

Modelling of hybrid Cuk converters using the methodology of voltage and current references

Modelado de convertidores híbridos Cuk utilizando la metodología de referencias de tensión y corriente

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Abstract

This paper presents a methodology for obtaining the voltage and current references that permits the modelling of Hybrid Cuk (HC) Converters. The passive sign convention when system elements absorb energy is used to derive the differential equations governing the behaviour of the converter. This allows the explanation of the operation principle of the converter that is performed through the switching states. The behavior of the converter is studied by means of an energy interchange analysis between inductors and capacitors. After the deduction of the references and operating principle, the differential equations (DEs) that allow the modelling of the converter are deduced. Finally, a comparison between the mathematical model and the circuital representation of the converter is performed in OpenModelica for validation purposes. The simulations' results allow to conclude that the obtained references and differential equations are coherent with the circuital implementation.

Keywords: hybrid Cuk converters; power electronics (PE) devices; differential equations; OpenModelica; voltage and current references; capacitor; inductor; power switch; diode; energy.

Resumen

Este artículo presenta una metodología para la obtención de las referencias de tensión y corriente que permiten el modelado de convertidores híbridos Cuk (HC). Se utiliza la convención pasiva de signos cuando los elementos del sistema absorben energía para deducir las ecuaciones diferenciales que rijan el comportamiento del convertidor. Esto permite la explicación del principio de funcionamiento del convertidor que se realiza a través de los estados de conmutación. Se estudia el comportamiento del convertidor mediante un análisis de intercambio de energía entre bobinas y condensadores. Luego de la deducción de las referencias y principio de funcionamiento, se deducen las ecuaciones diferenciales que permiten el modelado del convertidor. Finalmente, se realiza una comparación entre el modelo matemático y la representación circuital del convertidor en OpenModelica con el objetivo de validar las ecuaciones. Los resultados de las simulaciones permiten concluir que las referencias y ecuaciones diferenciales obtenidas son coherentes con la implementación circuital.

Palabras clave: convertidores híbridos Cuk; dispositivos de electrónica de potencia (EP); ecuaciones diferenciales; OpenModelica; referencias de tensión y corriente; capacitor; inductor; interruptor de potencia; diodo; energía.

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1. Introducción

The main objective of this paper is to describe a methodology for obtaining the voltage and current references for HC converters that permits its modelling. Basically, the Differential Equations (DEs) that govern the behavior of the converter are obtained. The proposed methodology corresponds to a straightforward procedure that takes into account the switching states of the converter. The technical literature shows that design engineers focus their efforts on designing control strategies; nonetheless, they usually do not pay attention to the reference setting that permits the proper deduction of DEs. In the specialized literature, the DEs that govern the converter are presented as a starting point for developing control strategies; nonetheless, the deduction of such equations is skipped. Therefore, papers, that develop theory concerning analysis or control strategies for power electronics converters, may be difficult to read and understand. In this context, this paper presents an understandable methodology for obtaining the voltage and current references for HC converters. This type of converter was chosen due to the fact that its topology is very complex

This paper is based on the passive law of signs when elements of the converter absorb energy, developing an easy but rigorous explanation for obtaining the references. Details concerning the operating principle are obtained, which may be useful to electrical, control and electronic engineers. The contributions of most power electronic design papers are related to the use of the model, failing to present details regarding the deduction of the model and the procedure for obtaining the references. However, details of the operating principle and deduction of equations through the references are the basis of power electronics (PE) designers [1], [2], [3], [4], [5], [6], [7], [8].

