UNIVERSIDADE FEDERALDE VIÇOSA
CENTRO DE CIÊNCIAS EXATAS E TECNOLÓGICAS
DEPARTAMENTO DE ENGENHARIA ELÉTRICA

BRUNO MARIN SILVEIRA

DESIGN AND ASSEMBLING OF A BUCK CONVERTER

VIÇOSA
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Monografia apresentada ao Departamento de Engenharia Elétrica do Centro de Ciências Exatas e Tecnológicas da Universidade Federal de Viçosa, para a obtenção dos créditos da disciplina ELT 490 – Monografia e Seminário e cumprimento do requisito parcial para obtenção do grau de Bacharel em Engenharia Elétrica.
Orientador: Prof. M. Sc.. Heverton Augusto Pereira.

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‘‘Á minha família e amigos...’’

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“Só é lutador aquele que sabe lutar consigo mesmo.”

Carlos Drummond de Andrade

Abstract

The researches about solar energy have been developed in the last years due to increasing of demand of new techniques to decrease our dependence on fossil fuels. Because of this, the efficiency of the solar panel has been improved in order to reduce the costs and making the Photovoltaic Systems one of the main renewable energy sources.

In isolated systems, power converters are used to improve the efficiency of the panel, increasing its voltage with a boost converter or connecting in a bank of batteries with a buck converter.

This paper presents a buck converter controlled in voltage-mode by a microcontroller PIC, which uses a PID controller to change the wide pulse of PWM that switches an IGBT. This system is able to keep the output voltage in 12V.

Two softwares are used to simulate the converter: Matlab/Simulink and Proteus. The first studies the behavior of the proposed converter on a step-up and step-down voltage, using a PID controller in closed loop to switch an IGBT, which controls the output voltage; the second uses a microcontroller PIC to vary the PWM of the switching device. Moreover, the software PIC-C is used to make all the programming of the microcontroller.

After building of the converter, it is compared the measured results with the results of softwares Simulink and Proteus to validate the project.

Key words: Buck Converter, Static Converter Self-Controlled, Photovoltaic Systems, Battery.

Contents

List of Figures

List of Tables

1. *Introduction*

Power electronics is an enabling technology, providing the needed interface between the electrical source and the electrical load. The electrical source and the electrical load can, and often do, differ in frequency, voltage amplitudes and the number of phases. The power electronics interface facilitates the transfer of power from the source to the load by converting voltages and currents from one form to another, in which it is possible for the source and the load to reverse roles [1]. Nowadays it is increasing the use of DC-to-DC voltage conversion. It is applicable to computers, TVs, electric cars and photovoltaic systems.

1.1. *Buck Converter*

The buck converter, Figure 1, is one of the simplest power electronic circuits to convert a DC voltage level to another DC voltage level, less than the first one. Over the past decades, many researchers have studied new models and control techniques for the process of switching power supplies [2].

In the circuit the input voltage is represented by an idealized DC source, *Vg*. The switch is usually an insulated-gate bipolar transistor (IGBT) and it works as a digital circuit, 0 - 1, which opens when the control signal is 0 and closes when the control signal is 1.

In the mode on of the switch, Figure 2a, the current flows directly through the load, because the diode is on reverse mode, i.e., the circuit is open. In mode off, Figure 2b, the switch is open but the current keeps flowing through the load and diode by the inductor [3].

The purpose of the converter is to quickly open and close the switch, making the current flow through the inductor to the load, represented by a resistor. If this state of on and off is in a high frequency, the current to the load cannot build up or decay, making it fairly constant, producing a dc voltage in the output of the converter [3].

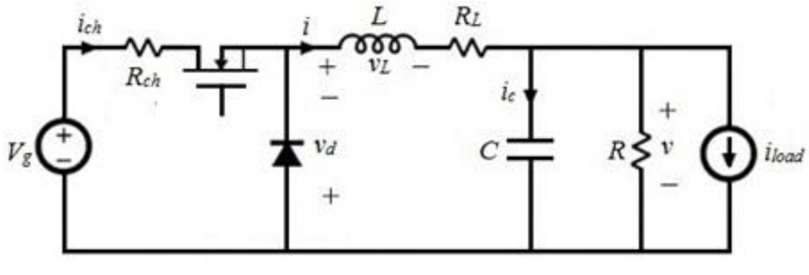
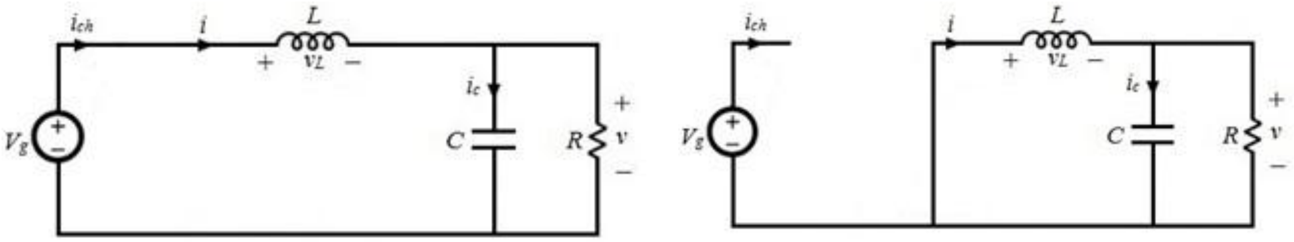


Figure 1 Circuit of buck converter



a) Switch in mode on

b) Switch in mode off

Figure 2 Operation modes of buck converter

If the current of the inductor does not drop to zero during the conduction mode of the diode, then the circuit is being operated in continuous conduction mode. Otherwise, the circuit is in discontinuous conduction mode.

Steady-State Analysis – Continuous Mode

In steady-state, it is presumed that the input voltage, output voltage, output current and the duty cycle are kept constant. Due to this, the current of the inductor flows during the entire switching time.

In continuous mode, there are two stages on the buck converter per cycle: the first one is when the switch is on, Figure 2a, and the diode is on the reverse mode; in the second, the switch is off and the diode is conducting, Figure 2b [4]. The operation of the devices is shown in Figure 3.

During the mode on, Ton, the current of the inductor increases linearly with the time, due to the input voltage Vg and the voltage of the capacitor. During mode off, Toff, the input current drops to zero, and because of this the current of the inductor decreases, causing a change of polarity in its voltage, which makes the current flow through the diode.

During Ton, it known that the voltage of the inductor is represented as showed (1) and (2).

$$V_L = Vg - V \tag{1}$$

$$V_L = L\,\frac{dI_L}{dt} = L\frac{\Delta I_L}{\Delta T} \tag{2}$$

During this time, there is a ripple current in the inductor, called as ΔI_L (3).

$$\Delta I_L\,(+) = \frac{Vg - V}{L}Ton \tag{3}$$

In the same way, in the time off, the ripple of current is calculated by (4).

$$\Delta I_L\,(-) = \frac{V - Vd}{L} Toff \tag{4}$$

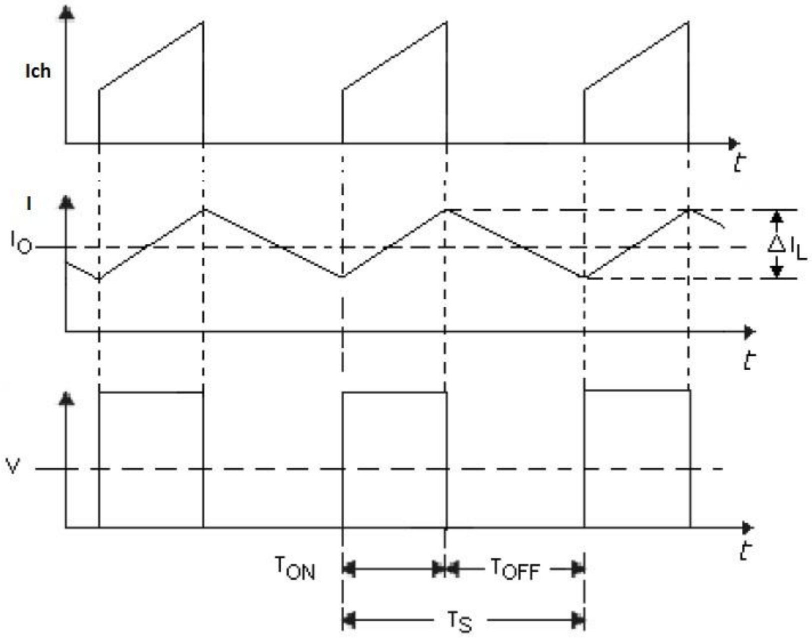


Figure 3 Voltage and current of buck converter operating in continuous conduction mode

In steady-state, $\Delta I_L\,(+)$ and $\Delta I_L\,(-)$ have the same value, and from (1), it results in:

$$D = \frac{Ton}{Ts} \tag{5}$$

The time Ts is the complete cycle of switching of the switch device.

Equation (6) shows the *duty cycle*, which is the main relation in the buck converter, and represents the fraction of time that the switch is closed [4].

$$\frac{V}{V_g} = D \tag{6}$$

Steady-State Analysis – Discontinuous Mode

The discontinuous mode occurs when the current of the load is less than or equal to zero, Figure 4. The average current is shown in (7) as follows:

$$\mathrm{I_{LB}} = \frac{1}{2}\mathrm{i_{L(peak)}} = \frac{\mathrm{DT_s}}{2\mathrm{L}}(\mathrm{V_i} - \mathrm{V_0}) \tag{7}$$

In discontinuous mode operation the duty cycle is a nonlinear function of the output current, in the load, and it cannot secure the maximum power output [5]. Because of this, buck converters operating in this mode have lower power efficiency compared to the continuous mode conduction [6].

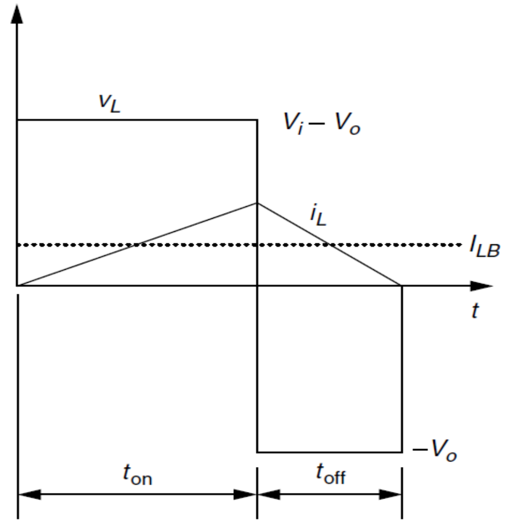


Figure 4 and current of buck converter operating in discontinuous conduction mode

1.2. *Equations of the Buck Converter*

In a model of the buck converter, it is necessary to calculate its inductance and capacitance. Combining Equations (3) and (4) results in:

$$T_s = \frac{\Delta I_L}{V_g - V} + \frac{\Delta I_L}{V} \tag{8}$$

Knowing that:

$$T_s = \frac{1}{f} = T_{on} + T_{off} \tag{9}$$

Substituting (9) on (8) results in an Equation (10) for the inductance of the buck converter:

$$L = \frac{V_g D(1-D)}{f\, \Delta I} \tag{10}$$

Depending on the value of the ripple current, ΔI, increasing the value of the frequency decreases the inductance. According to [4], the voltage on the capacitor can be written by:

$$V_c = \frac{1}{C}\int I_C\ dt\ + V \tag{11}$$

The current variation of the load is almost the same as the variation of the inductor, and then the average current on the capacitor is:

$$I_c = \frac{1}{T}\int_0^{T/2} \frac{\Delta I}{2}\, dt \tag{12}$$

Substituting (12) in (11) results in:

$$C = \frac{V_g D(1-D)}{8Lf^2\, \Delta V_c} \tag{13}$$

The Equation (13) is the Equation of the capacitance of the buck converter. As the same as in (10), increasing the frequency *f* decreases the value of the capacitance.

1.3. *Modeling of Buck Converter*

This section shows a mathematical model of the buck converter, Figure 1. In this circuit, R_L is the resistance of the inductor, and R_{ch} is the resistance of the IGBT. The energy losses on the windings of the inductor and on the switches will be considered [7]. In the sections, 1.3.1 and 1.3.2, the model of both stages of the switch will be developed.

