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Design of a bidirectional converter for charging/discharging a supercapacitor

Diseño de un convertidor bidireccional para la carga/descarga de un supercapacitor

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Abstract

This article presents the analysis and design of a new converter that combines the current doubler topology and the parallel converter to achieve greater stability and effective reduction of ripple in both voltage and current parameters. Basically, the DC-DC (Direct Current to Direct Current) converter operates with pulse modulators to control the current in the desired charging or discharging direction. Extensive simulations were carried out at nominal values of 48 V and 8.5 A of output, and 100 V of input to confirm the performance of this converter. The approach used has benefits in terms of safety, reduced electrical noise, practical implementation for interconnecting energy sources with high voltage ratios, and increased lifespan of supercapacitors as well as batteries. Simulation results are presented and the advantages and applications of this new configuration are discussed.

Supercapacitor, Bidirectional, Energy

Resumen

Este artículo presenta el análisis y diseño de un nuevo convertidor que combina la topología del doblador de corriente y el convertidor paralelo para lograr una mayor estabilidad y una reducción efectiva del rizo en ambos parámetros de tensión y corriente. Básicamente el convertidor de CD-CD (Corriente directa a corriente directa) operara con moduladores de pulso para dirigir la corriente en el sentido deseado de carga o descarga. Se realizaron extensivas simulaciones en valores nominales de 48 V y 8.5 A de salida, y 100 V de entrada para confirmar el rendimiento de este convertidor. El enfoque utilizado tiene beneficios en términos de seguridad, menor ruido eléctrico, una implementación práctica para interconectar fuentes de energía con altas relaciones de tensión y un aumento en la vida útil de los supercapacitores, así como de baterías. Se presentan los resultados de simulación y se discuten las ventajas y aplicaciones de esta nueva configuración.

Supercapacitor, Bidireccional, Energía

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Introduction

Today, new technological developments and population growth have led to a significant increase in global electricity consumption. As a result, fossil fuel-based sources of electricity such as gas, oil and coal have increased to meet the world's electricity consumption. Consequently, the environment has been adversely affected due to the increase in greenhouse gases. One alternative to reduce this effect is renewable energy sources (RESs) such as solar or wind power. However, due to the fluctuating and intermittent nature of RESs, it is necessary to equip them with energy storage systems (ESS) to improve their overall efficiency, reliability, and power quality (Hidalgo-Reyes et al., 2019).

For this reason, energy storage devices are becoming very essential elements to take advantage of these renewable energy sources; because their purpose is to store energy for use in times when energy is not produced and thus increase the efficiency of the system. Among all these devices are supercapacitors, which are a technology that is capable of delivering high power pulses in an instant of time; in addition to supporting a large number of charge and discharge cycles as well as providing high efficiency during this process, but despite this they have the disadvantage of being unable to maintain the same voltage for a long time. (Hidalgo-Reyes et al., 2019), due to the above described, power converters are required to regulate to a certain desired voltage.

Direct current to direct current (dc-dc) converters are now being widely used in such applications, since they can be used both to store energy and to help the system deliver energy when it is not generating it, thus offering greater autonomy to power grids, as well as superior sustainability to renewable energy sources.

In recent years, different configurations of bidirectional DC-DC converters have been proposed for supercapacitors. In (Rico-Secades et al., 2016) elaborated a one-branch bidirectional converter (switch array) for charging and discharging two battery modules, using complementary pulse modulator (PWM) circuits in the transistors used; thus allowing that with a small duty cycle the battery is discharged and a larger duty cycle will cause its respective charge.

