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Topological Derivation of DC-DC Multiplier Converters

J. C. Rosas-Caro, J. C. Mayo-Maldonado, A. Gonzalez-Rodriguez, E. N. Salas-Cabrera, M. Gómez-García, O. Ruiz-Martinez, R. Castillo-Ibarra and R. Salas-Cabrera,

***Abstract*— This paper extends the traditional family of PWM DC-DC converters. By employing voltage capacitor-multipliers, converters provide high voltage gains. The capacitor multiplier of each converter is driven by the same transistor of the well-known basic topology. The main features of these new converters are: *(i)* high-voltage gain without extreme duty cycles and transformer-less. Therefore, high switching frequency is allowed; *(ii)* low voltage stress in switching devices; and *(iii)* more output levels can be added without modifying the main circuit. These features are highly desirable in some applications such as renewable energy generation systems.**

***Index Terms*— DC-DC power conversion, power conversion, pulse width modulated power converters, boost converter.**

I. Introduction

High voltage gain is difficult to achieve with traditional topologies of DC-DC converters because the extreme duty cycles, transformer requirement limitations, switching frequency and systems size [1-5].

For green energy generation, the low voltage from a renewable energy source needs to be boosted for feeding a grid connected inverter. A transformer with a large voltage gain is undesirable because it enhances the transformer non-idealities [4]. To reduce the DC-DC converters' size, the use of high switching frequencies results in small inductors and capacitors with equivalent current and voltage ripples [1-5]. This is the motivation for using several hundred of kilohertz [1].

The natural switching delay in actual switches limits the switching frequency. In order to avoid extreme duty ratios either too small or too big; transformers are usually employed. However, the transformer's losses limit the switching frequency also; along with the development of high speed MOSFETs the switching frequency limitation becomes a transformer's issue [1-4].

The use of the diode clamped multilevel converters for renewable energy micro generation brings the promise to build compact converters with small power MOSFETS, with a minimum ESR and transformer-less connected to the utility grid. There exists the challenge to couple the low DC voltage from the renewable energy source to the high DC-link voltage of the multilevel converter. It is highly desirable the DC-link to be self-balanced.

This work proposes a family of DC-DC multiplier converters as an extension of the traditional topologies hybridized with capacitor-multipliers. The proposed structures achieve high voltage gain without extreme duty cycles and transformer-less, which allow high switching frequency, low voltage stress in switching devices, modular structures, and more output levels can be added without modifying the main circuit.

Some multiplier converters have been proposed and studied in the literature [3-5], the focus of this paper are converters which can be seen such a traditional topology extended with the traditional diode-capacitor multiplier some converters such as the buck-boost, Cuk and SEPIC multiplier converters are totally new.

II. The multiplier boost converter

Fig. 1(a) shows the traditional boost converter; Fig. 1(b) shows the 2x *multiplier boost converter MBC*, initially proposed in [5] as a multilevel boost converter combines a boost converter with a capacitor multiplier. The name multiplier is used in this work instead of multilevel for avoiding confusion with the DC-AC converter topology.

Fig. 1(c) and Fig. 1(d) indicates the devices utilization when the switch is on and off respectively.

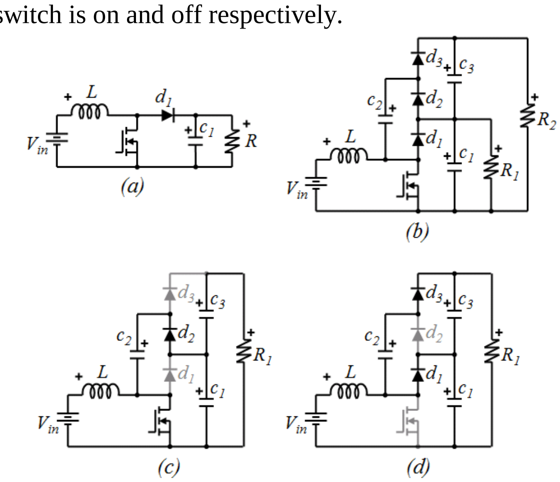

Fig. 1. (a) boost converter, (b) *2x* MBC, (c) *2x* MBC when the switch is on, (d) *2x* MBC when the switch is off.