There is a great variety of Cuk and HC converters [9], [10], [11], to mention some aspects: 1) HC converters can be used with coupled or uncoupled inductors, that make the current through the inductors have a very small ripple. 2) For increasing the step-down nature of the converter, it is possible the use of a switched-capacitor that is inserted in the traditional Cuk converter. 3) Also; it is possible to add a switched inductor structure. This could lead to a higher voltage gain than the one obtained with the classical Cuk topology. 4) Cuk converters can also be configured in an isolated topology. Validation and results were obtained using OpenModelica software [12], [13], [14], [15], [16]. OpenModelica is a consolidated open-source tool designed for simulation of dynamic systems; it also allows multi-domain simulation of linear and non-linear systems. OpenModelica is made of an equation-

based and object-oriented language that is called Modelica. Therefore, OpenModelica includes many useful model libraries in electric and electronic fields. OpenModelica has begun to be used in industry as well as educational institutes.

This paper is organized as follows: Section 2 presents the methodology for obtaining voltage and current references. Section 3 corresponds to the deduction of the DEs. Section 4 presents the simulation results. Finally, Section 5 concludes and highlights the most relevant aspects of this paper.

2. Methodology for obtaining voltage and current references

The methodology corresponds to successively closing and opening the power switches which permits observing the transfer of energy between passive elements. Each closing and opening state corresponds to a commutation that is depicted one by one using a graphical method. Voltage polarities and currents directions when each passive element absorbs energy (passive law sign) are drawn in red color and correspond to the references. While negative voltage polarities and negative current directions that are drawn in blue color are defined as the reactions, under this condition the element delivers energy. The HC converter under study is depicted in Figure 1. It is composed of the following elements: 1) an input DC voltage source (v_i), 2) two inductors (L and L_2), 3) three capacitors (C_1 , C_2) and (C_3), 4) two diodes (D_1) and (D_2), 5) a power switch (Q), and 6) an output resistance (R).

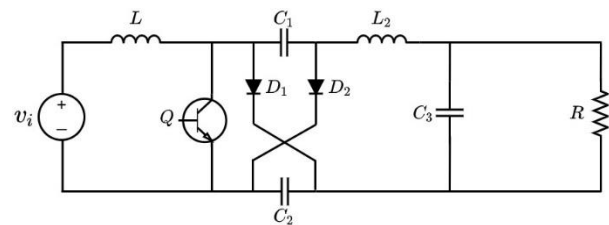


Figure 1. HC converter topology under study.

Figure 2 shows the circuit when the switch is closed (first commutation), the inductor (L) is parallel with the source (v_i) which means that (L) is charging. Using the passive law of signs, voltage and current references are labeled. In this step, there is still no information available for obtaining the references for other components.

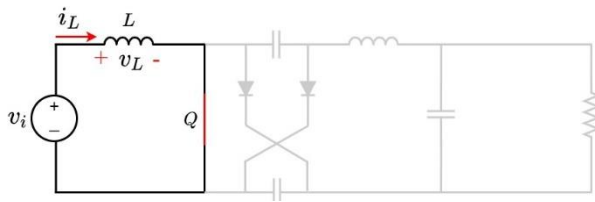


Figure 2. First commutation: Q closed

When Q opens, L reacts meaning that it starts delivering energy. As it is well known, inductors can not have sudden changes in their current, so what happens is that the voltage reacts (blue color) due to the opening of Q . In this switching state, C_1 and C_2 are absorbing since diodes, D_1 and D_2 are directly polarized, allowing the flow of current through the capacitors as shown in Figure 3 C_1 and C_2 references are labeled in this step

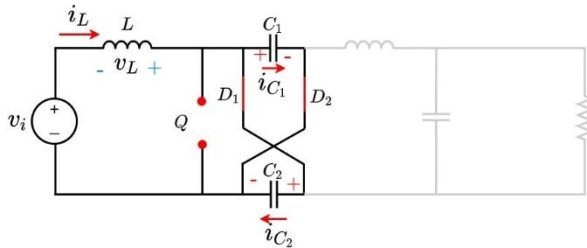


Figure 3. Second commutation: Q open.

Figure 4 shows the third commutation. When Q is closed again, C_1 and C_2 react again delivering energy and changing their current direction. D_1 and D_2 are reversed polarized causing their opening. This produces that the current passing through the capacitors is the same as the one that goes through L_2 . References of L_2 are labeled in this step.