At (Huang et al., 2018; Ibanez et al., 2013; Kim & Sul, 2006) they propose a 3-branch and 4-branch step-up parallel converter, each branch uses the same duty cycle, but has an offset of 120 and 90 degrees respectively between each of them, this with the purpose of reducing the ripple of the current in the supercapacitors and even if one of the branches presents a failure, the system will be able to remain operational. In (López-Flores et al., 2010) present a phase-shifting full-bridge converter, in which they use the current doubler to be able to deliver a greater amount of current while helping to reduce the ripple, although it depends on the duty cycle used. There are also (Kayaalp et al., 2016; Lai et al., 2016; Shreelekha & Arulmozhi, 2016; Zhixiang Ling et al., 2015) which use phase-shift control, rather than duty-cycle control, thus enabling their more efficient use in multiport systems; (Rahimpour & Baghramian, 2017; Zakis et al., 2012) use the Z-source and Γ-source topologies for greater voltage and current stability, while reducing the reactive components of the circuit.

The previously analyzed works present appropriate activation methods for the switches of bidirectional dc-dc converters, and thus properly achieve the stability of the operating voltage and current at terminals with an acceptable ripple in both parameters. However, the ripple in the operating voltage and current can be variable and higher.

This paper presents a converter in which the current doubler topology is used in conjunction with the parallel converter topology (Figure 1), where the latter will operate at a duty cycle close to 0.5. Moreover, complementary PWMs circuits are used for a simple and efficient control of the charging and discharging of a supercapacitor (Not addressed in this paper). This approach leads to the following contributions:

i. Stability in the operating voltage and current of the bidirectional dc-dc converter, as well as effective ripple reduction in both parameters. This results in a positive impact on the lifetime of ESS systems (e.g. batteries and SCs).

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ii. Easy and practical implementation of the bidirectional dc-dc converter for interconnecting two power sources with high voltage ratios (e.g. ESS systems and RESs).

The implicit benefits of the approach used in the proposed bidirectional dc-dc converter are: personnel safety, reduced electrical noise.

In this article the following sections are presented; in section II a detailed analysis of the converter to be studied is made, as well as the obtaining of the different values of each component of the circuit; in section III the simulation results of such proposed circuit are presented, as well as the power semiconductor devices MOSFETs that were selected; in section IV the respective conclusions of the results obtained are exposed; and in section V the literature used is shown.

DC-DC Converter Analysis and Design

In order to implement the converter, a steady-state analysis of the converters will be performed separately and in a forward direction (supercapacitor as a load), taking into account that the transistors T_3 and T_4 (see Figure 1) will have duty cycles complementary to T_2 and T_1 respectively, and S_3 y S_4 with respect to S_1 and S_2; the simulation results are presented in the following sections.

I. Two-Branch Parallel Converter

The two-branch parallel converter as explained above will be used only to decrease the current ripple to near zero percent and as this depends on the direction in which it will be used, then it can operate as a boost or buck converter.

Although in the buck mode and with the phases shifted 180 degrees between the two branches, then the output current ripple can be reduced as far as the duty cycle is increased. The maximum point where the current ripple is almost zero is when the sum of each duty cycle of each branch gives one, i.e., 0.5.

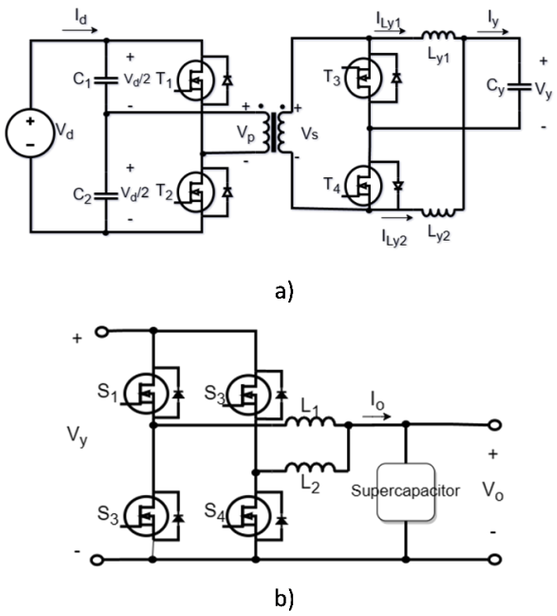

Figure 1 Schematic diagram of proposed topologies a) half-bridge converter complete with current doubler, b) two-branch parallel converter
Source: Own elaboration

For the design of the proposed converter, its voltage gain will be determined first, taking into account that the phase shift must be 180 degrees and the inductors of the same value, so analyzing one of the branches is more than enough.

