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Methodology for teaching the operation principle of the boost converter: a rigorous description and solution using OpenModelica

Metodología para la enseñanza del principio de funcionamiento del convertidor elevador: una descripción rigurosa y solución usando OpenModelica

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Abstract

This paper presents a methodology for teaching the principle operation of the boost converter which includes a rigorous explanation that is useful to electrical and electronic engineers as well as to undergraduate students of these programs. The methodology consists on a deep explanation of the converter switching states to obtain the information necessary to understand its operation principle. An interchange of energy explanation between inductors and capacitors is included. Also, physical considerations are taking into account in order to provide a more realistic approximation of the application. Finally, differential equations which model the converter are presented and solved using the OpenModelica software to obtain both the stationary and transitory responses.

Key words: Boost converter, operation principle, differential equations, OpenModelica.

Resumen

Este artículo presenta una metodología para la enseñanza del principio de funcionamiento del convertidor elevador que incluye una explicación rigurosa que es útil para ingenieros eléctricos y electrónicos, así como también para estudiantes de estos programas. La metodología consiste en una explicación profunda de los estados de conmutación para obtener la información necesaria y poder entender el principio de funcionamiento. Una explicación del intercambio de energía entre bobinas y condensadores es presentada. También, algunas consideraciones físicas son tenidas en cuenta para proveer una aproximación más realista de la aplicación. Finalmente, las ecuaciones diferenciales que modelan el convertidor son presentadas y solucionadas usando el software OpenModelica para obtener las respuestas estacionaria y transitoria.

Palabras clave: Convertidor elevador, principio de funcionamiento, ecuaciones diferenciales, OpenModelica

1. Introduction

This paper deals with a rigorous explanation of the operation principle of boost converters. The explanation is presented to give specific details useful to students of electrical engineering and related programs. This paper can be used as the first class of power electronic and affine curses. The contributions of most power electronic design papers are

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related to the use of the model, failing to present details regarding the deduction of the model. However such details are of paramount importance, especially for undergraduate students, since they allow the understanding of the operating principle and also facilitate the design of the control structure (Arango *et al*., 2013; Bi, Z. and Xia, W., 2010).

Understanding the operation principle permits to improve the dynamical performance of the converter and at the same time fulfills all of its requirements (Liu *et al*., 2007). There are many papers which partially include the explanation of the operation principle for converters (Beldjajev, and Roasto, 2012; Davoudi *et al.*, 2013). The main contribution of this paper lies on a deeper explanation of the operation principle for the boost converter which is presented as step by step methodology; this methodology can be easily applied for other converters (Geyer *et al*., 2008;. Liang, and Tseng, 2005; Restrepo *et al*., 2013).

Boost converters are widely used in industry and constitute a research field for many researchers around the world, to mention some recent papers: (Rouzbehi *et al*., 2019) used a boost converter for controlling the DC voltage for microgrids applications; (Martínez-García *et al.*, 2019) included the modeling of a boost converter using Hardware-in-the-Loop; (Duong et al., 2019) developed a transformerless high-boost converter with switched-capacitor Network; (Yang and Liao, 2019) tuned a discrete sliding mode control for boost converters. Also, boost converters have been used for maximum power point tracking on solar photovoltaic systems (Shaw, 2019) and for measurement of current-voltage and power-voltage curves on solar panels (Velilla *et al*., 2019).

OpenModelica (Fritzson *et al*., 2019) is an open source environment for modeling and simulation. It allows dynamic multi-domain simulation of linear and non-linear systems. OpenModelica is based on an equation-based and object-oriented language (Modelica), it also includes an extensive model library, a graphic connection editor (OMEdit), compiler, simulator and plotting tools. OpenModelica usage for industrial and research applications on electric engineering has been reported on literature, i.e: (Dizqah *et al*., 2015) uses Modelica language to model DC microgrids, (Bartolini, 2019) models power grids and proposes a Power System Library, (Reid, 2015) uses OpenModelica to implement control algorithms for power inverters. OpenModelica has also been proposed as a tool to improve formation of future engineers (Murad *et al.*, 2017). In this paper, OpenModelica is used as a teaching tool to verify the model deduction methodology and to reinforce the explanation of the boost converter operating principle.

This paper describes in detail the operating principle of the boost converter. Technical literature is focus on using the boost converter model for controlling and developing purposes; nevertheless, there is not reported a procedure or methodology to obtain its differential equation and operating principle. The objective of the work is to propose a methodology for teaching the operating principle of boost converters giving details that permits students of electrical engineering and related programs to easily understand it.

2. Proposed methodology for a detailed explanation of the operation principle of the boost converter

This paper describes in detail the behavior of the boost converter considering the information that is possible to get through the switching states. An understandable methodology for teaching the operation principle of the boost converter must at least include the following steps: 1) Define components and variables in the equivalent circuit. 2) Define considerations and conventions. 3) Explain switching states in detalil. 4) Draw the references in the circuit and obtain the differential equations that model the converter. 5) Draw waveforms for voltages and currents of the converter. 6) Make a power and interchange of energy analysis. 7) Simulate the differential equations to verify model predictions. In this last step compare OpenModelica was used to check waveforms and discuss differences.