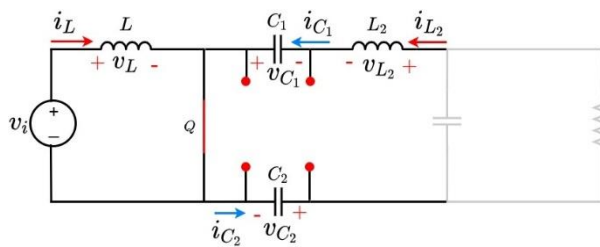


Figure 4. Third commutation: Q closed again.

Figure 5 shows the fourth commutation. When Q is open again, L and L_2 start delivering energy to capacitors C_1 and C_2 that also react by changing their current direction. The current direction of L_2 cannot suddenly change, this allows to determine the direction of the current passing through C_3 . References of C_3 are labeled in this step.

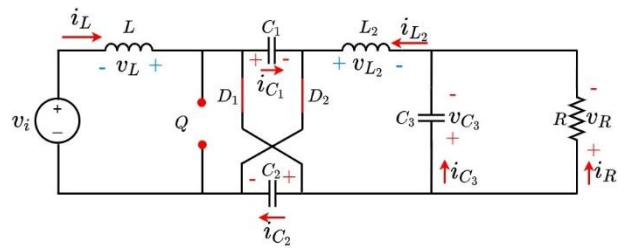


Figure 5. Third commutation: Q closed again.

3. Deduction of differential equations

Voltage and current references must be used for both switching states when the purpose is the obtention of DEs that govern the behavior of the convert. Figure 6 shows the HC converter when Q is closed while Figure 7 shows it when Q is open.

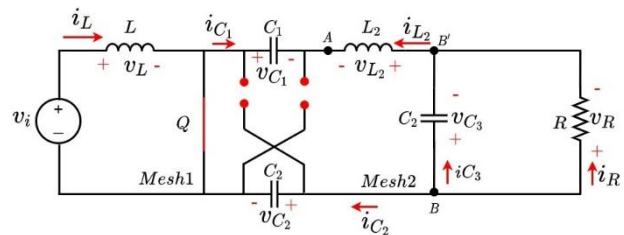


Figure 6. References: Q closed.

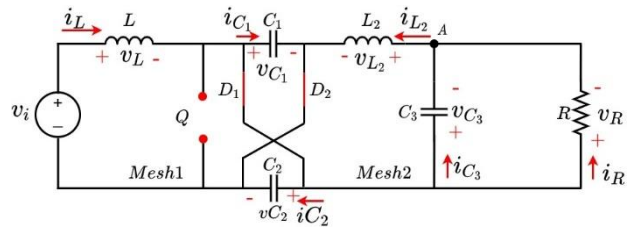


Figure 7. References: Q open.

To obtain the differential equations of the HC converter, it is considered that $C_1 = C_2 = C$. These capacitors share terminals; therefore, they are in parallel connection, which indicates that they have the same voltage V_c . Furthermore, the capacitor currents are considered equal to i_c .

3.1. Procedure for deduction of differential equations for Q closed

For the case of Q open which is illustrated in Figure 6, Equation (1) is obtained by applying Kirchoff's voltage law to mesh 1, taking the mesh current in a clockwise direction and applying the passive law of signs.

$$\frac{di_L}{dt} = v_i \quad (1)$$

Applying Kirchoff's voltage law in mesh 2, the inductor L_2 is charging, Equation (2) is obtained.

$$L_2 \cdot \frac{di_{L_2}}{dt} = 2 \cdot v_C - v_{C_3} \quad (2)$$

Equations (3) and (4) are obtained from Kirchoff's current law at nodes A and B, while Equation (5) is the result of ohm's law for capacitor C_3 .