Authors are with the Instituto Tecnologico de Ciudad Madero, Av. 1o Mayo S/N Col. Los Mangos Ciudad Madero, Mexico (email rosascarojc@itcm.edu.mx).

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From the equivalent circuits shown in Fig. 1(c) and Fig. 1(b), and by using the small ripple approximation [6], the average voltage in the inductor during one switching cycle can be expressed as:

$$\langle v_L(t)\rangle = \frac{1}{T}\left[t_{on}V_{in} + t_{off}(V_{in} - V_{C1})\right] \qquad (1)$$

Where t_{on} is the time interval when the switch is on and the converter behaves such as the equivalent circuit Fig. 1(c), t_{off} is the time interval when the switch is off and the converter behaves as the equivalent circuit shown in Fig. 1(d), T is the total switching period equal to $t_{on}+t_{off}$.

The first part of (1): $t_{on}V_{in}$ represents the volts per-second in the inductor during the time when the switch is *on* while the second part $t_{off}(V_{in}-V_{C1})$, represents the volts per-second in the inductor during the time when the switch is *off* and the diode is *on*, defining the duty cycle D as the relation of t_{on} over T, (1) can be written as:

$$\langle v_L(t)\rangle = DV_{in} + (1-D)(V_{in} - V_{C1}) \qquad (2)$$

Considering the operation in an equilibrium point, this average voltage should equal to zero during one switching state and then:

$$\begin{aligned} &DV_{in} + (1-D)(V_{in} - V_{C1}) = 0 \\ &DV_{in} + (1-D)V_{in} - (1-D)V_{C1} = 0 \\ &V_{in} = (1-D)V_{C1} \\ &\frac{V_{C1}}{V_{in}} = \frac{1}{1-D} \end{aligned} \qquad (3)$$

Equation (3) expresses the relation between V_{C1} and V_{in}, which is (as expected) the same relation between output and input voltage in the boost converter, the interesting behavior is observed in Fig. 1(c) when the switch is on, if V_{C2} is lower than V_{C1}, then c_1 transfer charge c_2 by closing d_2 and when the switch opens, the inductor current closes d_1 and allows c_2 to charge c_3 by closing d_2. Evidently the output voltage in Fig. 1(b) is twice of the voltage expressed in (3). The conventional capacitor multiplier is used to get a high voltage gain in the AC-DC conversion, see Fig. 2(a).

As shown in Fig. 2, in the same way as the AC-DC capacitor multiplier can be extended either in the positive or in the negative side, the MBC can be extended in both sides. The capacitor multiplier in the MBC make all capacitors to be charged to the same voltage, this allows the load to be connected as R_2 in Fig. 1(b), or as R_1, or even several loads can be connected in the different output capacitors with self voltage balancing in all output capacitors, a more detailed analysis of this converter can be found in [5].

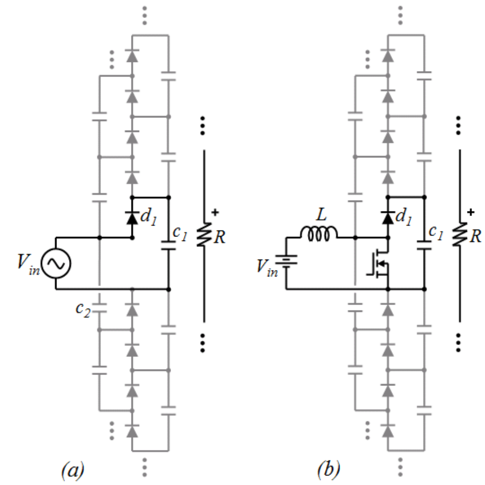

Fig. 2. (a) conventional capacitor multiplier, (b) *Nx* MBC.