2.1. Step 1: Definitions of the components and variables in the equivalent circuit

The boost converter function is to maintain a regulated output voltage higher than its input voltage. Figure 1 illustrates the equivalent circuit of the boost converter. v_i is the input voltage or source while v_o is the output voltage. The boost converter has the following elements: inductor (L), capacitor (C), resistance or load (R), power transistor (Q) and diode (D).

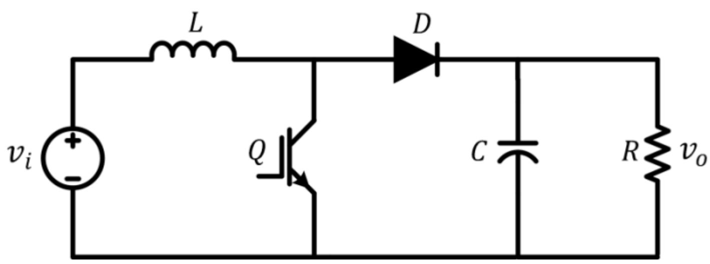

Fig 1. Equivalent circuit of boost converters

2.2. Step 2: Considerations and conventions

For didactic purposes, this paper makes the following assumptions: 1) Losses are neglected in the converter (please refer to (Urrea-Quintero, *et al.*, 2018) to consult a deeper analysis of the boost converter including losses). 2) There drop voltage in power switches is not considered. 3) The passive sign law is used to obtain the references of the system; references are marked in red color. 4) Blue color is used to indicate negative voltages or currents in the circuit. 5) According to the system of references selected (passive sing law), if ${dx}/{dt} > 0$, means that variable x increases its value; on the contrary; if ${dx}/{dt} < 0$, the value of x decreases. 6) if $p = v \cdot i > 0$, the element (L or C) stores energy; on the contrary, the element delivers energy. 5) Lowercase letters are used to denote variables in time domain while uppercase letters are used to denote parameters and average values.

2.3. Step 3: Detailed explanation of switching states

The information for explaining the operation principle of the boost converter is obtained by successive commutation. Two "closed" and one "open" commutations were used to obtain the information for the explanation.

This step begins explaining what happens when Q is closed as indicated in Figure 2. The following remarks can be made in this first closed commutation: 1) There is information to label the polarity of v_L and direction of i_L by using the passive sign law. 2) The source v_i is in parallel with inductor L, so v_i imposes the polarity to v_L while, according to the passive sign law, the direction of i_L is from left to right. 3) v_i is delivering energy to L, so L is absorbing energy. 4) The voltage and diode polarities are neglected in this part of the analysis (they will be explained in detailed latter). 5) When Q is closed and remains closed, i_L increases linearly until it reaches the saturation elbow, and later the saturation zone when short circuit occurs. It is recommended to tuned the current of the converter previous to the saturation elbow to obtain the most of ferromagnetic core. It is not recommended to tune the converter in the elbow or saturation zone to avoid the non-linear behavior of the core which produces problems related to control tuning. The next paragraph explains what happens when Q is open.

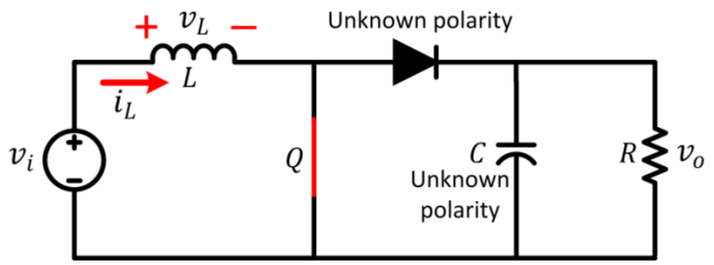

Fig 2. Boost converter when Q is closed

When Q is open, as indicated in Figure 3, the following remarks can be made: 1) L reacts and v_L becomes negative (blue color, ${di_L}/{dt} < 0$), this indicates that L is no longer absorbing energy as in the previous state; in this state, L is delivering energy to C and R. 2) The output voltage corresponds to the sum of v_i and v_L, therefore $v_o \geq v_i$, this indicates that boost converter lets step up the input voltage. 3) If it is supposed that initial condition of v_o is zero, D is directly polarized. 4) C and R are in parallel; therefore, their voltage polarities are equal. 5) There is information to mark the references for polarities of v_C and v_o and directions of i_C and i_R by using passive sign law (red color).

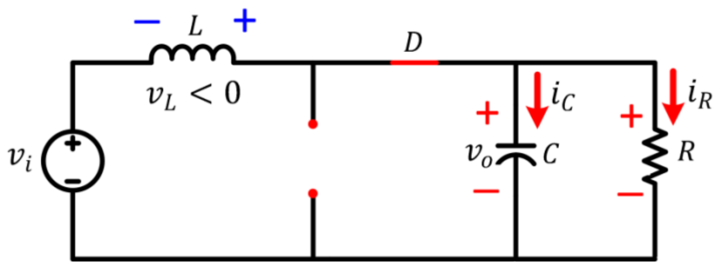

Fig 3. Boost converter when Q is open

A more detailed analysis for the boost converter when Q is closed is described in the following paragraph (please see Figure 4). In this case, the following statements can be made: 1) Since Q is closed the diode anode has zero volts (it coincides with the negative label of v_i), while the diode cathode coincides with the positive sign of v_o; therefore, D is inverse polarized. 2) The left side of the circuit is disconnected from the right side and its behavior was already explained at the beginning of this section. 3) The right part of the circuit is the parallel connection of C and R; therefore, C delivers energy to R. 4) Blue color in i_C arrow indicates that i_C is negative, which indicates that the magnitude of v_C decreases.