$$i_{L_2} = i_{C_3} + i_R \quad (3)$$

$$i_{L_2} = -i_C \quad (4)$$

$$i_R = \frac{v_{C_3}}{R} \quad (5)$$

Replacing (4) and (5) in (3), it is obtained Equation (6) which is lower than zero. This indicates that capacitors C_1 and C_2 are delivering energy.

$$C \cdot \frac{dv_C}{dt} = C_3 \cdot \frac{dv_{C_3}}{dt} + \frac{v_{C_3}}{R} \quad (6)$$

Equation (7) is obtained from Kirchoff's current law at node B, replacing Equation (5) in (7) which gives Equation (8). This indicates that when Q is closed, L_2 is charging; therefore, capacitor C_3 delivers energy.

$$i_{C_3} + i_R - i_{L_2} = 0 \quad (7)$$

$$C_3 \cdot \frac{dv_{C_3}}{dt} = i_{L_2} - \frac{v_{C_3}}{R} \quad (8)$$

The Equations that model the HC converter when Q is closed are (1), (2), (6), (8).

3.2. Procedure for deduction of differential Equations for Q open

Figure 7 shows the converter when Q is open; however, Figure 8 indicates the trajectories of meshes 1 and 2 to facilitate the comprehension of the deduction of the DEs. The blue trajectory represents the closed path of mesh 1, while the green one represents the closed path of mesh 2.

Equation (9) is obtained by applying Kirchoff's voltage law to mesh 1, taking the mesh current in a clockwise direction and applying the passive law of signs. This Equation is lower than zero, so the inductor L delivers energy.

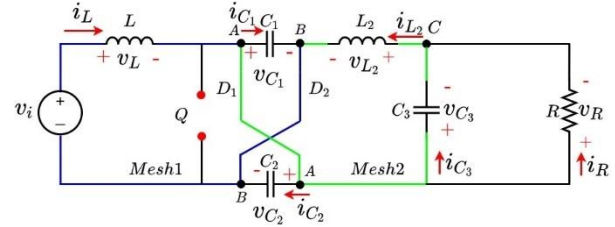


Figure 8. Illustration of meshes 1 and 2 of Figure 7.

$$L \cdot \frac{di_L}{dt} = v_i - v_C \quad (9)$$

Bearing in mind the considerations described above regarding capacitors C_1 and C_2 , from Kirchoff's voltage law in mesh 2, Equation (10) results; which, being lower than zero, indicates that the inductor L delivers energy.

$$L_2 \cdot \frac{di_{L_2}}{dt} = v_C - v_{C_3} \quad (10)$$

From Kirchoff's current law at node C, Equation (11) is obtained, which together with Equation (5) results in Equation (12). This last Equation is lower than zero; in consequence, C_3 is storing energy.

$$i_{L_2} = i_{C_3} + i_R \quad (11)$$

$$C_3 \cdot \frac{dv_{C_3}}{dt} = i_{L_2} - \frac{v_{C_3}}{R} \quad (12)$$

The points labeled with letter B highlighted in Figure 8, refer to the same node, so when applying Kirchoff's current law at node B, Equation (13) is obtained, which is greater than zero, indicating that C is storing energy.

$$C \cdot \frac{dv_C}{dt} = \frac{1}{2} (i_L - i_{L_2}) \quad (13)$$

In summary, the equations that model the HC converter when Q is open are (9), (10), (12), (13).