III. THE MULTIPLIER BUCK-BOOST CONVERTER

Fig. 3(a) shows the traditional buck-boost converter; Fig. 3(b) shows the 2x *multiplier buck-boost converter MBBC*,

Fig. 3(c) and Fig. 3(d) show the devices utilization when the switch is on and off respectively.

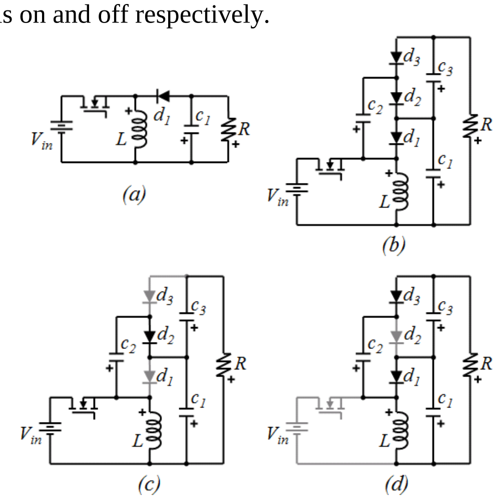

Fig. 3. (a) buck-boost converter, (b) *2x* MBBC, (c) *2x* MBBC when the switch is on, (d) *2x* MBBC when the switch is off.

Assuming the small ripple approximation and the duty cycle defined in the previus analysis, $D=t_{on}/T$, the average voltage in the inductor during one switching cycle, can be expressed as:

$$\langle v_L(t)\rangle = DV_{in} - (1-D)V_{C1} \qquad (4)$$

Considering the steady state operation, this voltage should be equal to zero and then:

$$\begin{aligned} &DV_{in} - (1-D)V_{C1} = 0 \\ &DV_{in} = (1-D)V_{C1} \\ &\frac{V_{C1}}{V_{in}} = \frac{D}{1-D} \end{aligned} \qquad (5)$$

The voltage in c_1 is as expected the same as in the conventional buck-boost converter, the voltage multiplier in

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this case charge c_2 with $V_{in}+V_{C1}$ throw d_2 when the switch is on, see Fig. 3(c), and it charges c_3 with V_{C2} throw d_3 when the switch is off, see Fig. 3(d). In steady state operation the voltage in both capacitors c_2 and c_3 with the small ripple approximation can be expressed as:

$$V_{C2} = V_{C3} = V_{in}\left(1+\frac{D}{1-D}\right) = V_{in}\frac{1}{1-D} \qquad (6)$$

And finally the voltage in the output resistor in Fig. 3(b) is the sum of V_{C1} and V_{C3}, and it can be expressed as:

$$V_R = V_{in}\left(\frac{1}{1-D}+\frac{D}{1-D}\right) = V_{in}\frac{1+D}{1-D} \qquad (7)$$

The MBBC has a more similar behavior to the conventional capacitor multiplier; see Fig. 2(a) where c_1 and c_2 are charged to the input voltage while all other capacitors are charged to twice of the input voltage. In the MBBC c_1 is charged to the voltage expressed in (5) while c_2 and c_3 are charged to the voltage expressed in (6) which is higher, see Fig. 4 where the voltage in c_1, all other capacitors, the output voltage in the *2x* MBBC and the output voltage in the *2x* MBC (only for comparison purposes.

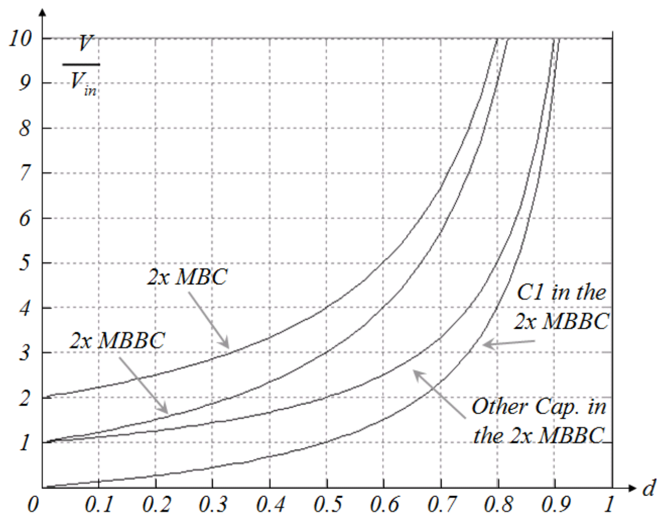

Fig. 4. Voltages again duty cycle.