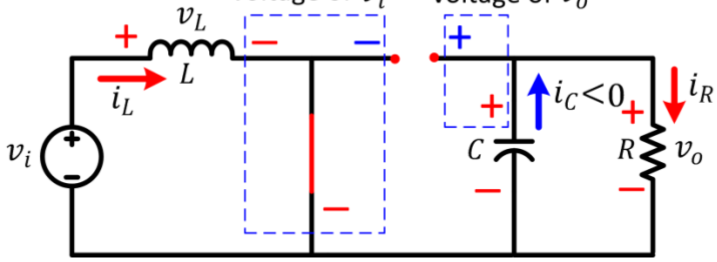

Fig 4. Boost converter when Q is closed (detailed explanation)

Based on the information of this section, references are drawn and differential equations are deduced in the following step.

2.4. Step 4: Labeling references and obtaining differential equations to model the converter.

References are labeled using red color following the passive sign law. References of v_L and i_L are obtained when Q is closed while references of v_C and i_C are obtained when Q is open. For a better comprehension, references should be drawn for both switching states, as indicated in Figure 5. Note that blue color polarities and arrows are not used in this step to avoid confusions in the deduction of equations or in the physical explanation of the converter.

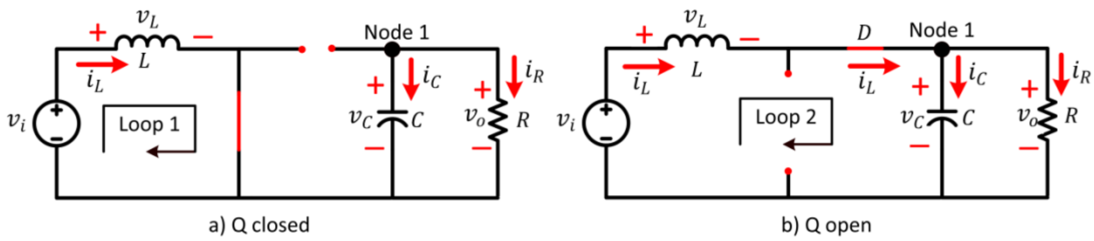

Fig 5. References depicted for both switching states: a) Q closed, b) Q open

The following differential equations were obtained by applying Kirchhoff's laws in Figure 5 . Equation (1) is obtained applying the voltage law in loop 1 of Figure 5a while equation (2) is obtained applying the current law in node 1 of the same figure.

$$L\frac{di_L}{dt} = v_i \tag{1}$$

$$C\frac{dv_C}{dt} = -\frac{v_C}{R} \tag{2}$$

Equation (1) indicates that i_L is increasing its value ($\frac{di_L}{dt} = {^{v_i}}/_{L} > 0$), so the inductor is storing energy. Equation (2) indicates that v_C is decreasing its value ($\frac{dv_C}{dt} = -{^{v_C}}/_{RC} < 0$), so the capacitor is delivering energy.

Equation (3) is obtained applying the voltage law in loop 2 of Figure 5b while equation (4) is obtained applying the current law in node 1 of the same figure.

$$L\frac{di_L}{dt} = v_i - v_C \tag{3}$$

$$C\frac{dv_C}{dt} = i_L - \frac{v_C}{R} \tag{4}$$

Equation (3) indicates that i_L is decreasing its value ($v_i - v_C < 0$; $\frac{di_L}{dt} = {^{v_i - v_C}}/_{L} < 0$), so the inductor is delivering energy. Equation (4) indicates that v_C is decreasing its value ($\frac{dv_C}{dt} = {^{(i_L - v_C)}}/_{RC} > 0$), so the capacitor is storing energy.

The switching function u is defined to conveniently write equations (1) to (4). When $u = 1$, the switch is closed; whereas when $u = 0$, the switch is open. Equations (1) and (3) are rewritten as follows:

$$L\frac{di_L}{dt} = v_i \cdot u + \ (v_i - v_C)(1 - u) \tag{5}$$

While equations (2) and (4) are rewritten as follows:

$$C\frac{dv_C}{dt} = -\frac{v_C}{R} \cdot u + (i_L - \frac{v_C}{R}) \cdot (1 - u) \tag{6}$$

Based on the information of this section, waveforms of voltages and currents of the converter are drawn in the following step.

2.5. Step 5: Waveforms of voltages and currents

For a better understanding and for providing more details of the operation principle in steady state, the waveforms of the boost converter are depicted in Figure 6.