3.3. Switched model

Using the equations obtained under the Q switch states, Equations (14) to (17) govern the behavior of the converter. The commutation function u is defined to conveniently write the DEs. When $u = 1$, the switch is closed, otherwise, when $u = 0$, the switch is open.

$$L \cdot \frac{di_{L_2}}{dt} = v_i \cdot u + (v_i - v_c) \cdot (1 - u) \quad (14)$$

$$L_2 \cdot \frac{di_{L_2}}{dt} = (2 \cdot v_c - v_{C_3}) \cdot u + (v_c - v_{C_3}) \cdot (1 - u) \quad (15)$$

$$C_3 \cdot \frac{dv_{C_3}}{dt} = \left(i_{L_2} - \frac{v_{C_3}}{R}\right) \cdot u + \left(i_{L_2} - \frac{v_{C_3}}{R}\right) \cdot (1 - u) \quad (16)$$

$$C \cdot \frac{dv_c}{dt} = -\left(C_3 \cdot \frac{dv_{C_3}}{dt} + \frac{v_{C_3}}{R}\right) \cdot u + \frac{1}{2} \cdot (i_L - i_{L_2}) \cdot (1 - u) \quad (17)$$

3.4. Applying average model to obtain the gains of the system

The average model allows to obtain the steady state of the system, that is, the values of voltage and current in which the system stabilizes. Applying the average model, the rate of change with respect to time of a voltage or current, being a constant, its derivative is zero, for this reason, Equations (14), (15), (16), and (17) must be equal to zero. The average model does not take into account fast dynamics (ripples), being slow dynamics the average of the signals.

The average of the signals is defined by: the average current of inductor L (I_L), the average current of inductor L_2 (I_{L_2}), the average voltage of capacitor C_3 (V_{C_3}), the average voltage of capacitors C (V_C), and the average value of the function u (D) that is called duty cycle.

$$V_i \cdot D + (V_i + V_c) \cdot (1 - D) = 0 \quad (18)$$

$$(2 \cdot V_c - V_{C_3}) \cdot D + (V_c - V_{C_3}) \cdot (1 - D) = 0 \quad (19)$$

$$\left(I_{L_2} - \frac{V_{C_3}}{R}\right) \cdot D + \left(I_{L_2} - \frac{V_{C_3}}{R}\right) \cdot (1 - D) = 0 \quad (20)$$

$$-\left(I_{C_3} + \frac{V_{C_3}}{R}\right) \cdot D + \frac{1}{2} \cdot (I_L - I_{L_2}) \cdot (1 - D) = 0 \quad (21)$$

Equation (22) is obtained by expanding Equations (18) and (19) and substituting one into the other. On the other hand, Equation (23) results from replacing $I_{C_3} + I_R = I_{L_2}$ and $I_R = I_{L_2}$ in (21).

$$\frac{V_{C_3}}{V_i} = \frac{1 + D}{1 - D} \quad (22)$$

$$\frac{I_R}{I_L} = \frac{1 - D}{1 + D} \quad (23)$$

Equations (22) and (23) refer to the voltage and current gains.

Figure 9 illustrates the voltage gain, which is higher at the converter output when duty increases. The opposite behavior occurs with the current gain, Figure 10, as the duty increases, the current at the converter output is lower. In both Figures there is a response similar to an exponential function, due to the fact that the converter does not present power losses.

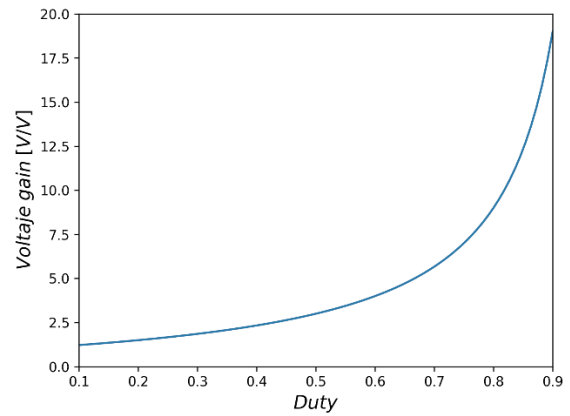


Figure 9. Voltage gain as a function of duty.