Important conclusions can be found from Fig. 4 and the developed equations, the multiplier buck-boost converter lost an important characteristic of the conventional buck-boost converter, the minimum achievable gain is one instead of zero, and an interesting behavior is found, the gain-gap around the duty cycle 0.5 in the *2x* MBBC is exactly the same as in the *2x* MBC.

As it has been mentioned, increasing the switching frequency of the converter is easier when the converter is designed for working with a duty cycle D around 0.5, that is why is important to know which converter have a higher gain-gap with the same duty-cycle-gap around $D=0.5$. If the duty cycle is limited for example from 0.3 to 0.7 then *2x* MBBC would have a gain from 1.85 to 5.66, while and the *2x* MBC would have a gain from 2.85 to 6.66, both of them have a gain-gap of 3.81.

Fig. 3 shows the multilevel extension of the buck-boost converter in the negative side, but the diode-capacitor multiplier can be extended in the positive side too. Fig. 5 shows the diode-capacitor multiplier extension in both sides. As it can be seen from the analysis, capacitors c_{1n} and c_{1p} in Fig. 5(c) has a voltage gain given by (5) and all other capacitors in Fig. 5(c) have a voltage given by (6).

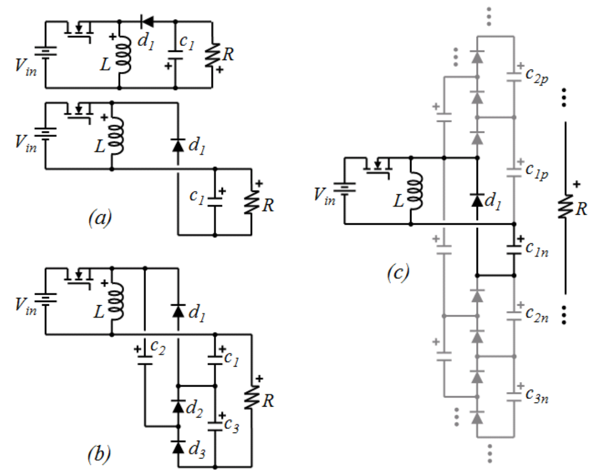

Fig. 5. (a) buck-boost converter (b) *2x* MBBC (c) *Nx* MBBC.

IV. The Multiplier Cuk Converter

Fig. 7 (a) shows the traditional Cuk converter, Fig. 7(b) shows the firs multiplier extension of the Cuk converter and Fig. 7(c) and Fig. 7(d) shows the devices utilization when the switch is on and off respectively.

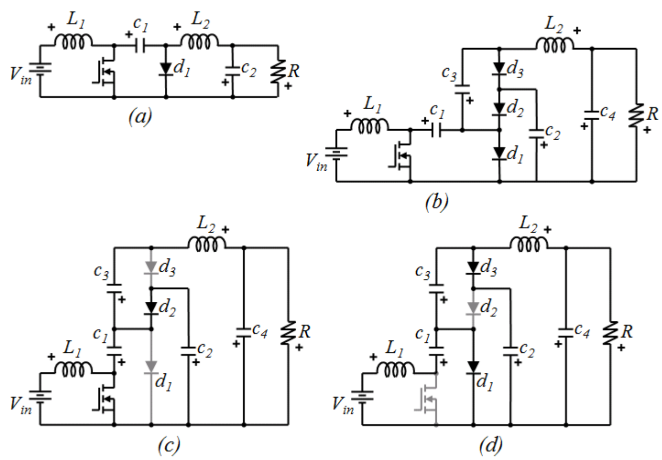

Fig. 7. multiplier Cuk converter.