1.3.1. *Switch in Conduction Mode*

The circuit in Figure 5 represents the case when the IGBT is closed, mode on, and the diode is on its reverse mode. Using both Kirchhoff's law, voltage and current law, on this circuit, obtains:

$$V_g - V_L - (R_L + R_{on}) \cdot i - v = 0 \tag{14}$$

$$i_C + \frac{v}{R} + i_{load} - i = 0 \tag{15}$$

Substituting (10) and (11) on the Equations (14) and (15) results in:

$$\frac{di}{dt} = \frac{V_g}{L} - \frac{(R_L + R_{on})}{L} \cdot i - \frac{v}{L} \tag{16}$$

$$\frac{dv}{dt} = \frac{i}{C} - \frac{v}{RC} - \frac{i_{load}}{C} \tag{17}$$

The system equations resulting from (16) and (17), are commonly written in matrix form as shown in (18) because it makes it easy to make the complete modeling of the system.

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{(R_L + R_{on})}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \cdot \begin{bmatrix} V_g \\ V_D \\ i_{load} \end{bmatrix} \tag{18}$$

The matrixes A1 and B1, taken from (18) are defined as follows:

$$A_1 = \begin{bmatrix} -\frac{(R_L + R_{on})}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \tag{19}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \tag{20}$$

These matrices will be used directly in the linearization of the model in section 1.3.3.

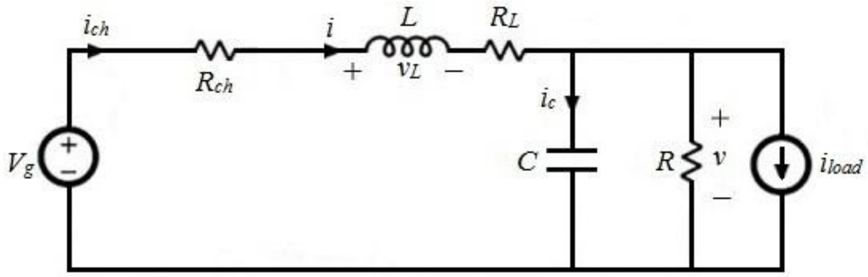


Figure 5 Buck converter for the IGBT in mode on

1.3.2. *Switch in Mode off*

Figure 6 shows the circuit in Figure 1 when the IGBT is not conducting, making the current of the inductor flow through the diode, as discussed in 0.

As in section 1.3.1, Kirchhoff's law, voltage and current law will be used in the circuit of Figure 6, resulting in the following Equations:

$$\frac{di}{dt} = -\frac{v}{L} - \frac{R_L}{L} \cdot i - \frac{V_D}{L} \tag{21}$$

$$\frac{dv}{dt} = \frac{i}{C} - \frac{v}{RC} - \frac{i_{load}}{C} \tag{22}$$

The matrix form of (21) and (22) is given as follows:

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \cdot \begin{bmatrix} V_g \\ V_D \\ i_{load} \end{bmatrix} \tag{23}$$

As in 1.3.1 it was took two matrices from (23), A1 and B1 as shown below:

$$A_0 = \begin{bmatrix} -\frac{R_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \tag{24}$$

$$B_0 = \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \tag{25}$$

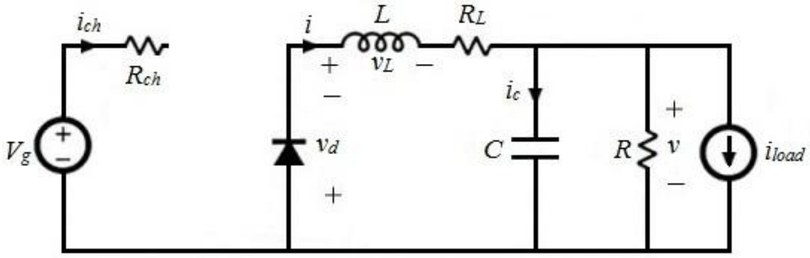


Figure 6 Buck converter for the IGBT in mode off

1.3.3. *Linearization of the model*

As shown in sections 1.3.1 and 1.3.2 for each stage of the switch, opened and closed, there are two different matrices represented by A and B. Using these matrices, the stage equations can be written as follows:

$$\dot{X} = A \cdot X + B \cdot U \tag{26}$$

A value δ, which represents the stage of the switch, will be defined as follows:

$$\delta = \begin{cases} 1 & switch\ on\ mode\ on \\ 0 & switch\ on\ mode\ on \end{cases} \tag{27}$$

The switched model and its average, is written bellow:

$$\dot{X} = \left(A_0 + \ \delta \cdot (A_1 - A_0)\right) \cdot X + (B_0 + \ \delta \cdot (B_1 - B_0)) \cdot U \tag{28}$$

$$< \dot{X} >= \left(A_0 + \ d \cdot (A_1 - A_0)\right) \cdot < X > +(B_0 + \ d \cdot (B_1 - B_0)) \cdot < U > \tag{29}$$

The average value of δis the duty cycle *d*.

A perturbing has been made in steady stage to make the linearization of the model, which: $\hat{d} \ll D, \hat{x} \ll x$ e $\hat{u} \ll u$.

$$\begin{cases} d = D + \hat{d} \\ < X > = x + \hat{x} \\ < U > = u + \hat{u} \end{cases} \tag{30}$$

Substituting (30) in (29), obtains:

$$< \dot{X} >= \begin{aligned} &[A_0 + D \cdot (A_1 - A_0)] \cdot \hat{x} + [B_0 + D \cdot (B_1 - B_0)] \cdot \hat{u} \ + \\ &+ [(A_1 - A_0) \cdot x + (B_1 - B_0) \cdot u] \cdot \hat{d} + \\ &+ [A_0 + D \cdot (A_1 - A_0)]x + \ [B_0 + D \cdot (B_1 - B_0)]u + \\ &+ \ (A_1 - A_0) \cdot \hat{d} \ \cdot \hat{x} + (B_1 - B_0) \cdot \hat{d} \cdot \hat{u} \end{aligned} \tag{31}$$

$$Ax + Bu = (1 - D) \cdot (A_0 \cdot x + \ B_0 \cdot u) + \ (D) \cdot (A_1 \cdot x + \ B_1 \cdot u) = 0 \tag{32}$$

Substituting $A = A_0 + D \cdot (A_1 - A_0)$, $B = \ B_0 + D \cdot (B_1 - B_0)$ in (32) then substituting in (31) obtains:

$$< \dot{X} >= \big(A_0 + \ d \cdot (A_1 - A_0)\big) \cdot < X > + (B_0 + \ d \cdot (B_1 - B_0)) \cdot < U > \tag{33}$$

Knowing that $< \dot{X} >$ is the same as $\dot{\hat{x}}$, in steady state, and defining:

$$M = \ (A_1 - A_0) \cdot x + (B_1 - B_0) \cdot u \tag{34}$$

results in:

$$\dot{\hat{x}} \ = A \cdot \hat{x} + [B \quad M] \cdot \begin{bmatrix} \hat{u} \\ \hat{d} \end{bmatrix} \Rightarrow \frac{d}{dt}(\hat{x}) = \ A \cdot \hat{x} + B_t \cdot \hat{u}_t \tag{35}$$

Knowing that $\mathrm{B_t} = [\mathrm{B} \quad \mathrm{M}]$ and $\hat{\mathrm{u}}_\mathrm{t} = \begin{bmatrix} \hat{\mathrm{u}} \\ \hat{\mathrm{d}} \end{bmatrix}$. Applying the Laplace's transform on (35) and writing it on matrix form results on the modeling of buck converter, is shown as follows:

$$\begin{bmatrix} \hat{\imath} \\ \hat{v} \end{bmatrix} = \begin{bmatrix} F_{11}(s) & F_{12}(s) & F_{13}(s) & F_{14}(s) \\ F_{21}(s) & F_{22}(s) & F_{23}(s) & F_{24}(s) \end{bmatrix} \cdot \begin{bmatrix} \widehat{V_g} \\ 0 \\ \hat{\imath}_{load} \\ \hat{d} \end{bmatrix} \tag{36}$$

The term $F_{21}(s)$ is the transfer function of the variation of the output voltage in relation to the duty cycle, and it will be redefined as G_{vd}. $F_{23}(s)$ is the transfer function between the variation of the output voltage in relation with the variation of the input voltage, and it will be redefined as G_{vg}. In the end, $F_{24}(s)$ is the transfer function between the variation on the output in relation with a variation on the load, and it will be redefined as Z_{out}.

Knowing that $G_{vd} = \frac{\hat{v}(s)}{\hat{d}(s)}\Big|_{\substack{\hat{v}_g = 0 \\ \hat{\imath}_{load} = 0}}$, $G_{vg} = \frac{\hat{v}(s)}{\hat{v}_g(s)}\Big|_{\substack{\hat{d} = 0 \\ \hat{\imath}_{load} = 0}}$ e $Z_{out}(s) = -\frac{\hat{v}(s)}{\hat{\imath}_{load}(s)}\Big|_{\substack{\hat{v}_g = 0 \\ \hat{d} = 0}}$, then replacing on (36), it results in (37) as follows:

$$\hat{v}(s) = G_{vd} \cdot \hat{d}(s) + G_{vg} \cdot \hat{v}_g(s) - Z_{out}(s) \cdot \hat{\imath}_{load}(s) \tag{37}$$

The Equation (37) is the variation of the output voltage on the buck converter.

1.3.4. *Control Loop*

The variation of the output voltage $\hat{v}(s)$ depends of the variation of duty cycle, input voltage and load, as showed on (37).

The control loop of the converter is shown in Figure 7. The sensor gain is represented by $H(s)$. $G_c(s)$ is the transfer function of the controller and V_M is the size of the PWM.

The output voltage $\hat{v}(s)$ calculated by the Figure 7 is shown as follows:

$$\hat{v}(s) = \left[\hat{v}_{ref}(s) - H(s) \cdot \hat{v}(s)\right] \cdot \frac{G_C(s)}{V_m} \cdot G_{vd}(s) + \hat{v}_g(s) \cdot G_{vg} - \hat{\imath}_{load} \cdot Z_{out} \tag{38}$$

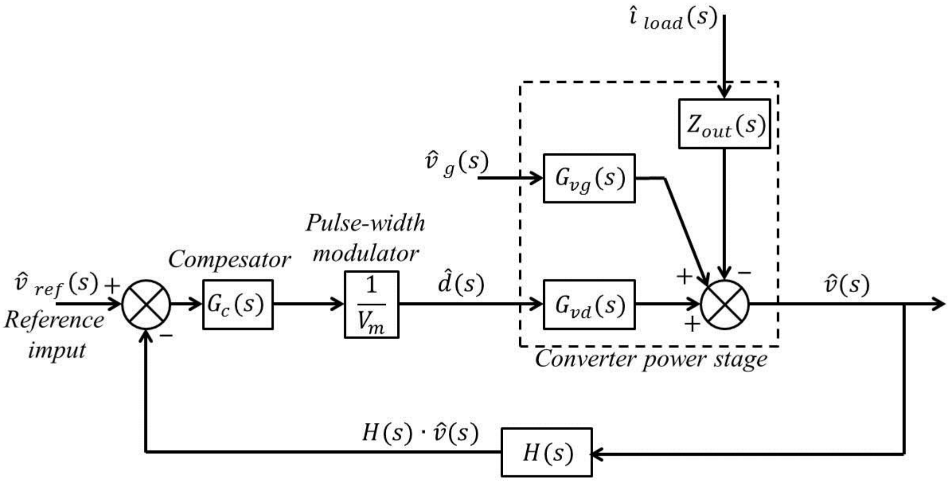


Figure 7 Block diagram of small-signals model of buck converter

1.3.5. *Ziegler-Nichols Method*

The PID controller is the most common control method, which have survived many changes in technology. Practically all PID controllers made today are based on microprocessors [8].

This form of feedback is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing [8].

There are some methods, called tuning methods, for control design that can be applied to PID control. It is essential always to consider the key elements of control, load disturbances, sensor noise, process uncertainty and reference signals [9].

The most known tuning method is the Ziegler-Nichols Method. This method is applicable in analog controller, as the PID controller shown in Figure 8, and it is based on process information in the form of the open loop step response, which is characterized by only two parameters R and L, as shown in Figure 9. The parameter L is a delay, and R is the maximum incline which depends of time T and the value reached in steady-state Yss, and it is given by Equation (39).

