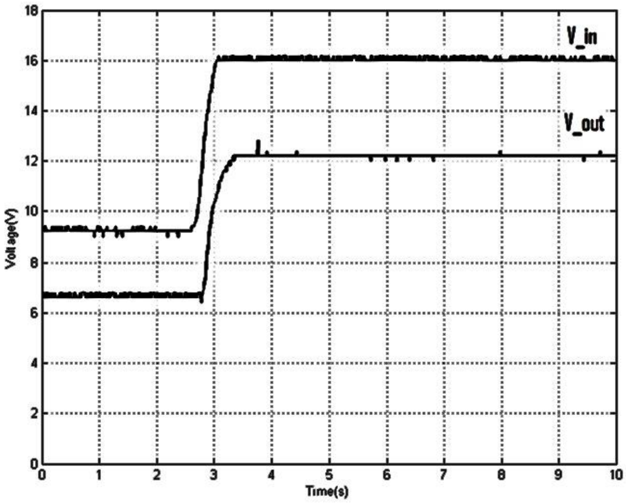

Fig. 7. Output voltage (V_out) behavior of the Buck converter due variations on input voltage (V_in).

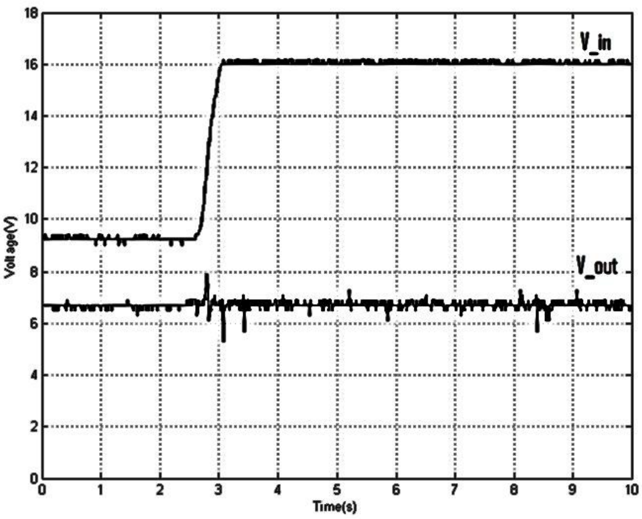

Fig. 8. Output voltage (V_out) behavior of the Buck converter under output voltage control and variations on input voltage (V_in).

VI. CONCLUSION

The authors have proposed a didactic kit, equipped with basic structure for laboratory experiments related with Buck, Boost, and Buck-Boost converters. The board layout was elaborated in line, as we can see in simple electronic schemes presented in the didactic literature, in such a way that the user can clearly distinguish the auxiliary circuits and the power circuit. The circuits were previously tested, what reduces the assembly time and avoids the difficulties derived from noise.

The authors recommend some practical procedures and encourage the users to develop closed loop control system for output voltage control, which assumes a multidisciplinary character. They suggest a simple controller schematic circuit.

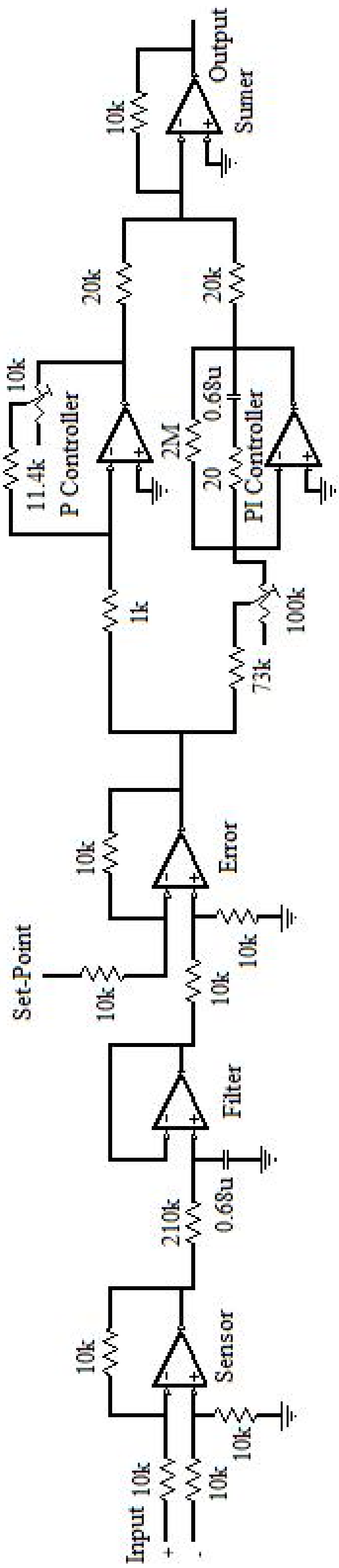

Fig. 9. Schematic circuit of the proposed analog controller.

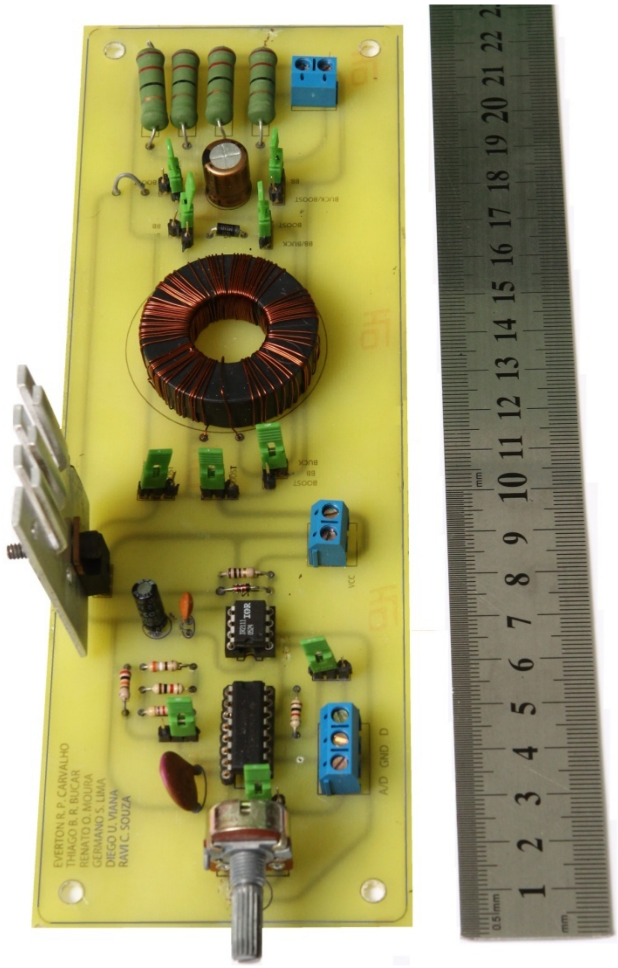

Fig. 10. Picture of the proposed didactic kit.

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