# A DC-DC Converter with Capability to Support the Voltage Balance of DC Bipolar Microgrids

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*Abstract*—**Bipolar DC microgrids are now starting to become an interesting solution for power distribution. Although presenting several advantages over DC unipolar microgrids, bipolar DC has the intrinsic problem of voltage unbalance that may appear depending on the converter topology and load sharing. Therefore, this paper presents a new DC-DC converter topology that can be used with renewable energy sources and has the capability to simultaneously ensure the bipolar microgrid voltage balance. The operation of the proposed topology together with its characteristics is described. A theoretical study of this converter will also be presented, complemented by a set of results from computer simulations. To support these simulations, results from a laboratory prototype will also be displayed. The voltage balance capability of the converter will be checked experimentally.**

*Index Terms*—**DC Microgrid, Bipolar, DC-DC Power Converters, Topology.**

## I. INTRODUCTION

With the increased introduction of renewable energy sources and storage systems, the use of microgrids started to become more and more appealing. Indeed, microgrids depart from the classical paradigm represented by an electric grid with few powerful power production plants [1-3]. Instead microgrids are characterized by a localized and distributed power generation. In this way, for many installations it is possible to obtain an efficient, low-cost, local resiliency and clean energy. There are several types of microgrids AC, DC or hybrid. Compared to AC, small local DC microgrids started to become advantageous [4-6]. They provide many advantages over AC microgrids, such as, reliable power and higher conversion efficiency. On the other hand, although the unipolar DC microgrid is the most used, the bipolar DC with symmetrical voltages started to become an interesting alternative [6-8]. This configuration presents several advantages over the unipolar configuration, namely regarding the higher efficiency and higher power quality. However, due to the presence of two poles, unbalanced loads between the poles, and generators that may be connected to only one pole, bipolar DC microgrids could present the issue of the voltage balance between poles.

Voltage balancing between the poles in the bipolar DC microgrids can be achieved in several ways. One strategy is using extra power electronic converters designated as Voltage Balancers. These devices are used in a bipolar DC microgrid with unbalanced unipolar loads and generators originating unbalanced power transfer and therefore voltage unbalances. In this way voltage balancers will transfer the energy from one pole to the other in order to balance the microgrid [8-11]. Therefore, voltage balancers must be based in reversible power flow electronic converters.

Another approach is through the use of power converter topologies, associated to renewable generators, allowing energy transmission to both poles. Generators like photovoltaic and fuel cells require DC/DC converters to connect to electrical networks. Due to the voltage level of the photovoltaic panels and/or fuel cells, typically a DC/DC converter with Boost characteristics is used [12-14]. However, the well-known Boost converter presents low voltage gains (considering a practical converter with losses) leading to the development of high gain DC-DC boost converters. In this way, several converters with extended voltage gains have been proposed [15-20]. However, most high-gain boost converters are not suited to connect to both poles of the bipolar DC microgrid, since in this case a converter with bipolar output is required. Consequently, several high-gain bipolar output boost converters have been proposed [21-29]. Besides the capability to transfer power to both DC poles, in order to ensure the voltage balance of the poles in case of unbalanced loads, converters should transfer most of the energy to the pole with lower voltage. Under this context, in [30] a quasi-Z based converter with high voltage gain was proposed having the capability to support the voltage balance of the DC poles through the

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injection of the energy to the pole with lower voltage. This quasi-Z converter needs only a single active switch. However, it requires a high number of passive components.

This paper proposes a new DC-DC converter topology specially designed to support bipolar DC microgrids. In the case of DC poles voltage unbalance this converter will allow to transfer energy to the pole with lower voltage. Moreover, it is also characterized by high voltage gains. Besides, this topology was fit to reduce the passive component count.

## II. PROPOSED DC-DC CONVERTER TOPOLOGY

Typically DC-DC converters used to connect renewable generators to DC microgrids are characterized by single input and single output. However, in the case of bipolar DC microgrids this type of DC-DC converters can contribute for the bipolar voltage unbalance, as they can supply only one DC pole. A new DC-DC converter topology to be used with renewable generators is proposed to transfer energy to both poles of bipolar DC-DC networks. The detailed power circuit of this topology is presented in Fig. 1. This topology presents a high voltage gain and requires two switches, one inductor and two capacitors.