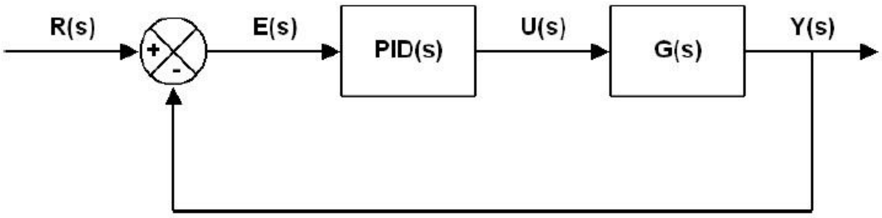


Figure 8 PID control loop

Using the Equation (39) and the parameter L, it is possible to calculate the controller parameters: Kp, Ki and Kd from Table 1.

$$\mathrm{R} = \frac{Yss}{T} \tag{39}$$

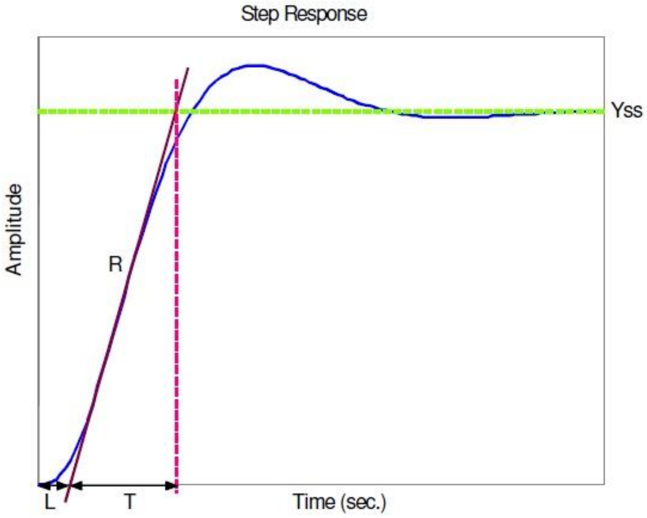


Figure 9 Characterization of a step response in the Ziegler-Nichols step response method.

Table 1 PID controller parameters obtained for the Ziegler-Nichols step response method.

Controller	Kp	Ki	Kd
P	$^{1}/_{RL}$		
PI	$^{0,9}/_{RL}$	$^{0,3}/_{RL}$	
PID	$^{1,2}/_{RL}$	$^{0,5}/_{RL}$	$0,5 \times L$

Objective

This manuscript aims the design of a buck converter self-controlled in voltage mode using a microcontroller. The purpose of the project is use two Softwares to design the model of the converter: the Software Simulink gives the parameter of the PI control, which is calculated using a technique of Ziegler-Nichols and it is used by the controller to modulate the wave that switches the device of control; and Software Proteus simulates the converter as in the practice using the components calculated by the equations of the chopper.

After the simulations, the project it will be assembly and the results will be compared with the Softwares to validate the project.

Moreover, it will be assembly an inductor with a small value of resistance that reduces the loses of energy into the device which guarantees a better efficiency of the converter

2. Methodology

2.1. Simulation of the buck converter in Simulink

Two different softwares are used in this project: Matlab/Simulink and Proteus. In the first, the calculus of the parameter is made according the Equations (10) and (13), section Equations of the Buck Converter shows the calculated values, considering the resistance of the inductor. The circuit is shown in Figure 10, which a voltage source is used in this simulation.

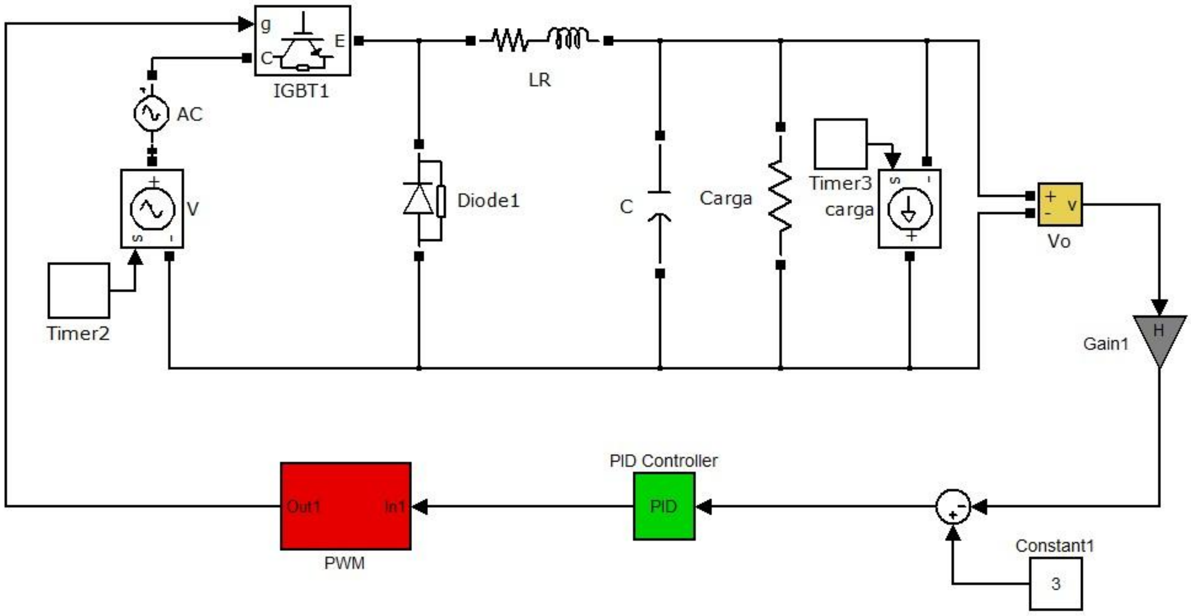


Figure 10 Simulation in Software Simulink

The switching control methods pulse-width modulation (PWM) based on fast switching and duty ratio control is used. Figure 11 shows the strategy of control using a PI control switching the DC-DC converter to accomplish a zero steady-state error between the output voltage and the desired *setpoint* in the presence of input voltage variations and load changes.

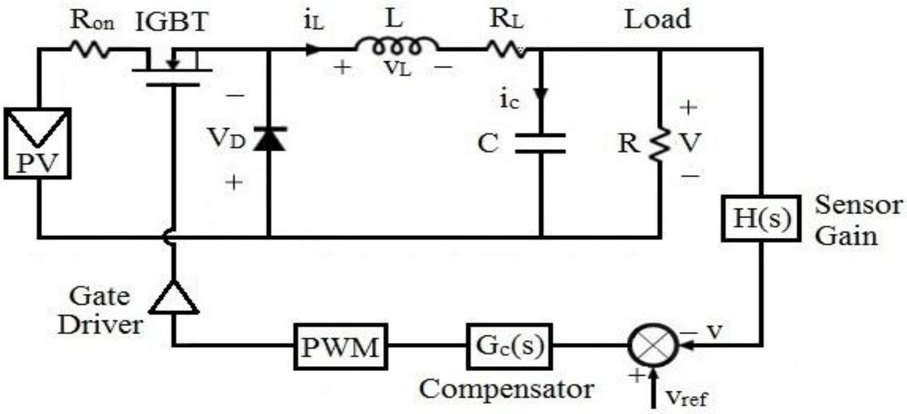


Figure 11 PID control of the buck converter

2.2. The PI controller

The parameters of the PI control are calculated by Ziegler-Nichols Method according to 1.3.5. It is necessary to obtain the transfer function *Gvd*, 1.3.3, and through this function is possible to obtain the parameters showed in Table 1.

Using the software Matlab, the transfer function *Gvd* is calculated as follows:

$$Gvd(s) = \frac{-1.819 \times 10^{-12}\, s \; + \; 1.215 \times 10^{9}}{s^{2} \; + \; 1.226 \times 10^{4}\, s \; + \; 5.185 \times 10^{7}}$$

According to this transfer function and using the toolbox *rltool* of software Matlab, it is calculated the step response of the system, as shown in Figure 12.

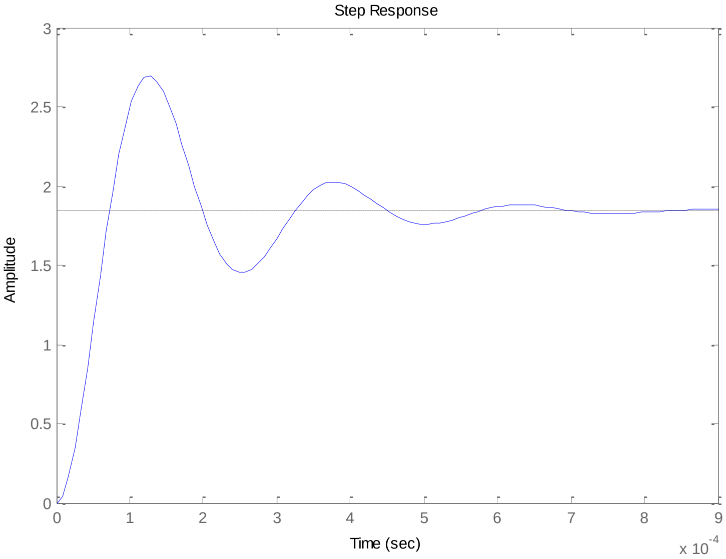


Figure 12 Step response of the transfer function *Gvd*.

According to 1.3.5, the parameters T, Yss and L are taken from the Figure 12. Knowing these values, the parameter R can be calculated by (39), as follows:

$$T = 3{,}5338 \times 10^{-2}, \qquad L = 0{,}4462 \times 10^{-4}, \qquad Yss = 10 \times 10^{3}$$

Then

$$R = \frac{Yss}{T} = \frac{10 \times 10^{3}}{3{,}5338 \times 10^{-2}} = 2{,}83 \times 10^{5}$$

According to Table 1, the parameters of PI control can be calculated and they are shown in Table 2.

Table 2 Calculated values of the parameters of PI control

Controller	**Kp**	**Ki**	**Kd**
P	0,07919		
PI	0,071273	0,04792	
PID	0,095030	0,07987	0,02231

2.3. Devices used in the project

The specification of the project is shown in Table 3. The input voltage is considered 25V and the converter keeps the output voltage in 12V, working in continuous conduction mode, as shown in 0. The parameters of the buck converter have been calculated according to the equations showed in 1.2, and they are shown in Table 4.

Table 3 Specifications of the project

Input voltage	25V
Output voltage	12V
Switching frequency	20KHz
Load resistance	6Ω
Current ripple on the inductor - ΔI	10%
Voltage ripple on the output voltage - ΔVo	5%

The duty cycle is calculated by the relation between the input and output voltage according to (6), as follows:

$$D = \frac{12V}{25V} = 0{,}48$$

Knowing the value of load and the output voltage kept by the converter, it knows that the output average current is:

$$Io = \frac{12V}{6\Omega} = 2{,}0\ A$$

Considering that the input power of the buck converter is the same as the output power, i.e., efficiency of 100%, the current ripple on the inductor and the voltage ripple on the output voltage, according to the specifications of Table 3, are given as follows:

$\Delta I = 0{,}1 \times 2{,}0 = 0{,}20A$ and $\Delta Vo = 0{,}01 \times 12{,}0 = 0{,}12A$.

Knowing all the parameters, it is possible to calculate the value of inductance using (10) and the capacitance of the buck converter using (13). These values are shown in Table 4.

Table 4 Components used in the project

Inductor	1,48mH
Capacitor	20,00µF
Semiconductor IGBT	IRG4BC30UD
Photoacoplator	4n25
Diode	In4007
Microcontroller	PIC18F4550

The inductor is built in this project according the value obtained in (10). Software FEEM is used to calculate the parameters of the inductor. It knows that:

$$L = \frac{\Phi}{I} \tag{40}$$

Φ is the linkage flux of the coil, which is shown in Figure 13 for each wire size. In this project, the wire size used is the AWG17

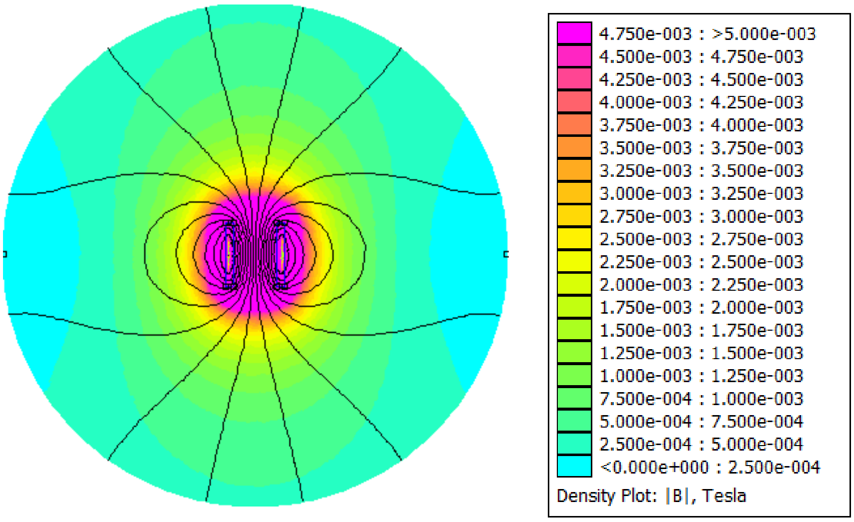


Figure 13 Distribution of magnetic density flux

The curve of Figure 14 shows the relation between the density of magnetic flux, which is proportional to the flux, and the magnetic field, which is proportional to the current. Using the value calculated by (10), the software FEEM gives the number of turns of the inductor that is used to build it.