Figure 6a corresponds to the switching function u which is “1” when Q is closed and “0” when Q is open. The switching period (T_{sw}) is defined as the period of time at which commutation occurs. For most power electronic applications the switching frequency ($f_{sw} = {}^{1}/_{T_{sw}}$) is commonly used instead of T_{sw}; nevertheless, for the purpose of this paper, it is more convenient to use T_{sw}. The duty cycle (D) is defined as the percentage of time when Q is closed that is limited between 0 and 1. If D is “0” it means that Q is open for the complete T_{sw} while if D is “1” it means that Q is closed for the complete T_{sw}. Switching function u is commonly named PWM since it can be obtained through a Pulse Width Modulation technique which consists of a comparison between a carrier (triangular or sawtooth) function and a modulating (constant) function. When the modulating function is greater than the carrier function, the switching function u is “1”; otherwise, it is “0”. The ratio between amplitudes of modulating and carrier functions determines the duty cycle while the frequency of the carrier function determines f_{sw}. In general terms, Q is closed for the time between 0 and DT_{sw} while is open for the time between DT_{sw} and T_{sw}.

Figure 6b corresponds to the inductor voltage (v_L). When Q is closed, the voltage of the source v_L is equal to v_i; as indicated in equation (1). When Q is open, the voltage of the source is $v_L = v_i - v_c$; as indicated in equation (3). For an appropriate operation of the converter, area 1 (A_1) must be equal to area 2 (A_2). This means that mean value of v_L is zero ($V_L = 0$) and the inductor adequately interchanges its energy with other components of the converter, being zero the net exchange of energy in the switching period. If $V_L > 0$ it means that $A_1 > A_2$ and the inductor is storing more energy when Q is closed than the energy delivered when Q is open; so, under this condition, the inductor becomes saturated (inappropriate operation of the converter and risk of short circuit). If $V_L < 0$ it means that $A_1 < A_2$ and the inductor is delivering more energy when Q is closed than the energy stored when Q is open; so, under this condition, the energy of the inductor becomes zero (no energy available in the inductor for interchange with other components of the converter).

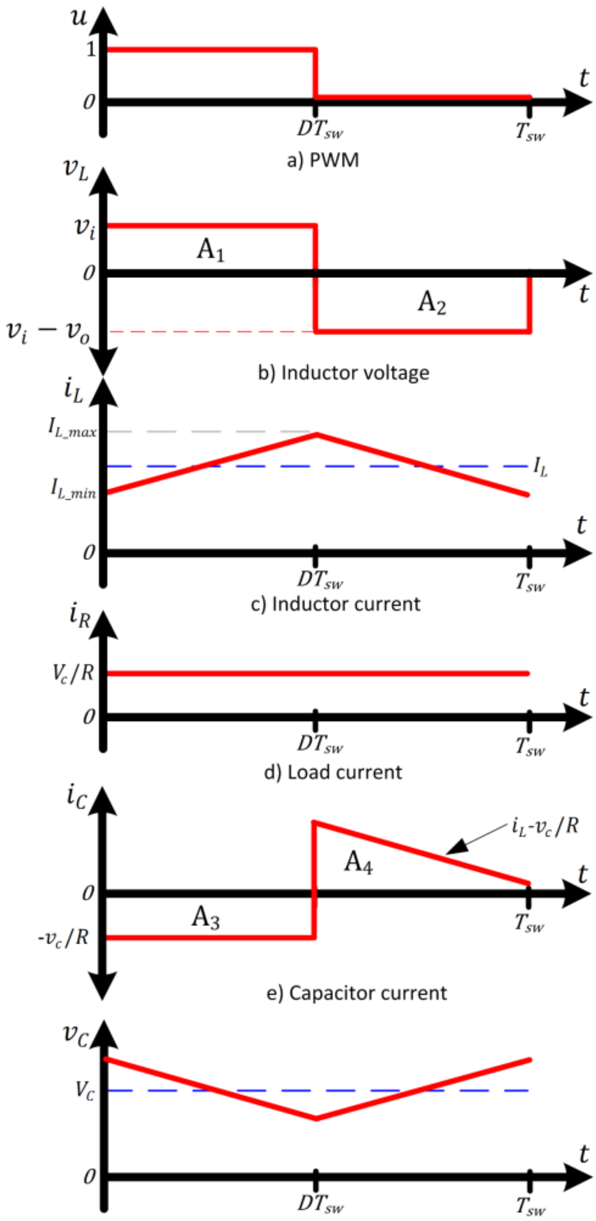

Fig 6. Boost converter waveforms

Figure 6c corresponds to the inductor current (i_L). When Q is closed, the source v_L is delivering energy to the inductor, for this reason, i_L is linearly increasing its magnitude. When Q is open, the inductor reacts and delivers its energy to C and R, this is why i_L is linearly decreasing its magnitude. i_L is delimited between I_{L_min} and I_{L_max} and the ripple current is $\Delta i_L = (I_{L\_max} - I_{L\_min})/2$. The mean value of i_L (I_L) is always positive for this converter, D and Q block negative values of i_L. In consequence, I_L is also positive and constant in stationary state, which means that the converter has a net interchange equal to zero; however, the inductor core has constant energy stored in a complete switching time period which permits to keep I_L constant. I_L could be the reference current for closed-loop controllers.

Figure 6d corresponds to the load current (i_R) or the current that circulates through the resistance R. It is assumed that v_c is constant ($v_c = V_c$), disregarding its ripple. So, i_R is also constant ($I_R = V_c/R$). When the ripple is disregarded, instantaneous values coincide with their corresponding average values, for this reason capital letters are used.