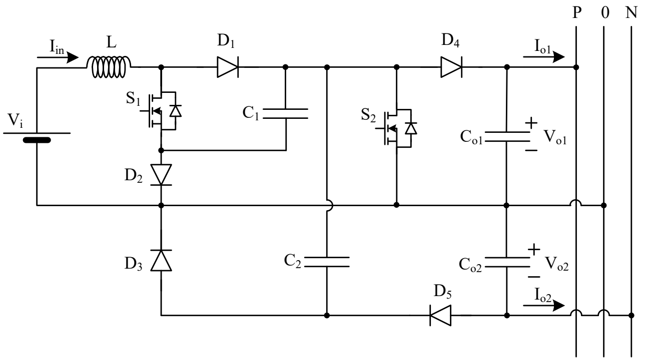


Fig. 1. Detailed power circuit of the DC-DC converter to be used in bipolar DC microgrids.

Considering the converter is sized for operation in the continuous conduction mode (CCM), the converter shows only two operating modes. Being the converter switches $S_1$, $S_2$ synchronized (the ON or OFF state of $S_2$ equals the same state of $S_1$) the two operation modes depend on the $S_1$ state, as hereafter described:

- During the switches ON state interval the energy is transferred from the input DC voltage source and capacitor $C_1$ to the inductor L. If the absolute value of the negative pole voltage is equal or lower than the positive pole $C_2$ voltage, then the energy stored in capacitor $C_2$ will be transferred to the negative pole capacitor.
- Regarding the time interval in which both switches are OFF the energy stored in the inductor L is now transferred to the capacitors $C_1$, $C_2$ and then to $C_3$, if the absolute voltage of positive pole is equal or lower than the negative pole the capacitor $C_1$, $C_2$ voltages. Otherwise, if the absolute voltage of positive pole is higher than the capacitor $C_1$, $C_2$ voltages, the inductor will discharge its energy to $C_1$, $C_2$ capacitors. In the next period $C_2$ will transfer energy to the negative pole capacitor.

The behaviour of the proposed topology can also be analysed through the voltages and currents waveforms that are presented in Fig. 2. These waveforms are associated to the current in the inductor and voltages across the power semiconductors. It is possible to verify that the maximum voltage across the diodes and switches are nearly half of the total output converter voltage (sum of $V_{C3}$ and $V_{C4}$). The input current of the converter in CCM does not present discontinuities, which makes the proposed topology highly indicated to photovoltaic generators and fuel cells.

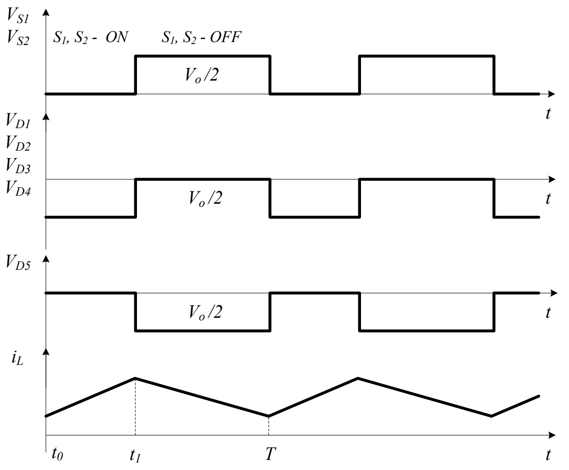


Fig. 2. Typical voltages and currents waveforms associated to the power converter circuit of Fig. 1 (being $i_L = I_{in}$).

## III. OPERATING PRINCIPLE AND ANALYSIS

The analysis of the converter will be carried out considering that the converter operates in continuous conduction mode and steady state behaviour has been reached.

To obtain the input-output voltage gain of the converter in steady-state, the principle of inductor volt-second balance and capacitor amp-second balance are used. It is also considered that both switches are ideal and switch at the same time. The application of the above principles returns the following expressions of the inductor average voltage and capacitor $C_1$ average current:

$$\frac{1}{T}\int_0^T v_L dt = \frac{1}{T}\left[\int_0^{t_1}(V_i - v_{C_1})dt + \int_{t_1}^{T}(V_i + v_{C_1})dt\right] = 0 \tag{1}$$

$$I_{C1} = 0 \Rightarrow I_{C1} = \frac{1}{T}\int_0^T v_{C1} dt = \frac{1}{T}\left(\int_0^{t1} v_{C1} dt + \int_{t1}^{T} v_{C1} dt\right) = 0 \tag{2}$$