Assuming the small ripple approximation and the duty cycle defined in the previus analysis, $D=t_{on}/T$, the average voltage in L_1 during one switching cycle, can be expressed as:

$$\langle v_{L1}(t)\rangle = DV_{in} + (1-D)(V_{in} - V_{C1}) \qquad (8)$$

Considering the operation in steady state, this voltage

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should be equal zero and then:

$$DV_{in} + (1-D)(V_{in} - V_{C1}) = 0$$
$$DV_{in} + (1-D)V_{in} - (1-D)V_{C1} = 0$$
$$V_{in} - (1-D)V_{C1} = 0$$
$$\frac{V_{C1}}{V_{in}} = \frac{1}{1-D} \tag{9}$$

In steady state, the voltage in c_1 is as expected the same as in the conventional Cuk converter, but, when the switch is on the voltage multiplier in this case charge c_2 with V_{C1} throw d_2, see Fig. 7(c), while c_1 and c_3 feed the output low pas filter in series. When the switch is off, c_3 is charged until their voltage gets V_{C2} when the switch is off, after that, boot capacitors feed the load in parallel. In this converter, as in the multiplier boost converter, all capacitors in the diode-capacitor multiplier are charged to the same voltage.

The average voltage in L_2 during one switching cycle, can be expressed as (10), remember V_{C2}=V_{C3} due the diode-capacitor multiplier operation.

$$\langle v_{L2}(t) \rangle = D(V_{C1} + V_{C3} - V_{C4}) + (1-D)(V_{C2} - V_{C4}) \tag{10}$$

As all capacitors in the diode-capacitor multiplier are charged to the same voltage which can be called V_{CX}, then:

$$\langle v_{L2}(t) \rangle = D(2V_{CX} - V_{C4}) + (1-D)(V_{CX} - V_{C4}) \tag{11}$$

Considering the operation in steady state, this voltage should be equal to zero and then:

$$D(2V_{CX} - V_{C4}) + (1-D)(V_{CX} - V_{C4}) = 0$$
$$2DV_{CX} - DV_{C4} + (1-D)V_{CX} - (1-D)V_{C4} = 0$$
$$(D+1)V_{CX} - V_{C4} = 0$$
$$V_{C4} = (D+1)V_{CX} \tag{12}$$

V_{CX} can be expressed as (9) then:

$$V_{C4} = (D+1)V_{in}\frac{1}{1-D} = V_{in}\frac{1+D}{1-D} \tag{13}$$

As in the traditional Cuk converter, a low-pass filter is located at the output side, this is necessary because the voltage is discontinuous, when the switch is on, the voltage in the input side of the LC filter is V_{C1}+V_{C3}, see Fig. 7, but when the switch is off the voltage is V_{C2}=V_{C3}, Fig. 8, shows another extension with two more capacitors in the voltage multiplier.

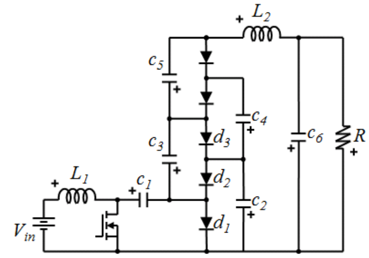

Fig. 8. extension of the multiplier Cuk converter.

In Fig. (7)b the traditional Cuk converter was complemented with *2* diodes and *2* capacitors, Fig. 8 shows the Cuk converter complemented with *3* diodes and *3* capacitores, if *N* diodes and N capacitors are added, the voltage in L_2 would be:

$$\langle v_{L2}(t) \rangle = D(NV_{CX} - V_{Cout}) + (1-D)((N-1)V_{CX} - V_{Cout}) \tag{14}$$

Considering the operation in steady state, the voltage in the output capacitor C_{out} can be found by using the former procedure and expressed as:

$$V_{Cout} = V_{in}\frac{N-1+D}{1-D} \tag{15}$$

In the multiplier Cuk converter, Fig. 7(b) and Fig. 8 the output inductor is smaller than in a traditional Cuk converter with the same output voltage because the voltage in the input side of the LC filter only changes one level (one capacitors voltage) during the switching operation.