Figure 6e corresponds to the capacitor current (i_C). When Q is closed, the capacitor is delivering its energy to R, this is why i_C is negative (equation (2)). When Q is open, the source v_i and L are delivering their energy to R and C, this is why i_C is positive (equation (4)). For an appropriate operation of the converter, area 3 (A_3) must be equal to area 4 (A_4). This means that mean value of i_C is zero ($I_C = 0$) and the capacitor adequately interchange its energy with other components of the converter, being zero the net exchange of energy in the switching period. If $I_C > 0$ it means that $A_3 > A_4$ and the capacitor is storing more energy when Q is closed than the energy delivered when Q is open; so, under this condition, a dangerous overvoltage occurs and the capacitor could blow up. If $I_C < 0$ it means that $A_3 < A_4$ and the capacitor is delivering more energy when Q is closed than the energy stored when Q is open; so, under this condition, the energy of the capacitor becomes zero (no energy available in the capacitor being no possible voltage regulation).

Figure 6f corresponds to the capacitor voltage (v_c). When Q is closed, the capacitor is delivering its energy to R, for this reason, v_C is linearly decreasing its magnitude. When Q is open, the capacitor is receiving energy from v_i and L, this is why v_C is linearly increasing its magnitude. v_C is delimited between V_{C_min} and V_{C_max} and the voltage ripple is $\Delta v_C = (V_{C\_max} - V_{C\_min})/2$. The mean value of v_C (V_C) is always positive for this converter. For both switching states, the capacitor has positive voltages. V_C could be the reference voltage for closed-loop controllers.

2.6. Step 6: Power and interchange of energy analysis

Power and interchange of energy analysis is performed in Tables 1 and 2. Table 1 corresponds to the analysis when Q is closed while Table 2 when Q is open. The first column contains the elements of the converter. The second, third and fourth columns contain their respective voltage, current and power. Positive values in voltage and current columns indicate that the element (L, C, D or Q) has the same voltage polarity or current direction than the polarities or current directions of the references. Positive values in the power column indicate that the element is storing (L and C) or demanding (R, D and Q) energy. Negative values in voltage and current columns indicate that the element (L, C, D or Q) has contrary voltage polarity or current direction than the polarities or current directions of the references. Negative values in the power column indicate that the element is delivering (L and C) energy. Zero values in current and power columns indicate that D or Q is inverse polarized (no current and power are dissipated in the semiconductor).

Table 1. Power and interchange energy analysis when Q is closed.

Element	Voltage	Current	Power
L	positive	positive	positive
C	positive	negative	negative
R	positive	positive	positive

v_i	positive	negative	negative
D	negative	zero	zero
Q	positive	positive	positive

Table 2. Power and interchange energy analysis when Q is open.

Element	Voltage	Current	Power
L	negative	positive	negative
C	positive	positive	positive
R	positive	positive	positive
v_i	positive	negative	negative
D	positive	positive	positive
Q	negative	zero	zero

2.7. Step 7: Simulation of differential equations using OpenModelica

Openmodelica is a multi-domain simulation software, thus different modeling strategies can be implemented for the same system. In this work, two different strategies were explored: simulation using the differential equations deduced in step 4 (equations (5) and (6)) and simulation by using the electrical components.

Simulation using differential equations: The block diagram and the model described by the differential equations are presented in Figure 7 and Figure 8, respectively.

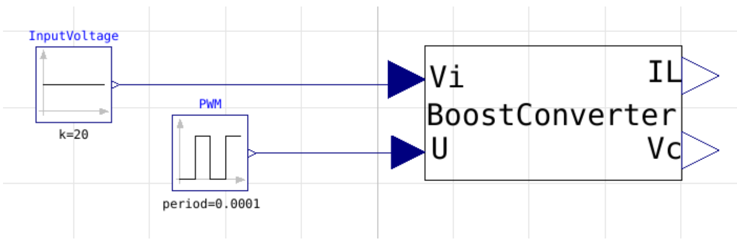

Fig. 7 Block diagram of the model.

```
model BoostConverterText "Ideal boost converter"
  Modelica.Blocks.Interfaces.RealInput Vi;
  Modelica.Blocks.Interfaces.RealInput U;
  Modelica.Blocks.Interfaces.RealOutput InductorCurrent;
  Modelica.Blocks.Interfaces.RealOutput CapacitorVoltage;
  parameter Real L = 10e-3;
  parameter Real C = 2e-3;
  parameter Real R = 100;
  Real Vc(start=0);
  Real Il(start=0);
  Boolean condition;

equation
  L * der(Il) = Vi * U + (Vi - Vc) * (1 - U);
  C * der(Vc) = (-Vc / R)*U + (Il - Vc / R) * (1 - U);
  condition=(Il < 0) and (U == 0);
  when condition then
    reinit(Il, 0);
  end when;
  InductorCurrent = Il;
  CapacitorVoltage = Vc;
end BoostConverterText;
```

Fig. 8. Model description using differential equations.