The value obtained after the built of the inductor is $1,502mH$, close to the calculated value.

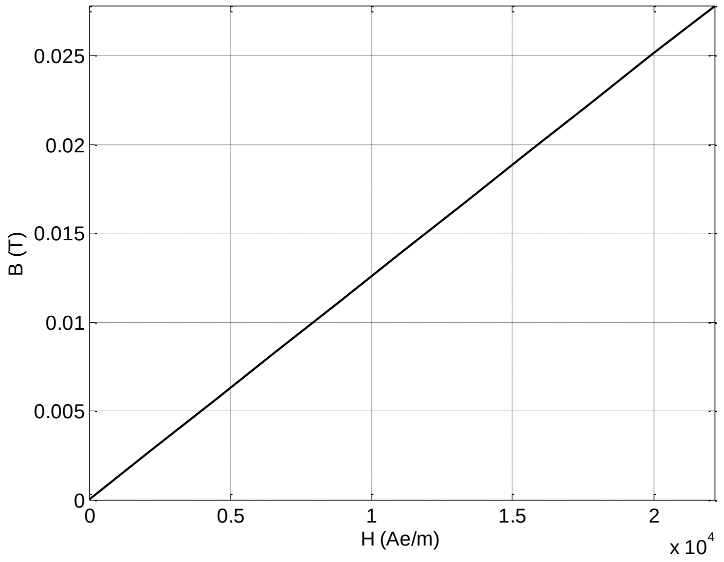


Figure 14 Relation between the density of magnetic flux and magnetic field

Software FEEM also gives the voltage drop in the coil, and knowing that, the resistance can be obtained as follows:

$$R = \frac{V(drop)}{I} \tag{41}$$

Figure 15 shows the curve of the resistance calculated by software FEEM and plotted in software Matlab.

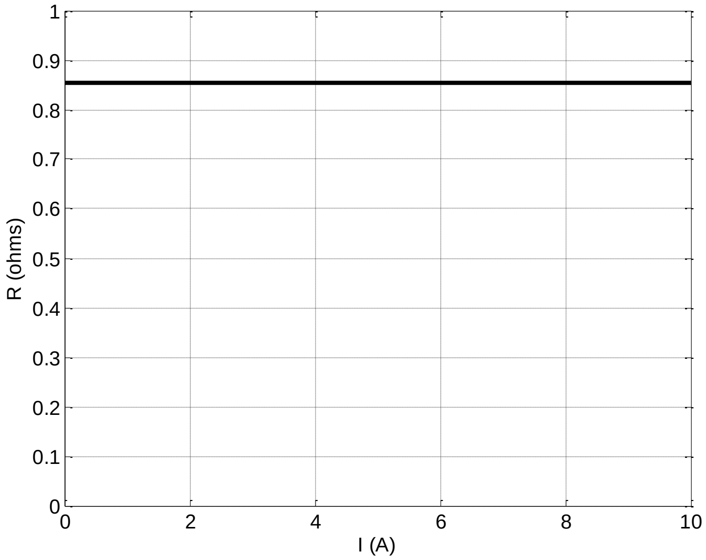


Figure 15 Curve of the resistance of inductor

The specifications of the device are shown in Table 5.

Table 5 Specifications of the inductor

Indutance	1,502mH
Resistance	0,9Ω
Area of the coil	16 cm²
Coil length	6 cm
Number of turns	230
Wire size	AWG 17

2.4. Simulation in software Proteus

The switching control of the IGBT is made by the microcontroller PIC specified in Table 4. The microcontroller can read the value of output voltage and compares it with the reference voltage, which generate a control signal to vary the pulse-width of the PWM. The strategy is the same as showed in Figure 11 used in Simulink.

The PIC C Compiler makes the programming and the simulation in software Proteus is shown in Figure 16. In this project, the IGBT is activated by a *photoacoplator* that guarantees the minimum voltage between the source and gate of IGBT.

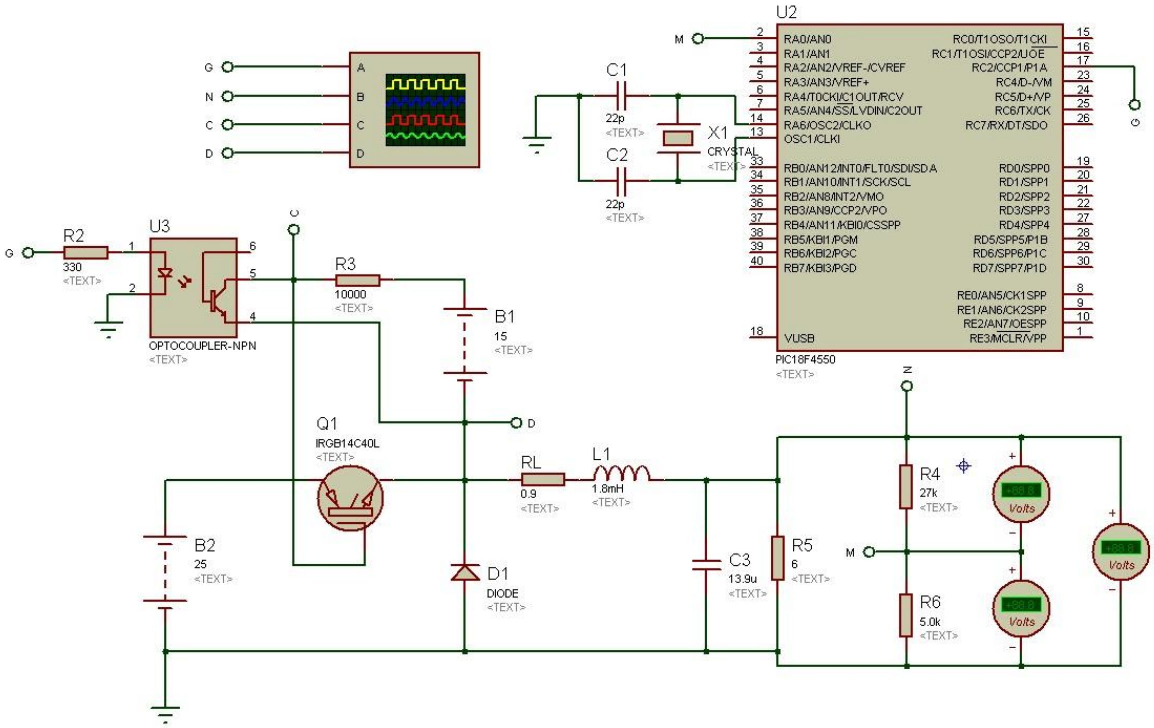


Figure 16 Simulation in software Proteus

3. Results

3.1. Simulated Results

a. Simulation in software Matlab/Simulink

According to the specifications of Table 3, the buck converter of Figure 10 was simulated in software Simulink.

The input voltage was varied in three different values: 18V, 23V and 32V. The goal is keeping the output voltage in 12V connected to a load, even with these variations in the input voltage.

Figure 17 shows the results of this simulation for an input voltage of 12V. The output voltage was kept in 12V during all the time.

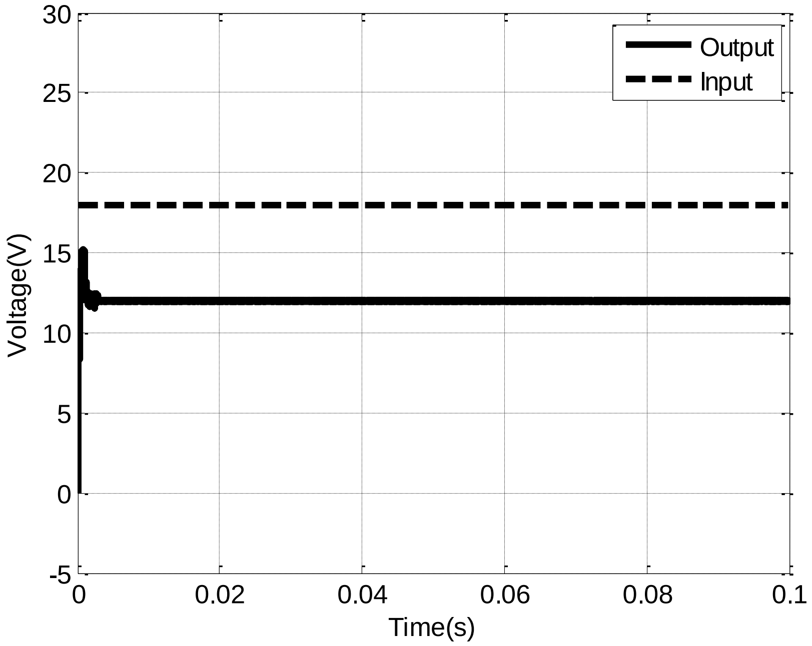


Figure 17 Result in software Simulink for 18V of input voltage

The input voltage was increased for 23V and the control has acted keeping the output voltage in 12V as shown in Figure 18.

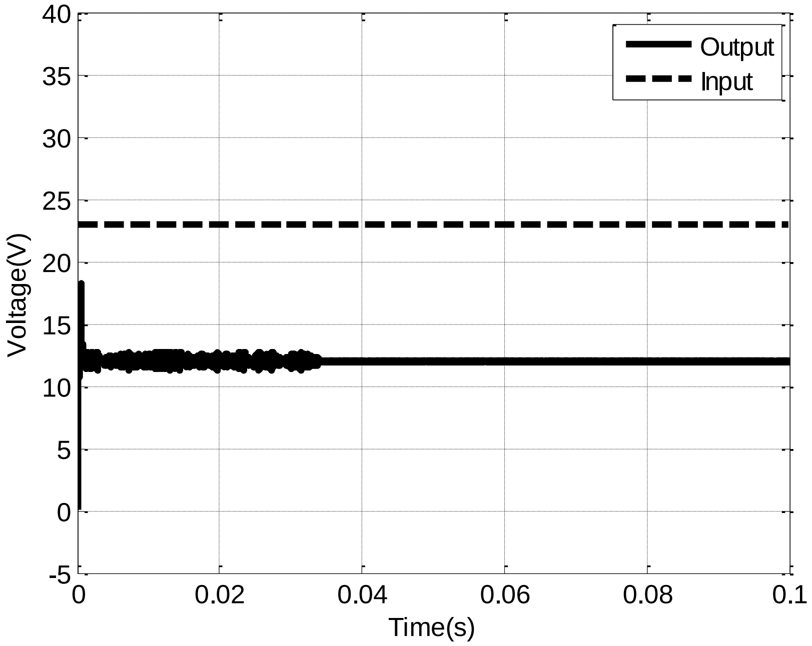


Figure 18 Result in software Simulink for 23V of input voltage

Figure 24 shows the results in Simulink for an input voltage of 32V. The control has kept precisely the output voltage in 12V, in accordance to the purpose of this paper.

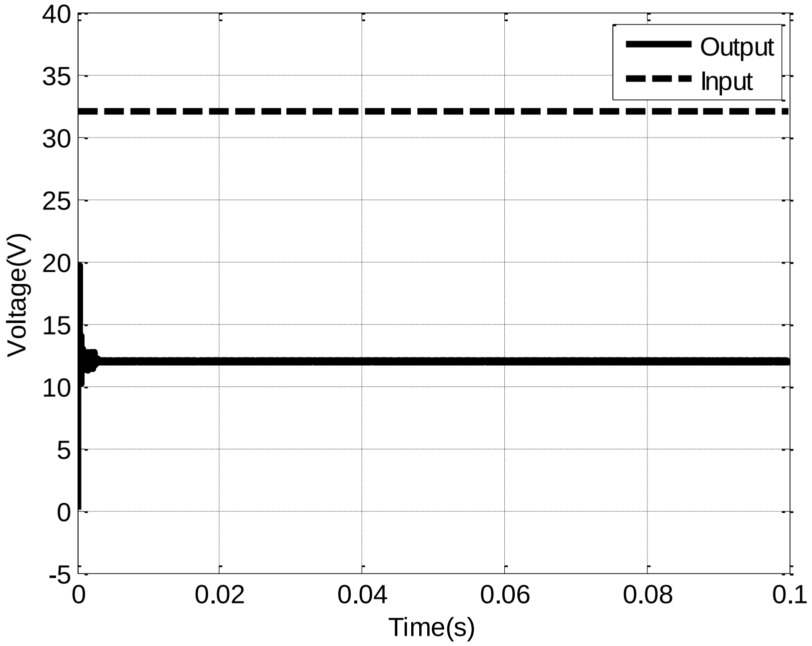


Figure 19 Result in software Simulink for 32V of input voltage

b. Simulation in software Proteus

The buck converter of Figure 1 was simulated in software Proteus. The results obtained with this software are the closest as the experimental tests results.