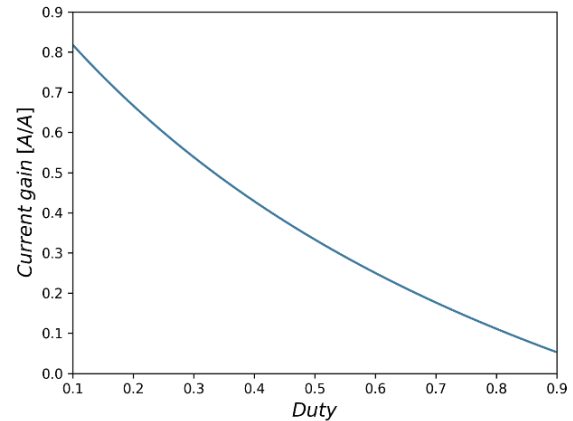


Figure 10. Current gain as a function of duty.

3.5. Voltage and current ripple

Equations (24), (25), (26) and (27) refer to the ripple of the inductor current L , the inductor current L_2 , capacitor voltage C_3 and capacitor voltage C , respectively. These equations resulted from discretizing Equations (14), (15), (16) and (17). Also, the switching frequency (f_{sw}) ($\Delta t = \frac{D}{f_{sw}}$) was considered.

$$\Delta i_L = \frac{D \cdot V_i}{2 \cdot f_{SW} \cdot L} \quad (24)$$

$$\Delta i_{L_2} = \frac{D \cdot \{(2 \cdot V_{C3}) - V_{C3}\}}{2 \cdot f_{SW} \cdot L_2} \quad (25)$$

$$\Delta v_{C_3} = \frac{D \cdot (I_{L_2} - I_R)}{2 \cdot f_{SW} \cdot C_3} \quad (26)$$

$$\Delta v_C = \frac{-D \cdot (I_{C_3} + I_R)}{2 \cdot f_{SW} \cdot C} \quad (27)$$

3.6. Continuous Condition Mode (CCM)

For facilitating the control of the device and reducing the risk of electromagnetic interference, the converter must operate in continuous conduction mode, ensuring that the instantaneous current of the inductor L has values greater than zero; this occurs when the average current of the inductor is greater than the current ripple. Otherwise, the converter will operate on discontinuous conduction mode (DCM). Replacing Equations (23) and (24) in $|I_L| > |\Delta i_L|$ yields equation 28.

$$K_c > K(D) \quad (28)$$

Where $K_c = \frac{2 \cdot L \cdot f_{SW}}{R}$ and $K(D) = \frac{D \cdot (1-D)^2}{(1+D)^2}$. The inequality in Equation (28) must be satisfied for the converter to operate in continuous conduction mode.

Figure 11 shows the plot of $K(D)$ and its maximum value that can be found using differential calculus. The maximum value of $K(D)$ is 0.9015 at a duty of $D = 0.2361$. So any converter with an K_c greater than this value will exhibit CCM for any duty cycle value at steady state.

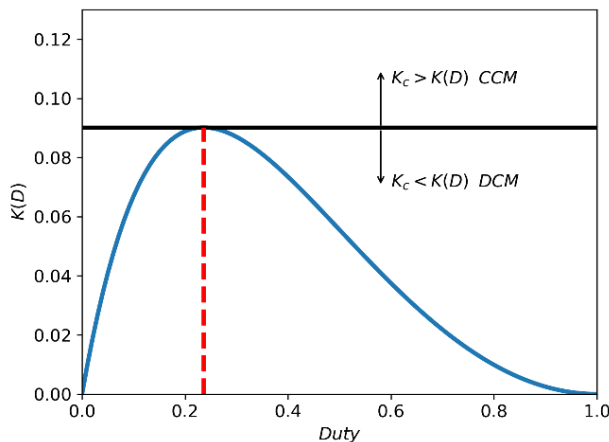


Figure 11. CCM and DCM for the hybrid cuk converter.

4. Results

A simulation was carried out using the default compiler and solver in OpenModelica Connection Editor (OMEdit), version 3.2.2. Figure 9 shows the implementation in OpenModelica of the converter depicted in Figure 1. The circuitual converter and the DEs that are in the right box at the top of Figure 12 were both implemented. Figure 13 corresponds to the script where DEs were written in OpenModelica for validating purposes.