When the switch S_1 is on the current flows through it and the transistor S_3 will be off, therefore, the inductor current I_{L1} is increased. This increase corresponds to a positive slope current ripple at L_1, which can be determined by the following equation:

$$\Delta i_{L1(ON)}=\frac{1}{L_1}\left(V_y-V_o\right)D_2T_s \qquad (1)$$

where D_2 represents the duty cycle, T_s the switching period, V_o the output voltage at the supercapacitor and V_y the input voltage. Now when the switch S_1 is turned off, then the current through the inductor L_1, is decremented by means of switch, S_3, resulting in a curl with negative slope, and (2) represents it in mathematical form.

$$\Delta i_{L1(OFF)}=\frac{1}{L_1}(-V_o)(1-D_2)T_s \qquad (2)$$

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Since both the increase and decrease in current ripple is of the same magnitude, therefore, the voltage gain can be determined by equating the absolute values of (1) and (2) as defined in (3).

$$\frac{V_o}{V_y}=D_2 \tag{3}$$

II. Half-Bridge Converter with Current Doubler

The design consists of four transistors (T_1, T_2, T_3 and T_4), two input capacitors (C_1 and C_2), one output capacitor (C_y) and two output inductors (L_{y1} and L_{y2}) and a transformer with two windings, as depicted in Figure 1B. The duty cycle of the transistors T_1 and T_2 in which it can operate is from 0 to 0.5, above that value a short circuit is caused between them. Since the inductors are connected to the ends of the secondary winding, then their currents will be 180 degrees out of phase, causing the ripple to decrease as the duty cycle increases.

As long as it is held on T_2 a voltage of $\frac{V_d}{2}$ will be present in the primary, consequently the secondary will have a voltage defined at (4) and the transistor T_3 will remain off, causing in the inductor L_{y1} an increase of the current $I_{L_{y1}}$ according to (5).

$$v_s=\frac{N_2}{N_1}\frac{V_d}{2} \tag{4}$$

$$\Delta i_{Ly1(ON)}=\frac{1}{L_{y1}}\left(\frac{N_2}{N_1}\frac{V_d}{2}-V_y\right)D_1T_s \tag{5}$$

Taking into account the above considerations, it can be calculated the variation of the current at L_{y1} as long as T_3 remains in on state (6),

$$\Delta i_{Ly1(OFF)}=\frac{1}{L_{y1}}(-V_y)(1-D_1)T_s \tag{6}$$

Performing in a similar way to how it is obtained (3) it is possible to obtain the voltage dc gain from (7).

$$\frac{V_y}{V_d}=\frac{N_2}{N_1}\frac{D_1}{2} \tag{7}$$

As the two converters (Figures 1a and 1b) are cascaded connected, therefore, the gains are multiplied, thus obtaining the gain between the output and input voltage as,

$$\frac{V_o}{V_d}=\frac{I_d}{I_o}=\frac{1}{2}\frac{N_2}{N_1}D_1D_2 \tag{8}$$

Regarding the value of the capacitor, the voltage V_y ripple must be calculated and for this it must first calculate the ripple of the current I_y, since in the sum of the current of the inductors the ripple decreases, then according to the Figure 2 the output current ripple is determined from (9).

$$\Delta I_y=\frac{V_y}{L_{y1}f_s}(1-2D_1) \tag{9}$$

Therefore, the ripple of the capacitor is defined as follows (10).