From equations (1) and (2), eq. (3) is obtained:

$$\begin{cases} t_1\left(V_i + V_{C_1}\right) + (T - t_1)\left(V_i - V_{C_1}\right) = 0 \\ t_1 V_{C_1} - (T - t_1) V_{C_1} = 0 \end{cases} \tag{3}$$

Considering now the duty cycle δ, associated with both switches, defined as δ=($t_1$/T), the average value of the $C_1$ capacitor voltage $V_{C1}$ is written as (4).

$$V_{C_1} = \frac{t_1}{(T-t_1)^2 - t_1^2} V_i = \frac{\delta}{1-2\delta} V \tag{4}$$

Using (4) in (1) and (2), the average value of the output capacitor voltages are written as in (5). These capacitor voltages are also the voltages of the DC microgrid poles:

$$V_{o1} = V_{o2} = \frac{1}{1-2\delta} V_i \tag{5}$$

The static input-output voltage gain of the proposed converter can be obtained from the sum of the output capacitor voltages, being expressed by the following expression:

$$V_o = V_{o1} + V_{o2} = \frac{2}{1-2\delta} V_i \tag{6}$$

As capacitors $C_2$ and $C_{o2}$ are connected through switch $S_2$, the final charging voltage can be estimated considering capacitor charge conservation ($Q_2 + Q_{o2} = Q_{C_2\|C_{o2}}$) and assuming a voltage unbalance of -ΔV in capacitor $C_{o2}$. The parallel voltage is estimated as in (7), where it can be seen that the capacitor $C_{o2}$ voltage is increased.

$$\begin{aligned} &C_2 V_{C_2} + C_{o2}\left(V_{C_2} - \Delta V\right) = \left(C_2 + C_{o2}\right) V_{o2} \Rightarrow \\ &V_{o2} = V_{C_2} - \frac{C_4}{C_2 + C_4} \Delta V \end{aligned} \tag{7}$$

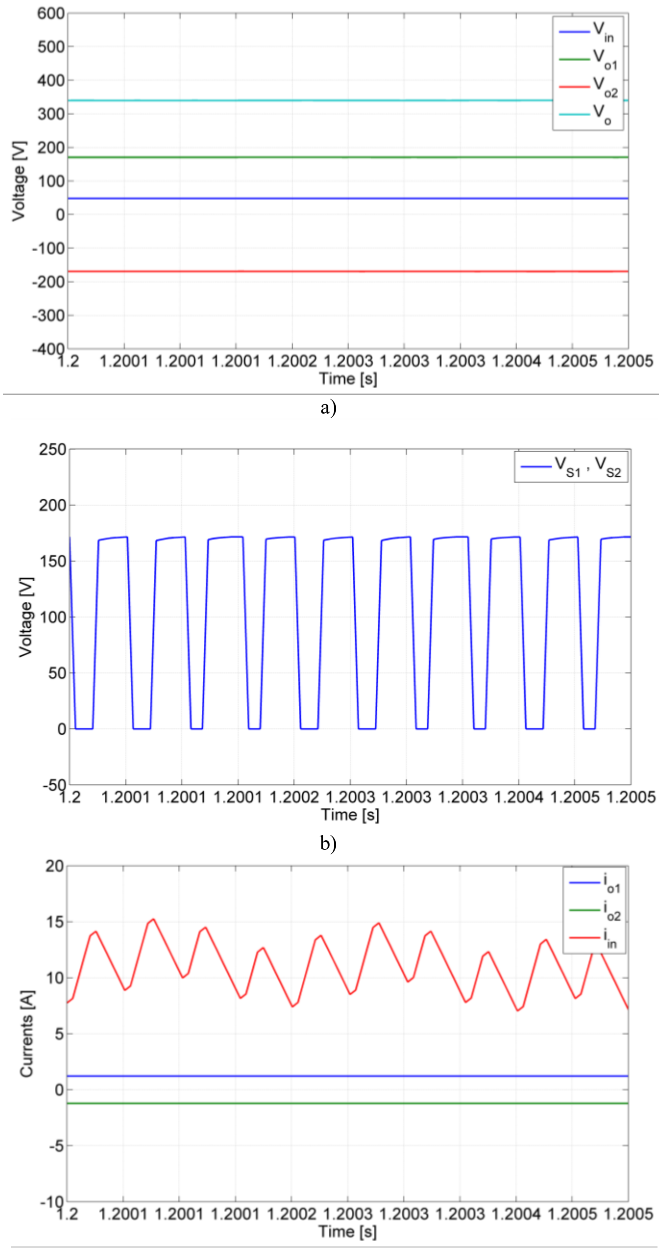
The power losses of this charging process are small, being estimated in (8) using the balance of initial energy and final energy of capacitors. It can be concluded that the power losses are proportional to the square of the voltage unbalance -ΔV, which is a small fraction of the output voltage.