The switching frequency is 10kHz, the duty cycle is 0.5 and the setpoint of the output voltage is 300V. The HB converter was parameterized as follows: $L_1 = L_2 = 10\text{mH}$, $C_1 = C_2 = C_3 = 500\mu\text{F}$, $R = 10\Omega$ and $v_i = 100\text{V}$.

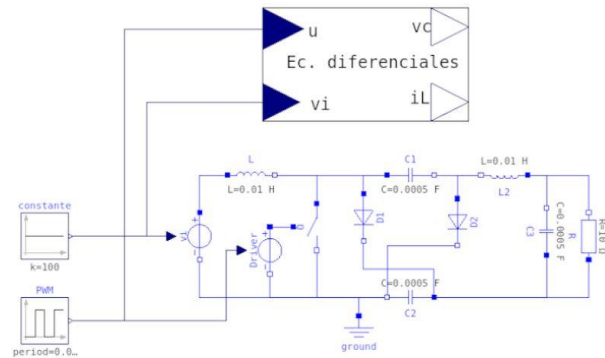


Figure 12. Implementation in OpenModelica.

```

1 model claseelectronicatexto22092020
2 parameter Real L1 = 0.01;
3 parameter Real L2 = 0.01;
4 parameter Real C3 = 0.002;
5 parameter Real C = 0.002;
6 parameter Real R = 10;
7 Boolean condition;
8 Real vc3(start=0);
9 Real vc(start=0);
10 Real il(start=0);
11 Real il2(start=0);
12 * Modelica.Blocks.Interfaces.RealInput u annotation( ... );
14 * Modelica.Blocks.Interfaces.RealInput vi annotation( ... );
16 * Modelica.Blocks.Interfaces.RealOutput currentL annotation( ... );
18 * Modelica.Blocks.Interfaces.RealOutput voltagevc annotation( ... );
20 equation
21 L1*der(il)=vi*u+(vi-vc)*(1-u);
22 L2*der(il2)=(2*vc-vc3)*u+(vc-vc3)*(1-u);
23 C3*der(vc3)=(il2-(vc3/R))*u+(il2-(vc3/R))*(1-u);
24 C*der(vc)=-((C3*der(vc3))+vc3/R)*u+0.5*(il-il2)*(1-u);
25 condition=(il<0) and (u==0);
26 when condition then
27   reinit(il, 0);
28 end when;
29
30 voltagevc=vc;
31 voltagevc0=vc3;
32 currentL=il;
33 currentL2=il2;
34 * annotation( ... );
35 end claseelectronicatexto22092020;

```

Figure 13. Script in OpenModelica.

Figures 14 and 15 correspond to the solution of L using the derived differential equations (DE) and the circuit implementation in OpenModelica (OM). It can be seen that both results are the same, they present the same average and ripple value.

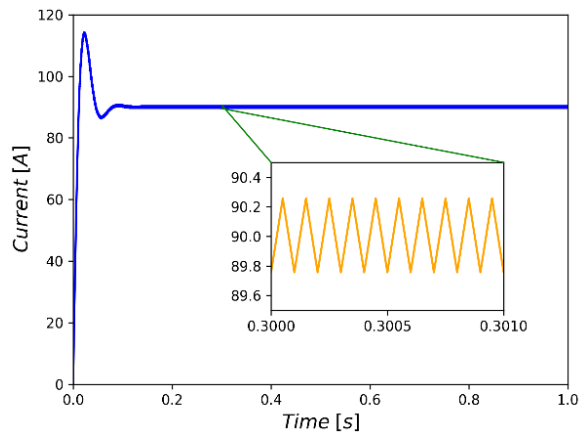


Figure 14. Current in L1 OM.