$$\frac{\Delta V_y}{V_y}=\frac{(1-2D_1)}{16L_{y1}C_yf_s^2} \tag{10}$$

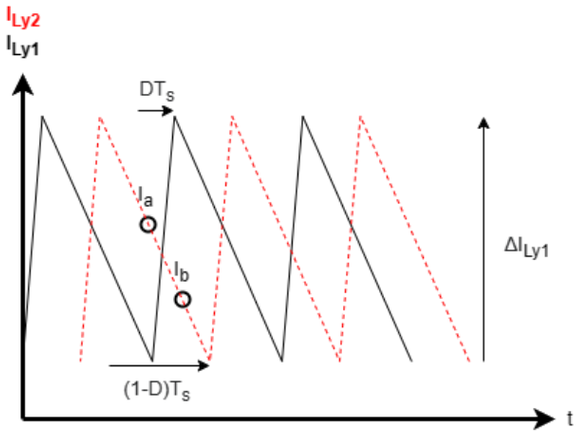

Figure 2 Variation of the currents with respect to time in inductors L_{y1} y L_{y2}
Source: Own elaboration

III. Relationship of Inductor Currents to Output Current

It is easy to deduce from Figure 1 (b) that I_o is the sum of the currents of the inductors L_1 y$L_2$and as both currents have the same waveform, except that they are 180 degrees out of phase; therefore, the average value of the output current is equal to the sum of the two currents of these inductors which leads to significantly reduce the output ripple of I_o of the two-branch parallel converter.

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To obtain a mathematical expression that relates I_o to the current of L_{y_1}, it is first necessary to know the waveform of current that pass over S_3, which according to Figure 3 the average current flowing through S_3 can be defined as,

$$I_{S3}=\left[\frac{1}{2}\Delta I_{L1}(1-D_2)T_s\right]\frac{1}{T_s}+\left[\widetilde{I_{L1}}(1-D_2)T_s\right]\frac{1}{T_s} \quad (11)$$

Simplifying (11) it is obtained the current in I_{S3} as shown,

$$I_{S3}=I_{L1}(1-D_2) \quad (12)$$

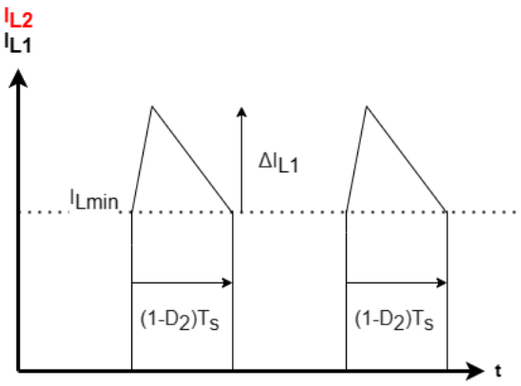

Figure 3 Current present in transistor S_3.
Source: Own elaboration

Now for the case of I_{Ly1} it is taken into account that it is half of I_y;knowing that the average current in a capacitor is zero, then I_y is the sum of the currents of S_1 and S_2, and I_{L1} is the sum of S_1 and S_3so this relation is defined by the next equation.

$$I_{Ly1}=\frac{D_2 I_o}{2} \quad (13)$$

IV. Maximum Transistor Voltages and Currents

This is done in order to determine the worst-case stress on the transistors and thus select the most suitable one. For the analysis it should be assumed that the maximum duty cycle D_1 level is 50%. For the voltages in the transistors S_1-S_4, it is easy to detect its maximum voltage since it is equal to V_y for all transistors, on the other hand for the current it is taken into account that when the transistor is in conduction, all the inductor current flows through it and because the inductor current is half of the output current, then this would flow through the transistor, only half of the inductor ripple must be added to obtain the maximum current as,

$$I_{Smax}=\frac{1}{2}I_{omax}+\frac{V_o}{4L_1 f_s} \quad (14)$$

The maximum voltage across the switches T_1 and T_2 when they are open is equal to the input voltage of V_d;the capacitors also supply current and have the same voltage as the source, so they supply the same amount of current I_d as the source, so the maximum current is defined as follows,