$$P_{loss} = \frac{1}{f_s}\left[\frac{1}{2}\left(\frac{C_2 C_{o2}}{C_2 + C_{o2}}\right)\Delta V^2\right] \underset{C_2 << C_{o2}}{\approx} \frac{C_2 \Delta V^2}{2 f_s} \tag{8}$$

## IV. SIMULATION RESULTS

The proposed converter with a bipolar output designed for a bipolar DC microgrid was tested using computer simulations. The proposed converter component values are L=600 μH, $C_1$=$C_2$=48 μF and $C_3$=$C_4$=470 μF. The converter is supplied by a DC voltage source of 48 V and the output of the bipolar DC microgrid was considered to be ±170 V. The duty cycle was controlled to output ±170 V from 48V with switches operating at 20 kHz. The initial load was considered to equal 140 Ω in each pole.

The behaviour of the converter is tested in CCM and steady-state. The input-output voltages and balance of the output voltages are presented in Fig. 3 a). The voltage gain is close to 7. The voltages across the controlled power semiconductors are presented in Fig. 3 b). The input and output currents of the converter are shown in Fig. 3 c). From this last figure it is seen that the output currents are balanced, as expected, while the input current is in CCM and presents some ripples.



a)

b)

c)

Fig. 3. Simulation results of the proposed converter with a dual output a) input and output voltages b) controlled power semiconductors voltage c) input and output currents.

The proposed converter capability to support the bipolar DC microgrid voltages was evaluated using a transient test. Prior to the transient test, the microgrid was balanced. After t=1.2 ms the load of the negative pole changes to 100 Ω is presented in Fig 4. This figure shows that the input current increases while only the output current associated to the negative pole increases. The current in the positive pole $I_{o1}$ stays constant, meaning the positive output voltage is not affected by the unbalance in the negative pole load. Thus, the converter is transferring more energy and in an unbalanced way to support the DC microgrid unbalance.

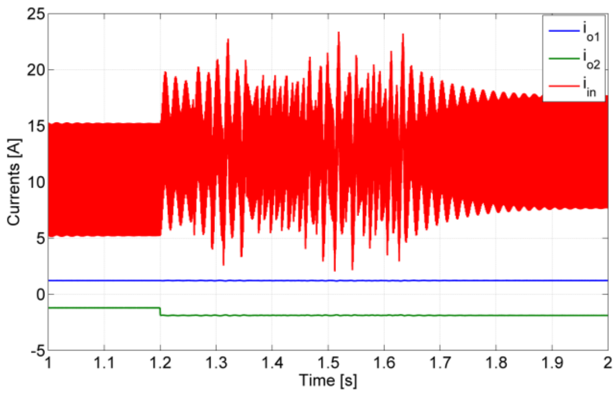


Fig. 4. Simulation results of the proposed converter with a dual output in transient mode and with a change of the load of the negative pole.

## V. CONCLUSIONS

This paper focused on the importance of balancing bipolar DC microgrids output voltages using suitable DC-DC converters connecting renewable generators. In this context, a new DC-DC converter topology was presented, which can be used for power conversion from photovoltaic panels or fuel cells. The converter is characterized by a single input and a dual output to connect to the positive, neutral and negative poles of the DC microgrid. The proposed topology is also characterized by using two synchronously controlled switches and a high input-output voltage gain. The operation and analysis of the proposed topology were presented in this work. The characteristics and capability to balance bipolar DC microgrids was verified through simulations and experimental results. Results show that, in the case of an unbalance in the DC microgrid, the converter will supply the extra input power to the pole with higher power load.

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