V. Other Topologies

From Fig. 8 it can be seen that the output can be connected to c_2 or c_4 and as the voltage in the series connected capacitors is continuous, no low-pass filter is needed, see Fig. 9.

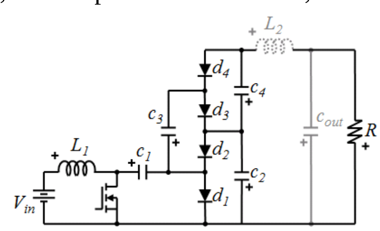

Fig. 9. Single inductor multiplier Cuk converter.

This converter can be called single inductor multiplier Cuk converter, and actually was initially proposed in [4] as a *three switches high voltage converter*. As all multiplier converters presented here can be extended by adding diodes and capacitors, in the either in the positive or in the negative side, see Fig. 10.

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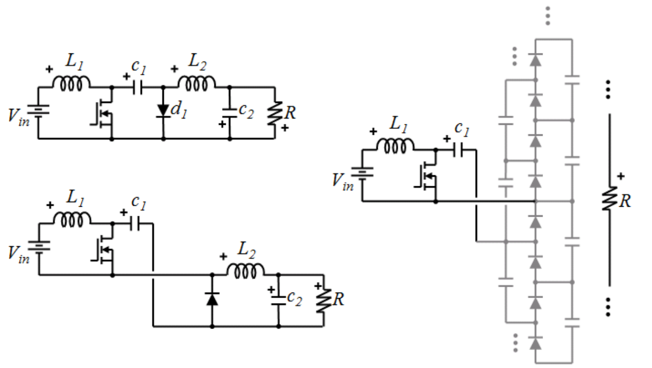
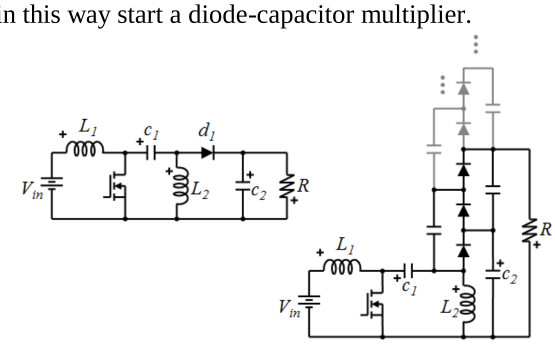


(a) (b)

Fig. 10. (a) traditional Cuk converter (b) positive and negative extension of the voltage multiplier.

Fig. 11 shows the multiplier SEPIC converter, the analysis used on former section can be used for analyzing the SEPIC multiplier converter.

All analyzed converters share a basic behavior; all of them have a diode which is open and closed by the converters operation, this diode is turning off by a reverse bias voltage which can be used to charge another capacitor throw a diode, and in this way start a diode-capacitor multiplier.



(a) (b)

Fig. 10. (a) traditional SEPIC converter (b) multiplier SEPIC conerter.

VI. Conclusion

A family of DC-DC multiplier converters was proposed as an extension of the traditional topologies hybridized with capacitors-multipliers. A couple of those converters have been independently proposed and analyzed in [4-5] and other topologies in the family are totally new.

The proposed structures achieve high voltage gain without extreme duty cycles and transformer-less, which allow high switching frequency, t low voltage stress in switching devices, modular structures, and more output levels can be added without modifying the main circuit. These features are highly desirable in applications such as PV and fuel cell generation systems. All proposed topologies were simulated to confirm the principle of operation, but since the principle of operation is very simple and available in the literature [4-6] no deeply analysis was shown.

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