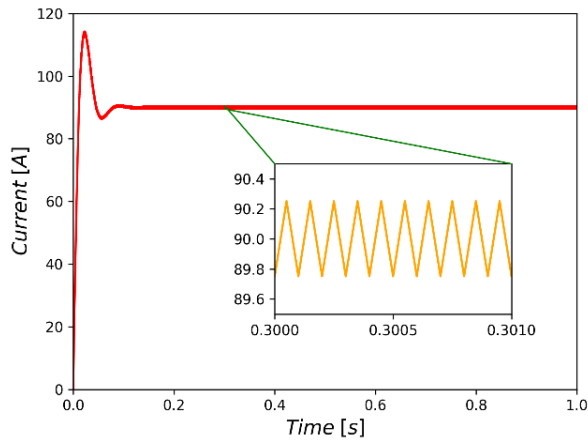


Figure 15. Current in L_1 DE.

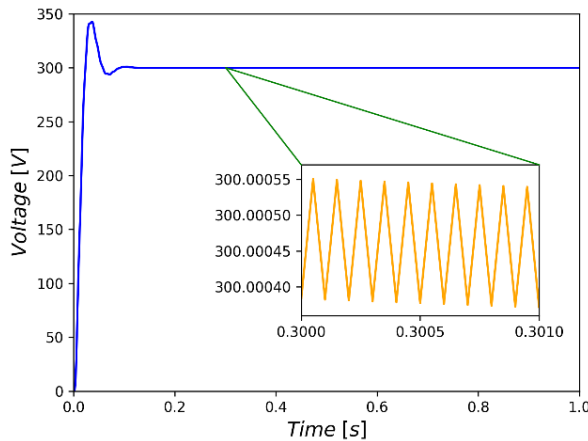


Figure 16. Voltage C3 OM.

Figures 16 and 17 correspond to the solution of the capacitor C_3 voltage using the derived differential (DE) equations and the implementation of the circuit (OM).

Table 1 permits validating the theoretical calculation with the simulation results. It can be seen that both results are similar, they present the same average and ripple value. It can also be seen that the voltage ripple in C_3 tends to zero because the inductor L_2 is close to the output.

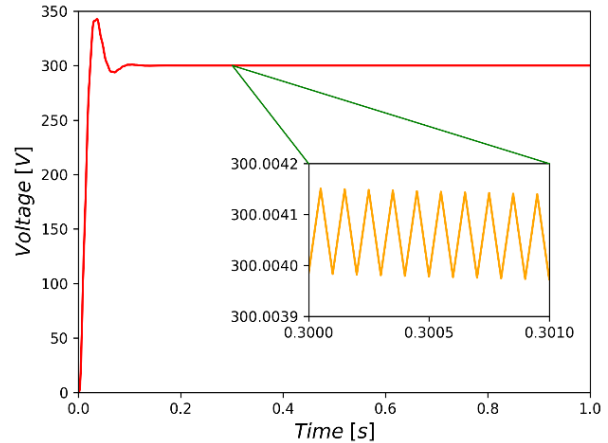


Figure 17. Voltage C_3 DE.

Table 1. Theoretical and simulated calculations

Variable	Simulation	Theoretical
I_L	90 A	90 A
Δi_L	0.2468%	0.25%
V_{C_3}	300 V	300 V
ΔV_{C_3}	0%	0%

Source: self-made.

5. Conclusions

The main contribution of this work is a methodology for the deduction of the voltage and current references that allow the modelling of HC converters. The methodology uses the passive law of signs which permits determining its principle of operation which consists on a detailed explanation of energy interchange between inductors and capacitors. This methodology allowed the proper deduction of the DEs that govern the behavior of HC converters. Ripples and continuous condition mode were established. DEs and circuital implementation of an HC converter were simulated using OpenModelica to validate the proposed methodology and references. All results indicated that inductor currents and capacitor voltages fit very well and their waveforms are very similar. According to the obtained results, it can be concluded that the methodology correctly determines the references that permit the obtention of HC converters' mathematical model.

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