$$I_{T2max}=I_{T1max}=\frac{1}{4}\frac{N_2}{N_1}I_{omax} \quad (15)$$

From Figure 1 (a) it can be deduced that the maximum stress at T_3 and T_4 is the same as V_s, that is to say $\frac{N_2}{N_1}\frac{V_d}{2}$. Therefore, the maximum current flowing through these is I_y as expressed as,

$$I_{T3max}=I_{T4max}=\frac{1}{2}I_{omax}+\frac{N_2 V_d}{8N_1 L_{y1} f_s} \quad (16)$$

V. Bidirectional Converter Design

The following design parameters were considered for the calculation of all converter components:

- Input voltage, V_d=100 V,
- Output voltage, V_o=48 V,
- Switching frequency, f_s=40 kHz,
- Output current, I_o=8.5 A,
- Current and voltage ripples of 5%,
- Transformer turns ratio, $\frac{N_1}{N_2}=\frac{1}{6}$.

With the equations defined above (1)-(16) it is determine a duty cycle D_1 of 32%, considering that D_2 is always 0.5. Based on the current relations and the current ripple formulas, the inductances of all the coils can be known, which are for L_1 and L_2 a value of 2.82 mH, and for L_{y1} and L_{y2} a value of 15.36 mH, respectively. Finally, the capacitor C_y which is determined to have a value of 18.31 nF.

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For the maximum voltages and currents, a duty cycle of 0.5 and an output current of 10 A are assumed. In the Table 1 it is shown the specifications of the voltage and current values of the power semiconductor devices to which they will be subjected in the bidirectional converter.

Although it must be taken into account that in the reverse operation mode (discharge of the supercapacitor), the proposed converter works as a boost and for a maximum input voltage, the duty cycle must be decreased to zero ($D_1 = 0$), but as physically the converters have a limit point where the voltage starts to decrease. For this reason, a duty cycle of 0.1 was selected to calculate the maximum voltages in the reverse direction of the transistors. T_1, T_2, T_3 and T_4, except for the others, since they will work with a fixed duty cycle of 50%.

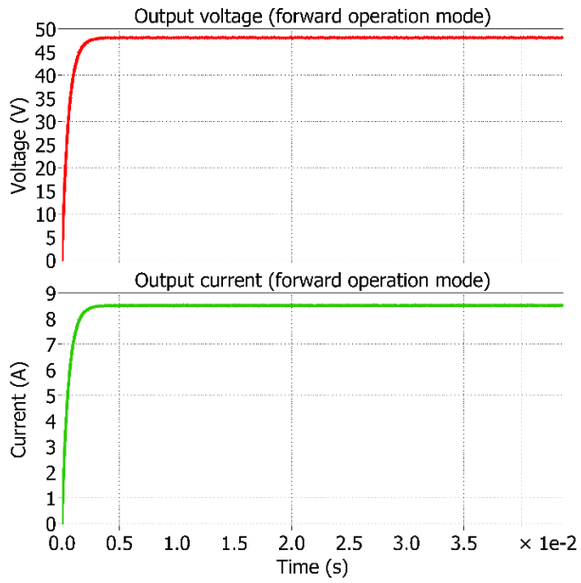
There will be no change in the currents since I_o is assumed as maximum, so a fuse will be used to avoid over currents.