As so as in software Simulink, the Ziegler-Nichols´s method was used to calculate the parameters of PI control. In software Proteus the PWM control of IGBT was made by the microcontroller PIC.

In this simulation, the input voltage is not varying as in a. The voltage was kept in 25V according to the specifications of Table 3.

Figure 24 shows the result of this simulation from an oscilloscope. The control has acted quickly to keep the output voltage in 12V, in accordance to the purpose of this project.

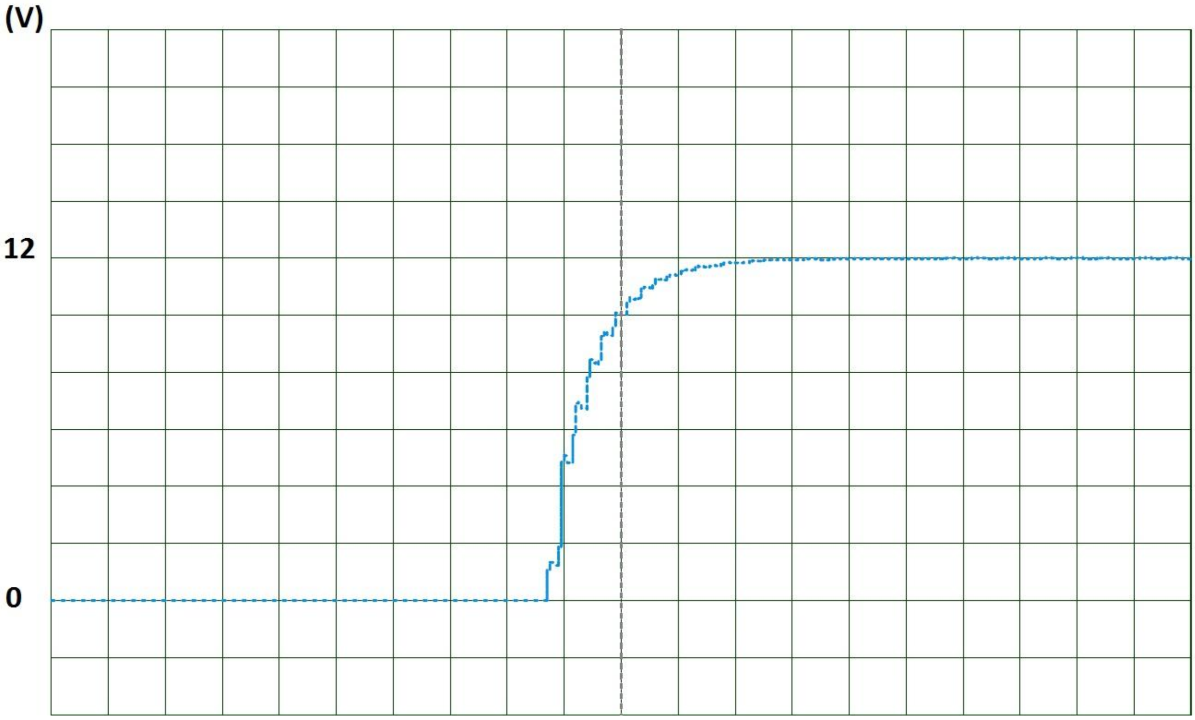


Figure 20 Results in software Proteus for 25V input

3.2. Experimental Results

After validating the project in softwares Simulink and Proteus it was built the project to compare with those simulations.

The experimental project is shown in Figure 21. Besides of buck converter, two voltages sources, one multimeter and one oscilloscope were used.

The first voltage source was used to supply the microcontroller and the input voltage, the second was used on the photoacoplator that supplies the gate of IGBT. The inductor was built according to the specifications of Table 5. All the results were taken by the oscilloscope and showed below.

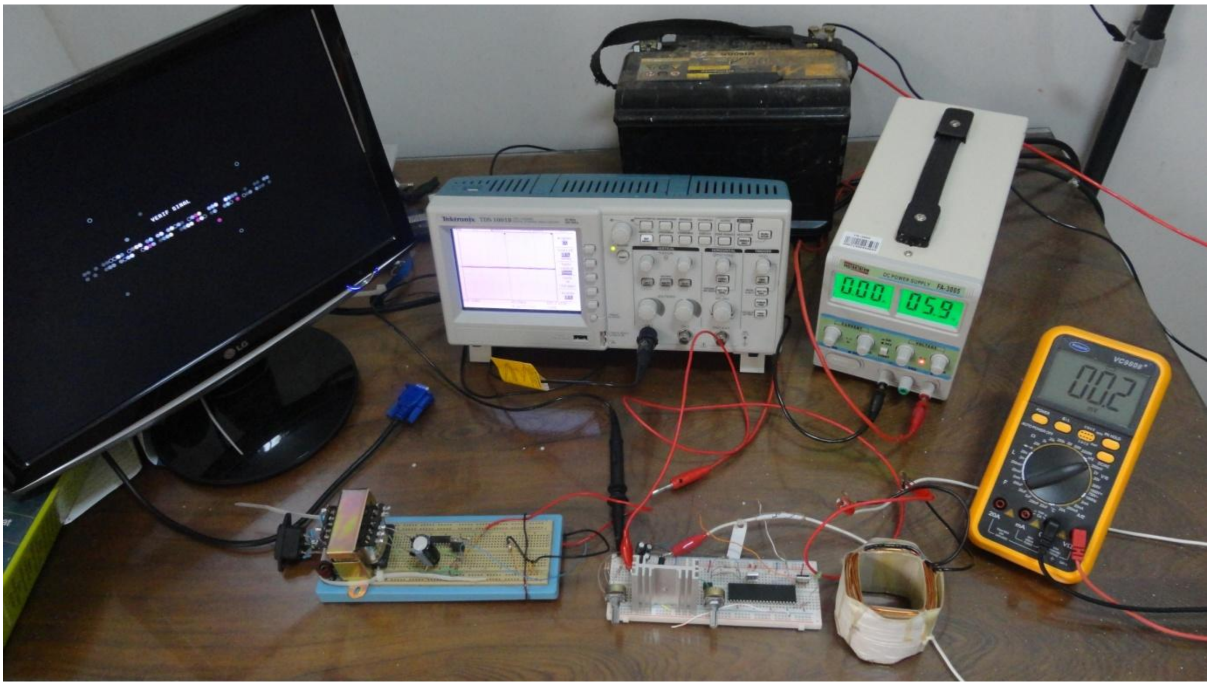
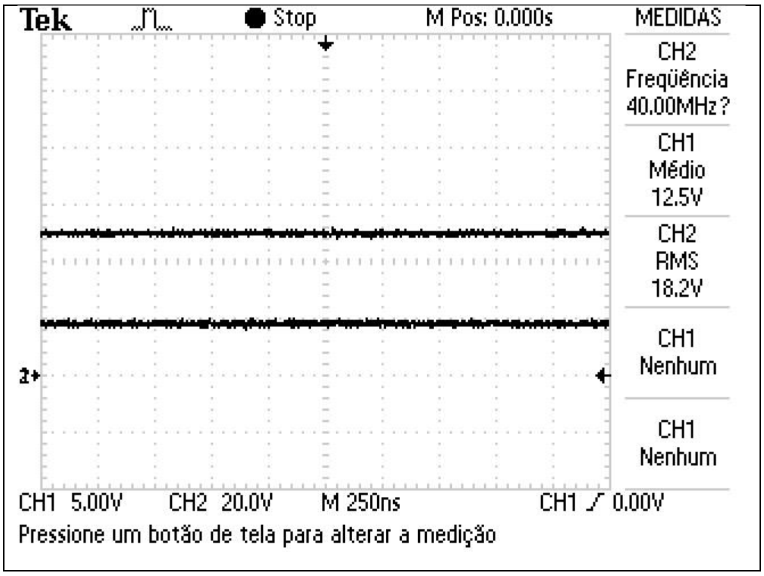


Figure 21 Experimental project

As so as in a the input voltage was varied and the behavior of the converter was analyzed. The voltage source used in these tests was the same as shown in Figure 16, and the values have varied during the time: 18, 23 and 32V.

The experimental results were taken in steady state mode and they are shown as follows.

Figure 22 shows the result for an 18V of input. The output voltage was kept in 12V, which is the goal of the converter.



Pressione um botão de tela para alterar a medição

Figure 22 Graphic from oscilloscope for 18V input voltage

Figure 23 shows the behavior of the converter when the input voltage was increased to 23V. The average value of the output voltage was kept in 12V.

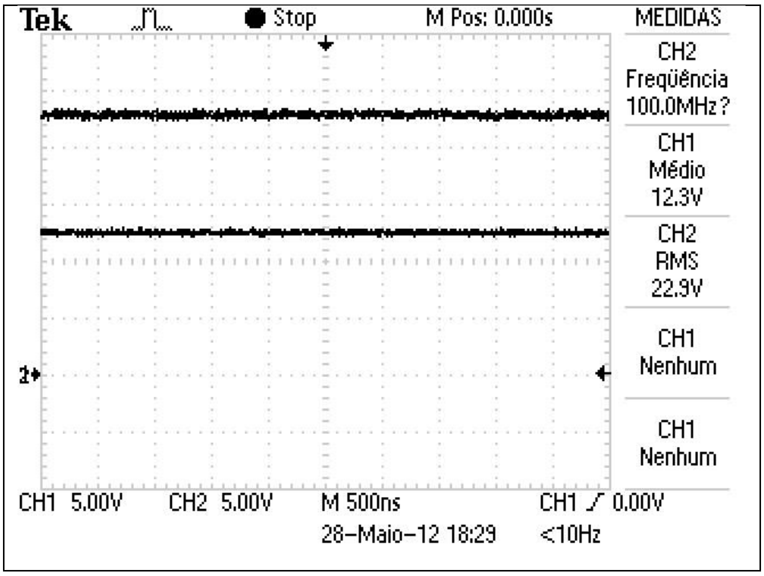


Figure 23 Graphic from oscilloscope for 23V input voltage

In the end, a high value of 32V of input voltage was kept and the control has acted, keeping an average value of the output voltage of 12V.

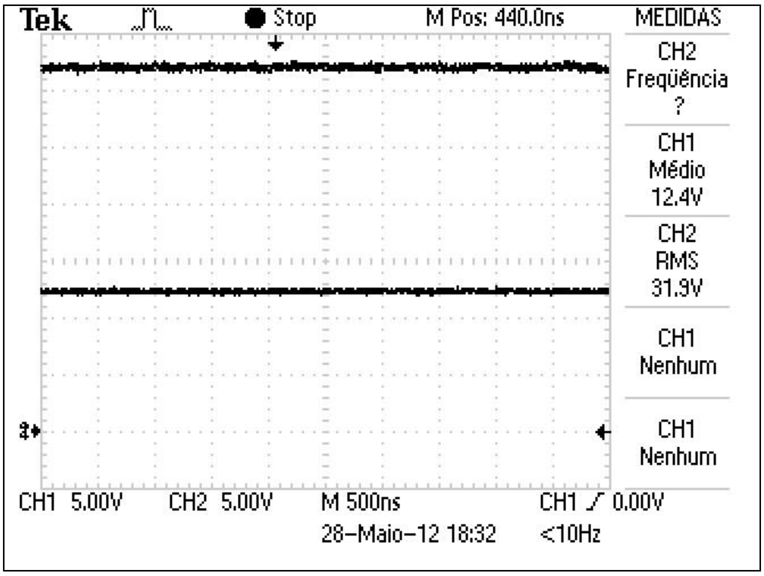


Figure 24 Graphic from oscilloscope for 32V input voltage

The same results of Figure 17 were obtained in these tests. The control has kept the output voltage in 12V, even with the large variations in the input voltage in accordance to the purpose of this paper.