The model description begins by defining its inputs and outputs (lines 2 to 5 of Figure 8), v_i and PWM signals are inputs to the model while i_L and v_C are outputs (see the block diagram of Figure 7). Then, passive element values are defined as model parameters (lines 6 to 8 in Figure 8). Real number variables v_C and i_L are used as state variables for simulation and their initial condition values are zero (lines 9 to 10). Please note that parameters and initial conditions can be modified afterwards at simulation time. Equation code (lines 13 to 22) defines the dynamic behavior of the model: 1) Lines 14 and 15 are equations (5) and (6) of the model. 2) Lines 16 to 19 implement a restriction in i_L that cannot be negative since Q and D are unidirectional switches. This restriction cannot be modeled with the differential equations. Finally, 3) state variables v_C and i_L are assigned to the model as outputs (Lines 20 and 21).

Simulation using electrical components: Figure 9 shows the simulation model created using basic electrical component models and their corresponding connections. Please note that the model has the same input signals that the differential equations model (input voltage value and PWM signal). The Inductor, capacitor, resistor and diode are provided by OpenModelica electric library. Q is simulated as a voltage controlled switch.

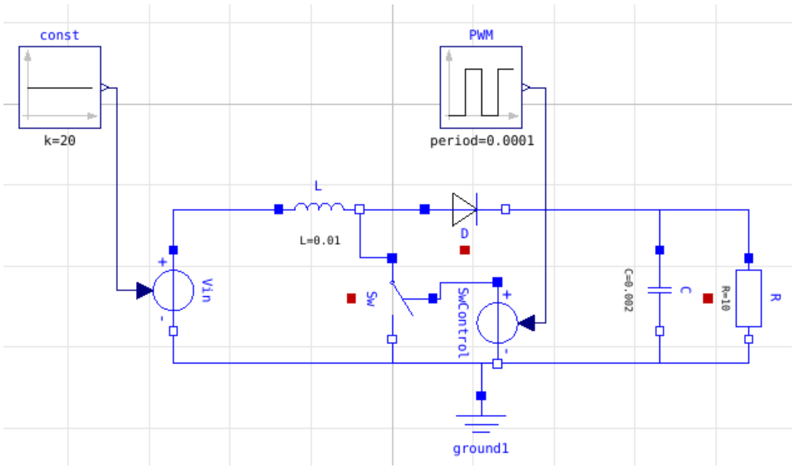

Fig. 9. Converter’s model created by using electric components.

3. Simulation results

A boost converter with the following specifications is considered: L=10 mH, $C = 2000\ \mu F$, $R = 10\ \Omega$, $f_{sw} = 10\ KHz$ and $v_i = 20\ V$. Zero voltage and zero current initial conditions are assumed for the capacitor and inductor, respectively. Simulation was carried out using the default compiler and solver in OpenModelica connection editor (OMEdit), version 3.2.2.

3.1 Validating differential equations by comparing simulation models

In this section, the two models described in step 7 are compared. Figure 10 shows the results obtained for v_C using both models (red: differential equation and blue: electric model) for a 75% of duty cycle. It can be seen that waveforms from both models overlap (it was necessary to use dash-dotted lines to visualize both curves). Also, two zoom windows are presented, the left one shows ripple during transient response of the converter and the right one shows ripple on steady state. It can be seen that both models responses continue to overlap. Figure 11 shows the same behavior for the inductor current response.

Different operation points where evaluated by varying the duty cycle and input voltage, observing the same overlapping shown in Figure 10 and Figure 11. Thus, it can be stated that the differential equations are a suitable representation of the ideal boost converter circuit not only in steady state but also in transient state. Also, the error between the model responses is small enough to evaluate the ripple using any of the models. This validates the assumptions and methodology described in steps 1 to 4.

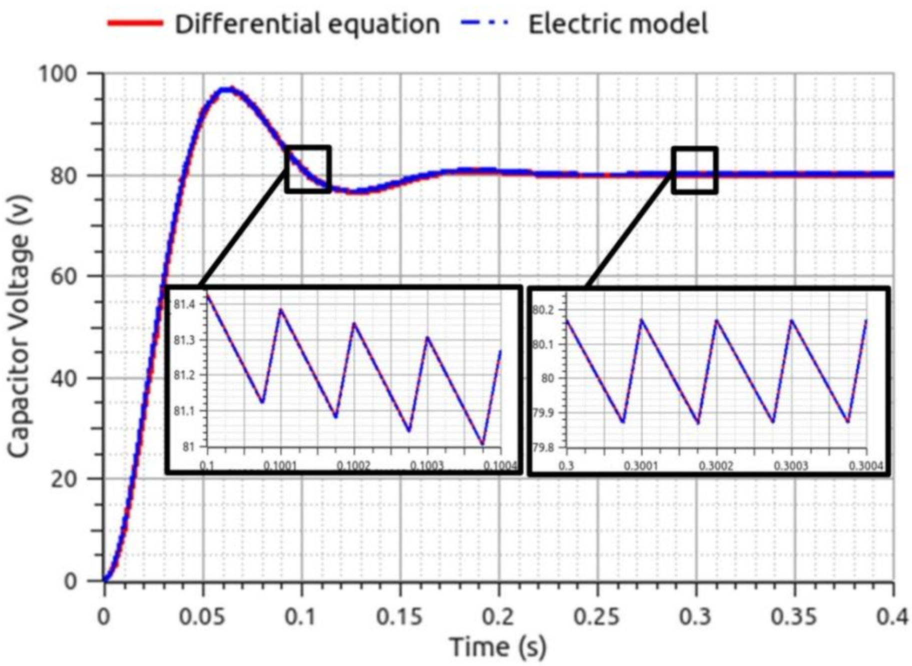

Fig. 10. Capacitor voltage solutions obtained from differential equation model (red) and electric component model (blue).