Transistors	Maximum stresses	Peak currents	Maximum stresses (Reverse)
T_1 and T_2	100 V	15 A	320 V
T_3 and T_4	300 V	5.12 A	960 V
S_1 and S_2	150 V	5.16 A	
S_3 and S_4	150 V	5.16	

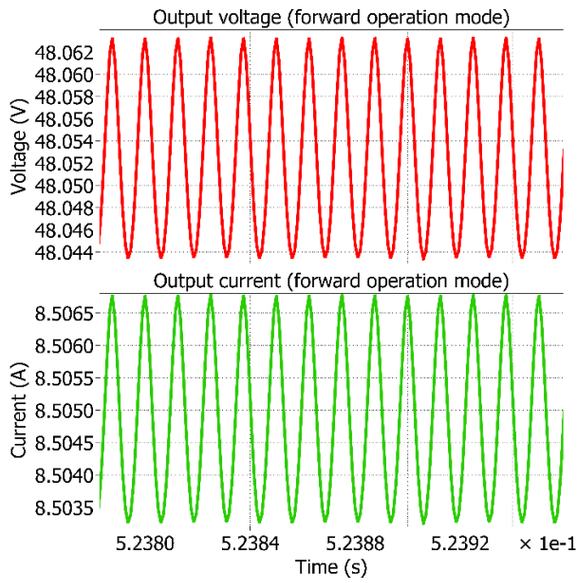
Table 1 Maximum voltages and currents in the converter
Source: Own elaboration

Simulation results

By means of the simulation tool of the PLECS© software, simulation results were performed and obtained, which represent the behavior of the output voltages and currents, as well as of the switches of the proposed converter. These simulations are carried out considering the design parameters and component calculations previously presented. Moreover, it is considered that, during the charging process, the supercapacitor is replaced with a power resistor with a value of 5.65 Ω in forward direction. Also, the inductor resistances were considered to be 0.5 Ω for the inductors L_y and 0.1 Ω for the inductors L.



Graphic 1 Output voltage and current (V_o, I_o respectively)
Source: Own elaboration



Graphic 2 Ripples in the output voltage and current (forward direction)
Source: Own elaboration

Because the converter is configured for minimum ripple, it can be seen Graphic 1 and Graphic 2 (amplified version of Graphic 1), that the desired voltages and currents are being achieved with a ripple of 0.04% for both.

As shown in Graphic 3 and Graphic 4, simulation results confirm that the maximum voltages and currents in the semiconductor devices are similar to those obtained in Table 1.

With this statement, MOSFETs devices can be selected to meet the requirements of the stress voltage and current to which they will be subjected, as well as the switching frequency power semiconductor devices will operate.

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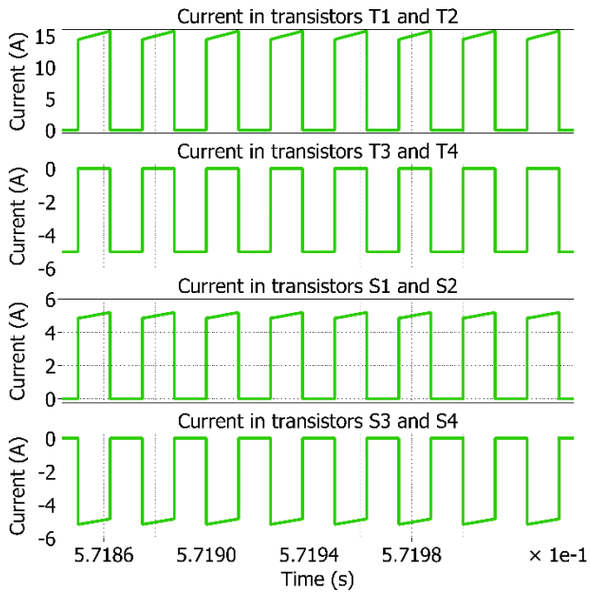
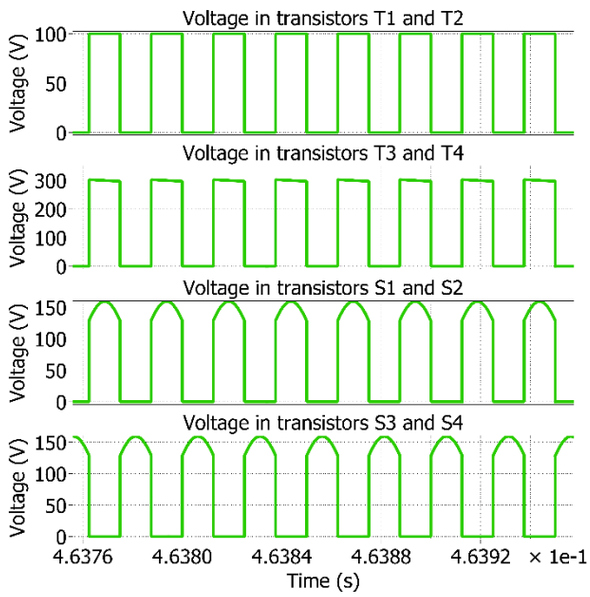
In this work, for the switches designated with the letter "T", the semiconductor device CMF10120D was selected, while for the switches designated with the letter "S", the semiconductor device IRF640N was chosen.