4. Conclusion

This manuscript has presented a strategy control based on PI control, which is responsible for the transfer of energy from the input to the output voltage of the buck converter. This control acts when there is a variation in the input voltage, keeping the output voltage in a fixed value of 12V.

The goal of this paper was to simulate and built a voltage mode controlled buck converter able to keep its output voltage in 12V. It was observed that the control has acted in form to keep the output voltage in the specified value, according to the purpose of this paper. The simulated results were too close of the practical results validating the project.

Futures works can be applied in a solar system, charging a bank of batteries. In photovoltaic systems, every variation in the radiation causes a change in the value of the output voltage, which makes useful a controller converter attached to this system.

5. Bibliography

1. MOHAN, N. **First Course on Power Electronics and Drives**. Minneapolis: [s.n.], 2003.
2. ANTUNES, F. Conversores CC-CC. [S.l.]: [s.n.], 2007.
3. SONS, J. W. &. **Renewable and Efficienct Electrical Power Systems**. New Jersey: [s.n.], 2004.
4. BERNARDO, P. C. D. M. **Análise e Aplicação Técnica de Rastreamento de Máxima Potência em um Conversor Buck para Sistemas Elétricos de Potência**. Pontifícia Universidade Católica de Minas Gerais. Belo Horizonte. 2008.
5. KOUTROULIS, E.; KALAITZAKIS, K.; VOULGARIS, N. C. Development of a Microcontroller-Based,Photovoltaic Maximum Power Point Tracking Control System, 2001.
6. SIEK, K. W.; CHEW, R.; LITER. Single Inductor Quad-Input-Dual-Output Buck, Singapore, 2010.
7. ERICKSON, R. W. **Fundamentals of Powe Eletronics**. New York: Chapman and Hall, 1997.
8. ASTRON, K. J. Control System Design. [S.l.]: [s.n.], 2002.
9. OGATA, K. **Engenharia de Controle Moderno**. 4º. ed. [S.l.]: Pearson Education do Brasil, v. 1, 2003.

Resumo Expandido

Projeto e Construção de um Conversor Buck

Bruno Marin Silveira, Heverton Augusto Pereira

1. Introdução

1.1. Modelagem não ideal

O circuito do conversor *Buck* para a modelagem completa é apresentado na Figura 1. A resistência do indutor representada por R_L; R_{ch} representa a resistência do semicondutor em saturação e V_D representa a queda de tensão no diodo.

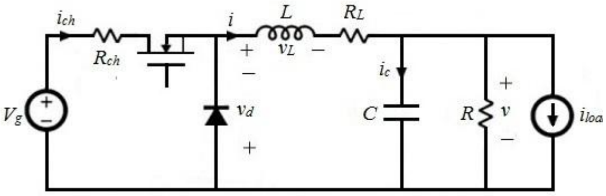


Figura 1: Conversor *Boost* utilizado na modelagem completa.

Dispositivo semicondutor em condução

No caso do dispositivo semicondutor estar conduzindo em um dado instante (situação idealizada como chave fechada) o circuito equivalente do conversor será o apresentado na Figura 2: Aplicando-se a lei de Kirchhoff das tensões (LKT) na malha de entrada obtêm-se que:

$$V_g - V_L - (R_L + R_{on}) \cdot i - v = 0 \qquad (1.1)$$

A queda de tensão nos terminais do indutor é dada pela equação (1.2).

$$V_L = L \cdot \frac{di}{dt} \qquad (1.2)$$

Substituindo-se (1.2) em (1.1), obteremos:

$$\frac{di}{dt} = \frac{V_g}{L} - \frac{(R_L + R_{on})}{L} \cdot i - \frac{v}{L} \qquad (1.3)$$

Por outro lado, aplicando-se a lei de Kirchhoff das correntes (LKC) no nó da carga obtêm-se:

$$i_C + \frac{v}{R} + i_{load} - i = 0 \qquad (1.4)$$

A corrente que atravessa o capacitor é dada pela equação (1.5):

$$i_C = C \cdot \frac{dv}{dt} \qquad (1.5)$$

Daí, substituindo-se (1.5) em (1.4), obtêm-se:

$$\frac{dv}{dt} = \frac{i}{C} - \frac{v}{RC} - \frac{i_{load}}{C} \qquad (1.6)$$

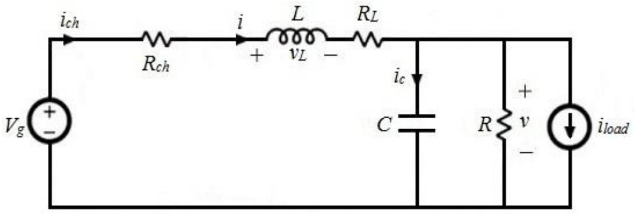


Figura 2: Circuito equivalente para o caso em que o IGBT em saturação.

O sistema de equações diferenciais que descreve o conversor *Boost* com a chave em condução será:

$$\begin{cases} \dfrac{di}{dt} = \dfrac{V_g}{L} - \dfrac{(R_L + R_{on})}{L} \cdot i - \dfrac{v}{L} \\ \dfrac{dv}{dt} = \dfrac{i}{C} - \dfrac{v}{RC} - \dfrac{i_{load}}{C} \end{cases} \qquad (1.7)$$

Uma forma muito conveniente de escrever o sistema formado pelas equações (1.3) e (1.6) é na forma matricial. Esta notação facilita a linearização do modelo e define grandezas muito comuns na modelagem de sistemas em geral. A forma matricial de (1.7) é apresentada na equação (1.8).

$$\begin{bmatrix} \dfrac{di}{dt} \\ \dfrac{dv}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{(R_L + R_{on})}{L} & -\dfrac{1}{L} \\ \dfrac{1}{C} & -\dfrac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} & 0 & 0 \\ 0 & 0 & -\dfrac{1}{C} \end{bmatrix} \cdot \begin{bmatrix} V_g \\ V_D \\ i_{load} \end{bmatrix} \qquad (1.8)$$

Deste modo no momento em que for feita a linearização do sistema tem-se que:

$$A_1 = \begin{bmatrix} -\frac{(R_L + R_{on})}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \qquad (1.9)$$

$$B_1 = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \qquad (1.10)$$

1.2. Dispositivo semicondutor em corte

No caso do dispositivo semicondutor estar em corte num dado instante (situação idealizada como chave aberta) o circuito equivalente do conversor será o apresentado na Figura 3.

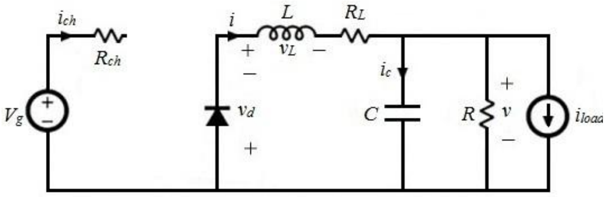


Figura 3: Circuito equivalente para o caso e que o IGBT está em corte.

Aplicando-se a LKT na malha 1, obtêm-se:

$$-V_L - v - R_L \cdot i - V_D = 0 \qquad (1.11)$$

De posse da equação (1.2) podemos reescrever (1.11) da seguinte forma:

$$\frac{di}{dt} = -\frac{v}{L} - \frac{R_L}{L} \cdot i - \frac{V_D}{L} \qquad (1.12)$$

Aplicando-se LKC no nó A, tem-se a equação (1.13).

$$i_C + \frac{v}{R} + i_{load} = i \qquad (1.13)$$

O uso da equação (1.5) em (1.13) resulta que:

$$\frac{dv}{dt} = \frac{i}{C} - \frac{v}{RC} - \frac{i_{load}}{C} \qquad (1.14)$$

Daí o sistema de equações diferenciais que descreve o funcionamento do conversor com a chave em aberto é:

$$\begin{cases} \frac{di}{dt} = -\frac{v}{L} - \frac{R_L}{L} \cdot i - \frac{V_D}{L} \\ \frac{dv}{dt} = \frac{i}{C} - \frac{v}{RC} - \frac{i_{load}}{C} \end{cases} \qquad (1.15)$$

Assim, escrevendo-se (1.16) na forma matricial:

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \cdot \begin{bmatrix} V_g \\ V_D \\ i_{load} \end{bmatrix} \qquad (1.16)$$

Deste modo no momento em que for feita a linearização do sistema teremos que:

$$A_0 = \begin{bmatrix} -\frac{R_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \qquad (1.17)$$

$$B_0 = \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \qquad (1.18)$$

É possível notar que as equações (1.8) e (1.16) podem ser escritas da seguinte forma:

$$\dot{X} = A \cdot X + B \cdot U \qquad (1.19)$$

Sendo que $\dot{X} = \begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix}$, $X = \begin{bmatrix} i \\ v \end{bmatrix}$ e $U = \begin{bmatrix} V_g \\ V_D \\ i_{load} \end{bmatrix}$.

1.3. Modelo chaveado e a linearização do modelo

Como se pôde verificar anteriormente, para cada situação em que chave se encontra as matrizes A e B mudam de valor. Deste modo, torna-se interessante obter uma única equação para descrever o comportamento de um conversor e assim facilitar sua análise.

Foi obtido na seção 1.3 que para o IGBT em corte, a equação de estado para o conversor pode ser escrita como:

$$\dot{X} = A_0 \cdot X + B_0 \cdot U \qquad (1.20)$$

Já para o IGBT em condução, foi obtida a seguinte relação (seção 1.2):

$$\dot{X} = A_1 \cdot X + B_1 \cdot U \qquad (1.21)$$

Seja a grandeza δ definida por:

$$\delta = \begin{cases} 1 & se\ a\ chave\ está\ fechada \\ 0 & se\ a\ chave\ está\ aberta \end{cases} \tag{1.22}$$

De posse desta grandeza podemos escrever o modelo chaveado definido pela equação (1.23):

$$\begin{aligned} \dot{X} = \left(A_0 + \ \delta \cdot (A_1 - A_0)\right) \cdot X + \\ (B_0 + \ \delta \cdot (B_1 - B_0)) \cdot U \end{aligned} \tag{1.23}$$

Calculando-se o valor médio dentro de um período de chaveamento das grandezas da equação (1.23), obtemos:

$$\begin{aligned} < \dot{X} >= \left(A_0 + \ d \cdot (A_1 - A_0)\right) \cdot < X \\ > + (B_0 + \ d \cdot (B_1 - B_0)) \cdot < U > \end{aligned} \tag{1.24}$$

$< \dot{X} >$ é o valor médio de $\dot{X}$ dentro de um ciclo de chaveamento. O valor médio de δ é o tempo médio na qual o dispositivo semicondutor está em condução durante o período de chaveamento, ou seja, a razão cíclica d. Para se realizar a linearização do modelo do conversor foi feita uma perturbação em regime permanente em cada uma das grandezas da equação (1.24). Assim:

$$\begin{cases} d = D + \hat{d} \\ < X > = x + \ \hat{x} \\ < U > = u + \hat{u} \end{cases} \tag{1.25}$$

Onde $\hat{d} \ll D, \hat{x} \ \ll x$ e $\hat{u} \ \ll u$.