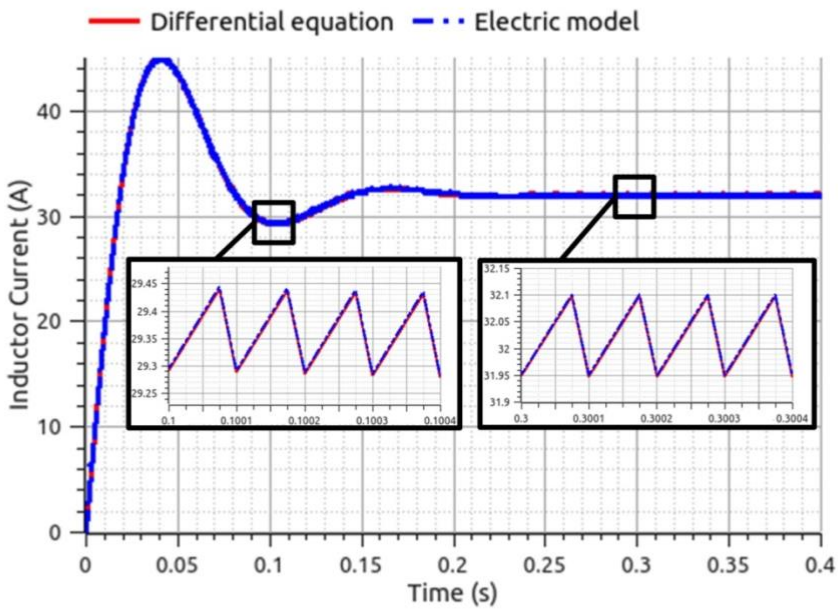

Fig. 11. Inductor current solutions obtained from differential equation model (red) and electric component model (blue).

3.2 Analyzing current and voltage ripple in steady state

This section aims to verify the analysis presented in step 5 and Figure 6. It can be easily note in Figure 10 that the ripple in the transient response (left zoom window) is not a periodic signal while ripple in steady state presents periodicity (right zoom window). Figure 11 shows simulation results in steady state for the converter at 50% and 75% of duty cycles, proper zoom has been applied in order to visualize signal ripples. All signals are in the same time base and can be considered as simultaneous measurements of the electric variables.