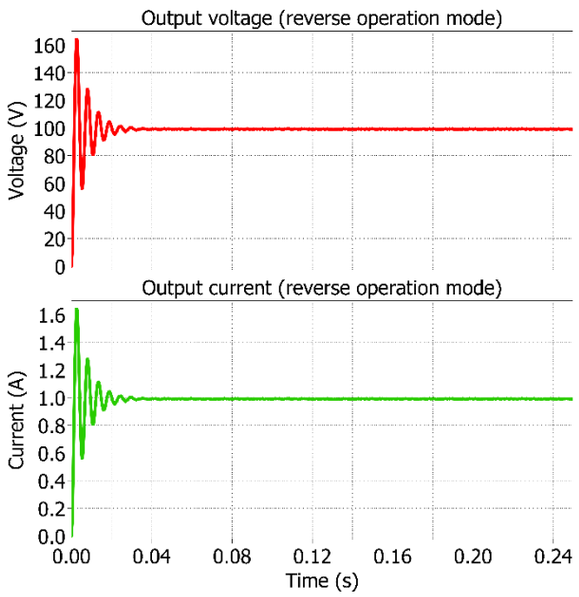


Graphic 3 Simulation results of currents of transistors T1-T4 and S1-S4, as a variation of time
Source: Own elaboration



Graphic 4 Simulation results of voltages of transistors T1-T4 and S1-S4, as a variation of time
Source: Own elaboration

For the case of the reverse operation of the proposed converter, the same duty cycle was used (D_1 =0.32), but the 100 V input source was eliminated and replaced by a 100 Ω power resistor, and the 5.65 Ω was replaced by a 48 V constant voltage source. With the control method by complementary PWMs it is achieved that, for the same duty cycle, the converter is able to operate in two operating directions, as shown in Graphic 5 that prove that can be able to work in discharge mode; Graphic 5 shows the output voltage and current in the resistor of 100 Ω, that is located in the input of the converter.



Graphic 5 Simulation results of the output voltage and current of converter operating in the reverse mode. Source:
Source: Own elaboration

Conclusions

In this work, a bidirectional dc-dc converter for charging and discharging applications of ESS systems (e.g. batteries and SCs) was presented. This converter was designed with an approach based on cascading two dc-dc converters. The first one consisted of an isolated half-bridge dc-dc converter with current doubler and the second one of a two-branch stepped parallel bidirectional. Both converters were driven by complementary PWM modulation, where in the first converter a variable duty cycle was used and in the second a fixed 50% duty cycle. The simulation results and the approach used demonstrated that the proposed converter can stabilize the operating voltage and current during the charging and discharging process management of ESS-based applications (e.g. batteries and SCs).

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In addition, an effective voltage and current ripple of 0.04% was achieved. This results in a positive impact on the lifetime of ESS systems. Finally, the approach used leads to an easy and practical implementation of the proposed converter in interconnection applications of two power sources with high voltage ratios (e.g. ESS systems and RESs). The latter, due to the implicit advantages offered by the galvanic isolation of the first converter used in the cascade connection.

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