Substituindo a relação (1.25) na equação (1.24), obteremos:

$$\begin{aligned} < \dot{X} > = \left(A_0 + \left(D + \hat{d}\right) \cdot (A_1 - A_0)\right) \cdot (x + \ \hat{x}) \\ + (B_0 + \ (D + \hat{d}) \cdot (B_1 - B_0)) \\ \cdot (u + \hat{u}) \ \Rightarrow \end{aligned}$$

$$\begin{aligned} < \dot{X} > = \ & \left[A_0 + D \cdot (A_1 - A_0) + \ \hat{d} \cdot (A_1 - A_0)\right] \cdot x + \\ & + \left[A_0 + D \cdot (A_1 - A_0) + \ \hat{d} \cdot (A_1 - A_0)\right] \cdot \hat{x} + \\ & + \left[B_0 + D \cdot (B_1 - B_0) + \ \hat{d} \cdot (B_1 - B_0)\right] \cdot u + \\ & + \left[B_0 + D \cdot (B_1 - B_0) + \ \hat{d} \cdot (B_1 - B_0)\right] \cdot \hat{u} \end{aligned} \tag{1.26}$$

Reorganizando-se os termos e fatorando obteremos:

$$\begin{aligned} < \dot{X} > = \ & [A_0 + D \cdot (A_1 - A_0)] \cdot \hat{x} + \\ & + [B_0 + D \cdot (B_1 - B_0)] \cdot \hat{u} \ + \\ & + [(A_1 - A_0) \cdot x + (B_1 - B_0) \cdot u] \cdot \hat{d} + \\ & + [A_0 + D \cdot (A_1 - A_0)]x + \\ & + [B_0 + D \cdot (B_1 - B_0)]u + \\ & + \ (A_1 - A_0) \cdot \hat{d} \ \cdot \hat{x} + (B_1 - B_0) \cdot \hat{d} \cdot \hat{u} \end{aligned} \tag{1.27}$$

Neste ponto devem ser feitas duas observações. A primeira é que $< \dot{X} >$ se reduz simplesmente a $\dot{\hat{x}}$. Isso é explicitado na equação (1.28), já que $\frac{d}{dt}(x) = 0$ (x é o valor em regime permanente). Além disso, é conveniente desprezar os termos de segunda ordem ($\hat{d} \ \cdot \hat{x}$ e $\hat{d} \cdot \hat{u}$), pois cada uma das perturbações é pequena.

$$\begin{aligned} < \dot{X} > = \ \frac{d}{dt}(x + \ \hat{x}) = \ \frac{d}{dt}(x) + \frac{d}{dt}(\hat{x}) \\ = \frac{d}{dt}(\hat{x}) = \ \dot{\hat{x}} \end{aligned} \tag{1.28}$$

Fazendo-se $A = A_0 + D \cdot (A_1 - A_0)$ e $B = B_0 + D \cdot (B_1 - B_0)$ e fazendo uso de (1.28) na equação (1.27) obteremos:

$$\begin{aligned} \dot{\hat{x}} \ = A \cdot \hat{x} + B \cdot \hat{u} \\ [(A_1 - A_0)x + (B_1 - B_0) \cdot u] \end{aligned} \tag{1.29}$$

Nota-se que para o termo $Ax + Bu$ pode ser escrito da forma:

$$\begin{aligned} Ax + Bu = (1 - D) \cdot (A_0 \cdot x + \ B_0 \cdot u) \\ + (D) \cdot (A_1 \cdot x + \ B_1 \cdot u) = 0 \end{aligned} \tag{1.30}$$

Pois é a condição de equilíbrio permanente (equação (1.24) com $\dot{x} = 0$). Finalmente, fazendo-se $(A_1 - A_0) \cdot x + (B_1 - B_0) \cdot u = M$ a equação (1.29) se reduzirá a:

$$\dot{\hat{x}} \ = A \cdot \hat{x} + B \cdot \hat{u} + \ \ M \cdot \hat{d} \tag{1.31}$$

Esta ainda pode ser escrita da seguinte forma:

$$\begin{aligned} \dot{\hat{x}} \ = A \cdot \hat{x} + [B \quad M] \cdot \begin{bmatrix} \hat{u} \\ \hat{d} \end{bmatrix} \Rightarrow \\ \frac{d}{dt}(\hat{x}) = \ A \cdot \hat{x} + B_t \cdot \hat{u}_t \end{aligned} \tag{1.32}$$

Sendo $B_t = [B \quad M]$ e $\hat{u}_t = \begin{bmatrix} \hat{u} \\ \hat{d} \end{bmatrix}$.

Aplicando-se a transformada de Laplace na relação (1.32) obtém-se que

$$s\cdot\hat{x}(s) = A\cdot\hat{x}(s) + B_t\cdot\hat{u}_t(s) \Rightarrow \hat{x}(s) = (sI - A)^{-1}\cdot B_t\hat{u}_t(s) \tag{1.33}$$

Escrevendo-se (1.33) na forma matricial obteremos:

$$\begin{bmatrix}\hat{\imath}\\ \hat{v}\end{bmatrix} = \begin{bmatrix}F_{11}(s) & F_{12}(s) & F_{13}(s) & F_{14}(s)\\ F_{21}(s) & F_{22}(s) & F_{23}(s) & F_{24}(s)\end{bmatrix}\cdot\begin{bmatrix}\widehat{V_g}\\ 0\\ \hat{\imath}_{load}\\ \hat{d}\end{bmatrix} \tag{1.34}$$

Que é a *Matriz Modelo* do conversor elevador *Buck.*

A variação da tensão de saída no conversor pode ser escrita da seguinte forma:

$$\hat{v}(s) = G_{vd}\cdot\hat{d}(s) + G_{vg}\cdot\hat{v}_g(s) - Z_{out}(s)\cdot\hat{\imath}_{load}(s) \tag{1.35}$$

Onde $G_{vd} = \left.\frac{\hat{v}(s)}{\hat{d}(s)}\right|_{\substack{\hat{v}_g\,=\,0\\ \hat{\imath}_{load}\,=\,0}}$, $G_{vg} = \left.\frac{\hat{v}(s)}{\hat{v}_g(s)}\right|_{\substack{\hat{d}\,=\,0\\ \hat{\imath}_{load}\,=\,0}}$ e $Z_{out}(s) = -\left.\frac{\hat{v}(s)}{\hat{\imath}_{load}(s)}\right|_{\substack{\hat{v}_g\,=\,0\\ \hat{d}\,=\,0}}$.

G_{vd} é a função de transferência da variação na tensão de saída em relação a variação na razão cíclica; G_{vg} é a função de transferência da variação na saída em relação a uma variação na tensão de entrada; Z_{out} é a função de transferência da variação na saída em relação a uma variação na carga. Finalmente, comparando-se as equações (1.34) e (1.35) obtemos as seguintes relações:

$$F_{21}(s) = G_{vg} \tag{1.36}$$

$$F_{23}(s) = Z_{out} \tag{1.37}$$

$$F_{24}(s) = G_{vd} \tag{1.38}$$

2 *Metodologia*

2.1 *Simulação do conversor buck no Simulink*

Para a simulação do circuito do conversor Buck foi utilizado o software Matlab/Simulink, conforme exibido na Figura 4.

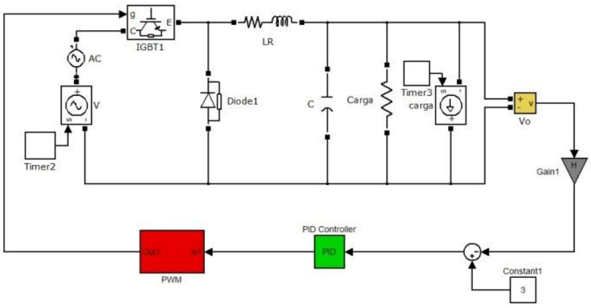


Figura 4: Circuito simulado no software Simulink.

A Figura 5 exibe a malha de controle utilizada para controlar a tensão de saída.

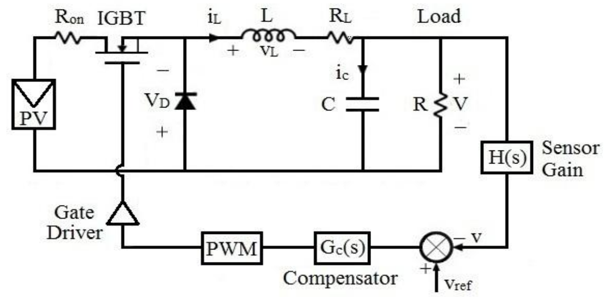


Figura 5: Controle PID do conversor buck

2.2 *Controlador PI*

Os parâmetros do controlador PI foram calculados através do método de Ziegler-Nichols. Para tal é necessário conhecer a resposta ao degrau da função de transferência em malha aberta do sistema, G_{vd}.

Usando o *Matlab* é possível calcular a função de transferência G_{vd}, como segue:

$$Gvd(s) = \frac{-1.819\times10^{-12}\,s + 1.215\times10^{9}}{s^2 + 1.226\times10^{4}\,s + 5.185\times10^{7}} \tag{2.1}$$

A resposta ao degrau da função de transferência (2.1) é apresentada na Figura 6.

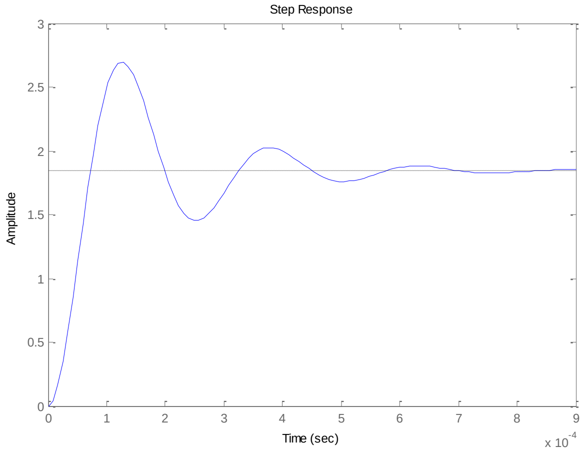


Figura 6: Resposta ao degrau de G_{vd}.

Utilizando-se o método de Ziegler-Nichols, serão obtidos os parâmetros da Table 2.

Tabela 1 – Valores calculados pelo Segundo método de Ziegler-Nichols.

Parâmetro	Kp	Ki	Kd
P	0,07919		
PI	0,071273	0,04792	
PID	0,095030	0,07987	0,02231

2.3 Dispositivos usados no projeto

As especificações de projeto são apresentadas Tabela 2. O projeto foi realizado para que o conversor trabalhe em modo contínuo.

Tabela 2 – Especificações do projeto.

Tensão de entrada	25V
Tensão de saída	12V
Frequência de chaveamento	20KHz
Resistência da carga	6Ω
Ripple da corrente no indutor - ΔI	10%
Ripple na tensão de saída - ΔVo	5%

O ciclo de trabalho nominal do conversor é dado por:

$$D = \frac{12V}{25V} = 0{,}48$$

A corrente na carga é calculada por:

$$Io = \frac{12V}{6\Omega} = 2{,}0\ A$$

De acordo com as especificações da Tabela 2, obtêm-se que:

$$\Delta I = 0{,}1 \times 2{,}0 \ = 0{,}20A$$

$$\Delta Vo = 0{,}01 \times 12{,}0 \ = 0{,}12A.$$

A indutância do conversor é calculada por:

$$L = \frac{V_g D(1-D)}{f\ \Delta I} \rightarrow L \ = 1{,}48mH$$

A capacitância do conversor é calculada por:

$$C = \frac{V_g D(1-D)}{8Lf^2\ \Delta V_c} \rightarrow C \ = 13{,}9\mu F$$

Tabela 3 – Componentes usados na construção do conversor.

Inductor	1,48mH
Capacitor	20,00μF
Semiconductor IGBT	IRG4BC30UD
Photoacoplator	4n25
Diode	In4007
Microcontroller	PIC18F4550

Utilizando o programa de simulação de elementos finitos FEMM, foi projetado o indutor utilizado no conversor, e a Figure 13 exibe a saída do FEMM. A bitola do fio utilizado foi o AWG17.

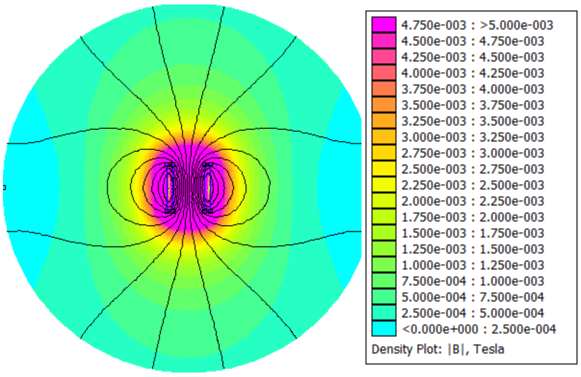


Figura 7: Distribuição do fluxo magnético

A curva da Figure 14 exibe a relação entre densidade de fluxo magnético e o campo magnético.

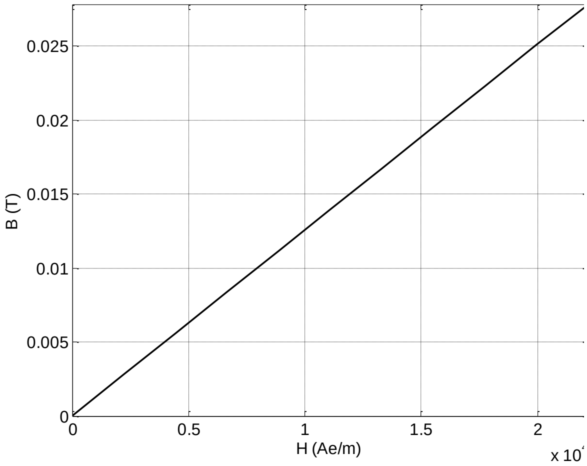


Figura 8: Relação entre a densidade magnética e o fluxo magnético

As especificações do indutor são exibidas na Tabela 4.