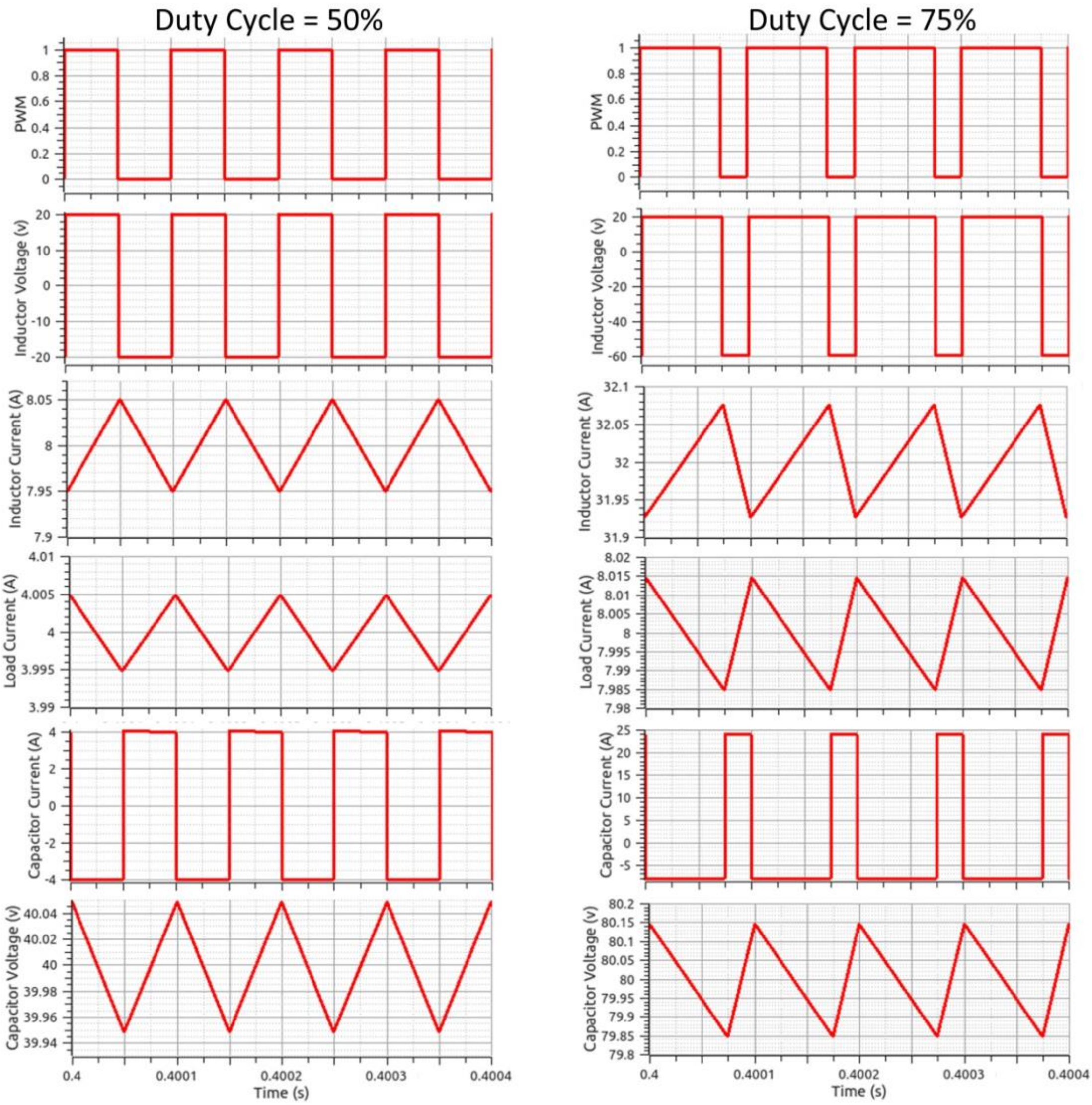

Fig. 11. PWM, inductor voltage and current, load current, capacitor current and voltage at steady state for 50% and 75% of duty.

By comparing Figures 6 and 11 some similarities and differences can be evidenced. The most obvious difference is the load current behavior; it was assumed constant in Figure 6, while for the simulation it has a triangle waveform. However, note that the load current ripple is the small current ripple in Figure 6, being four times lower than the inductor ripple current (30mA against 140mA approximately). This shows that constant load current can be considered as a good approximation to a well-designed converter.

The inductor current, inductor voltage and capacitor voltage show a similar behavior to the one stated in step 5. The inductor voltage has the predicted squared waveform, varying between v_i (20v for both cases) and $v_i - v_c$ (calculated using the average load current as $20v - (4A)(10\Omega) = -20v$ for 50% of duty and $20v - (8A)(10\,\Omega) = -60v$ for 75% of duty). It can also be verified that the areas below the inductor voltage curve are equal during closed and open states. As predicted, the inductor current presents a triangle waveform, confirming the validity of linear charging and discharging profiles assumption; this also occurs for the capacitor voltage signal.

Capacitor current slope during closed state cannot be visualized in Figure 11. Thus, a zoomed version of the capacitor current waveform is shown in Figure 12. Considering this figure, capacitor current waveform is consistent with the waveform drawn in step 5.

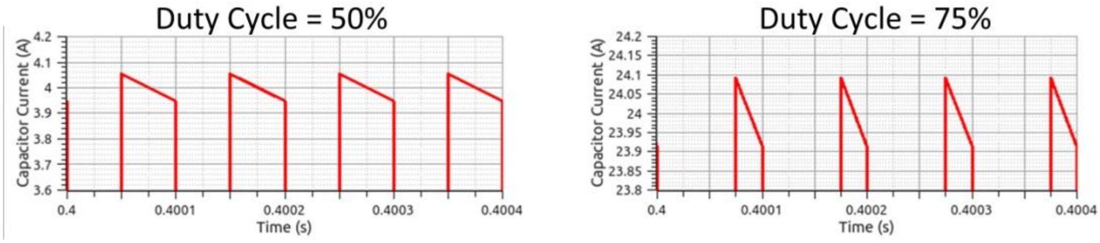

Fig. 12. Zoom of the capacitor current slope during open state.

4. Conclusions

This paper presented a methodology for teaching the operation principle of boost converters with seven steps that permits a deep understanding of its operating principle and main particularities. Details for stablishing the references of voltages and currents are presented. References were used to obtain the Differential equations which allows to model the behavior of the converter. Simulation by using OpenModelica permitted to obtain details that analytic explanations do not reveal.

The first step of the analysis presented the definitions of the components and variables of the equivalent circuit for the boost converter. Step two included some considerations and conventions. Step 3 presented a detailed explanation of the switching states. This explanation consisted in making successive commutations for getting the necessary information to explain the operation principle. Step 4 consisted in drawing the references following the passive sign law; then by using the references, differential equations that model the converter were obtained and explained. Step 5 included waveforms of voltages and currents of the converter, some concepts were also strengthened in this step. Step 6 consisted on an analysis of power and energy interchange summarized in tables for a better understanding. Step 7 presented the simulation results by using OpenModelica. OpenModelica simulation allowed verifying the validity of the differential equations deduced at Step 4 by comparing its solutions against a model created using the basic electric components. It was shown that differential equations are a valid model for evaluating transient, steady state and ripple for the different electrical variables of the converter.

The methodology presented in this paper can be applied on the initial teaching on power electronics systems. By combining a detailed mathematical deduction, a physical interpretation of the equation and switching states and experimentation through the use of an open source simulator a complete vision of converter operation is provided to students, improving results thanks to the use of different learning strategies.

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