Tabela 4 – Especificações do inductor

Indutância	1,50mH
Resistência	0,9Ω
Área	16 cm²
Comprimento	6 cm
Voltas	230
Fio	AWG 17

3 *Resultados*

3.1. Simulação no software Proteus

O controle de comutação do IGBT é feito pelo microcontrolador PIC especificado na Tabela 3. O microcontrolador pode ler o valor da tensão de saída e compará-lo com a tensão de referência, o que gera um sinal de controle para variar a largura de pulso do PWM. A estratégia é a mesmo vista na Figura 5.

A programação é feita através do compilador do microcontrolar PIC e a simulação é realizada no software Proteus, Figura 10. Neste projeto, o IGBT é ativado por um photoacoplator que garante a diferença de tensão entre drive a gate do IGBT.

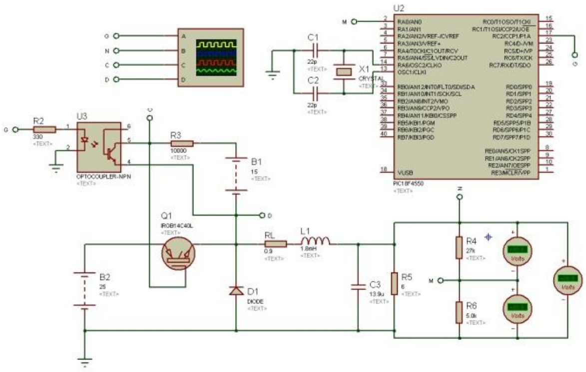


Figura 9: Simulação no Software Proteus

Os resultados obtidos com este software são as mais próximas como os resultados de ensaios experimentais. Assim como no software Simulink, o método de Ziegler-Nichols´s foi usado para calcular os parâmetros de controle PI. No software Proteus o controle PWM de IGBT foi feita por microcontrolador PIC. Nesta simulação, a tensão de entrada não está variando, o valor manteve-se em 25V de acordo com as especificações. A Figura 10 mostra o resultado desta simulação em um osciloscópio. Nota-se que o controle agiu rapidamente para manter a tensão de saída em 12V, de acordo com a finalidade deste projeto.

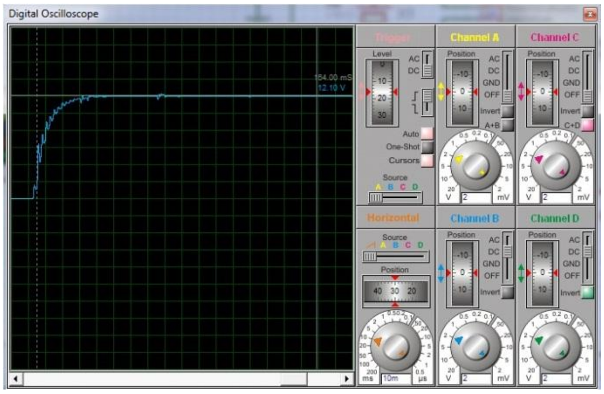


Figura 10: Resultados software Proteus para uma tensão de entrada de 25V

3.2. Simulação no Software Simulink

A simulação no software Matlab/Simulink foi realizada de acordo com as especificações do conversor buck. A tensão de entrada foi variada em três valores diferentes: 17V, 23V e 32V.

O objetivo é manter a tensão de saída em 12V conectado a uma carga, mesmo com as variações de tensão de entrada. A Figura 11 mostra os resultados desta simulação para uma tensão de entrada de 17V.

Nota-se que a tensão de saída foi mantida em 12V durante todo o intervalo de tempo.

A tensão de entrada foi aumentada para 23V e nota-se que o controle agiu mantendo a tensão de saída em 12V, como mostrado na Figura 12.

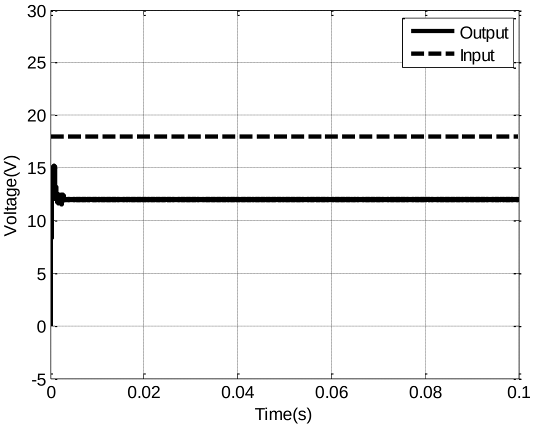


Figura 9: Resultado do Sofware Simulink para 17V de entrada

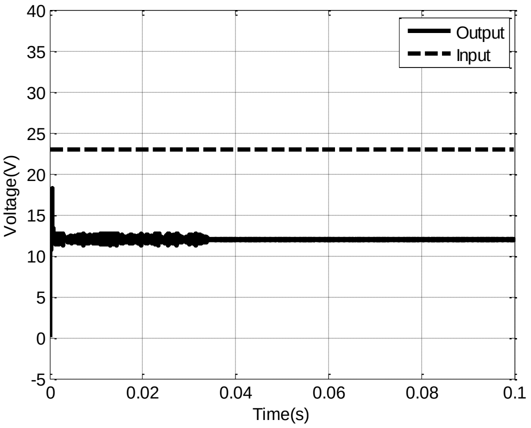


Figura 10: Resultado do Sofware Simulink para 23V de entrada

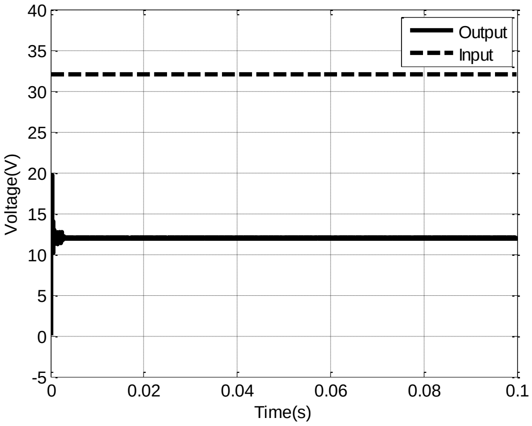


Figura 11: Resultado do Sofware Simulink para 23V de entrada

A Figura 13 mostra os resultados em Simulink para uma tensão de entrada de 32V. O controle tem mantido precisamente a tensão de saída em 12V, de acordo com as especificações do projeto.

3.3. Resultados experimentais

Após a validação da técnica de controle utilizada no conversor buck pelos softwares Simulink e Proteus colocou-se em prática o projeto a fim de comparar os resultados experimentais com as simulações. O projeto experimental é mostrado na Figura 15. Além do conversor buck, duas fontes de tensãs, um multímetro e um osciloscópio foram utilizados. A primeira fonte de tensão foi usada para fornecer o microcontrolador e a tensão de entrada, utilizou-se o segundo sobre o photoacoplator que fornece o gate do IGBT. O indutor foi construído de acordo com as especificações da Tabela 4.

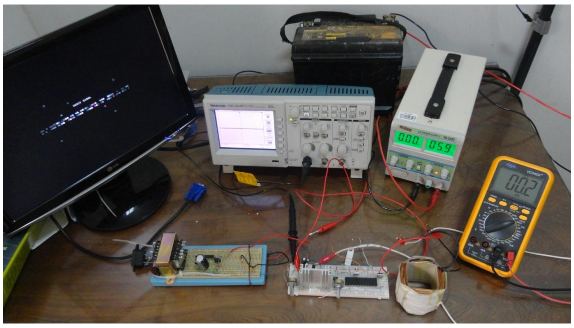


Figura 14: Projeto Experimental

A tensão de entrada foi variada do mesmo modo que em 3.2, e foi analisado o comportamento do conversor. A fonte de tensão usada nesses testes foi o mesmo, como mostrado na Figura 14. Os valores variaram durante o tempo: 18, 23 e 32V. Os resultados experimentais foram tirados no modo de estado estacionário.

A Figura 16 mostra o resultado para 17V de entrada. A tensão de saída manteve-se em 12V, que é o objetivo do conversor.

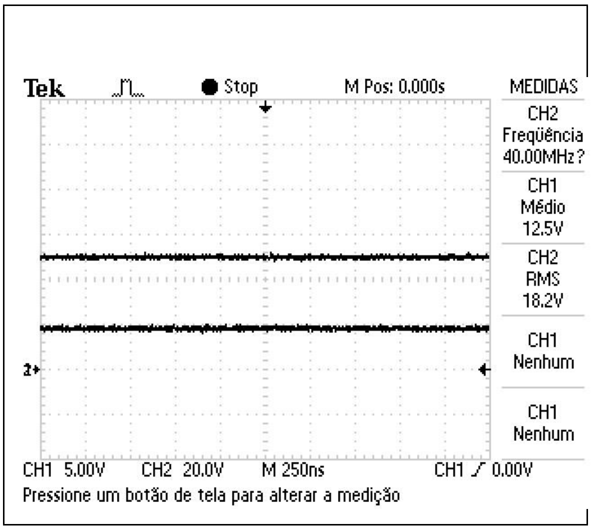


Figura 15: Graphic from oscilloscope for 18V input voltage

A Figura 16 mostra o comportamento do conversor quando a tensão de entrada aumentou para 23V. Manteve-se o valor médio da tensão de saída em 12V.

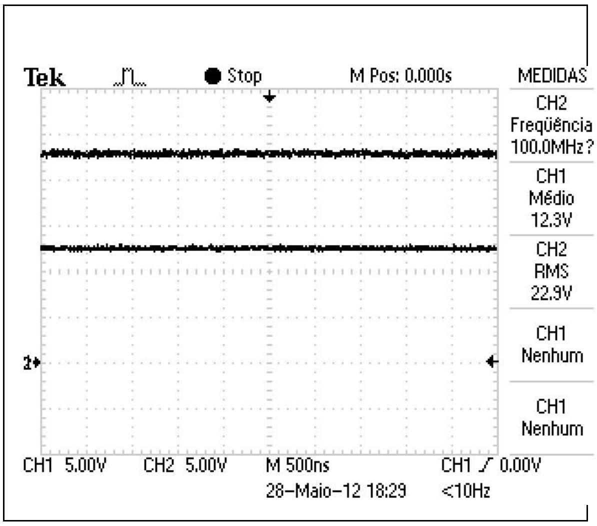


Figura 16: Tensão de saída para uma entrada de 23V

Por fim, a tensão de entrada do conversor aumentou para 32V e notou-se que o controle atuou, mantendo um valor médio da tensão de saída de 12V.

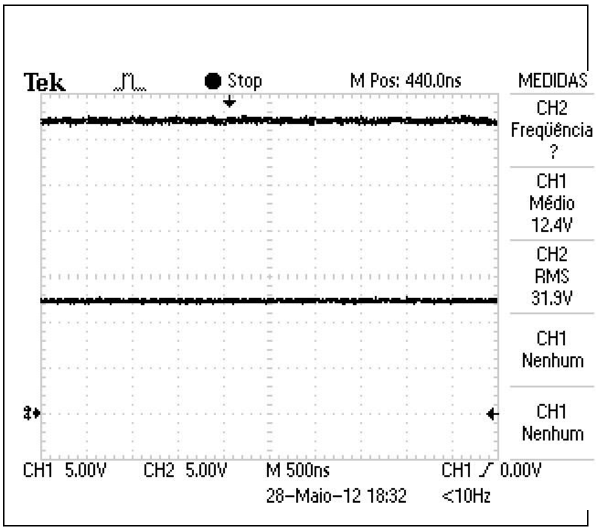


Figura 17: Tensão de saída para uma entrada de 32V

Nos 3 testes realizados, notou-se que o controle manteve a tensão de saída em 12V, mesmo com grandes variações na tensão de entrada de acordo com a finalidade deste trabalho.

4 Conclusão

Este trabalho apresentou um controle de estratégia baseado no controle de PI, que é responsável pela transferência de energia da entrada para a tensão de saída do conversor buck. Este controle atua quando há uma variação na tensão de entrada, mantendo a tensão de saída em um valor fixo de 12V.

O objetivo deste trabalho foi simular e construir um conversor buck em modo controlado de tensão capaz de manter sua tensão de saída em 12V.

Observou-se que o controle agiu de forma a manter a tensão de saída no valor especificado, de acordo com o propósito deste trabalho. Os resultados simulados foram muito perto dos resultados práticos validando o projeto.

Trabalhos futuros podem ser aplicados em um sistema solar, um banco de baterias de carga. Em sistemas fotovoltaicos, todas as variações na radiação provoca uma mudança no valor da tensão da saída, o que torna útil de um conversor de controlador conectado a este sistema.