

# Study of Bi-Directional Buck-Boost Converter Topologies for Application in Electrical Vehicle Motor Drives

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**Abstract** - The use of a bi-directional dc-dc converter in motor drives devoted to EVs allows a suitable control of both motoring and regenerative braking operations. In particular, during motoring operations of a battery-fed dc motor drive, a dc-dc converter is to be used to adjust the motor current in order to follow the torque reference signal. On the other hand, a bi-directional arrangement of the converter is needed for the reversal of the power flow, in order to recover the vehicle kinetic energy in the battery by means of motor drive regenerative braking operations. This paper deals with the study and comparison of two bi-directional buck-boost converter topologies. Each of them allows stepping the battery voltage level either up or down, according to motor drive modes of operation. For each converter topology computer simulations of modes of operation are presented together with experimental test results.

## I. INTRODUCTION

The use of a bi-directional dc-dc converter in motor drives devoted to the propulsion of EVs allows suitable control of both motoring and regenerative braking operations [1], [2]. This paper deals with the study and comparison of bi-directional buck-boost converter topologies. Each of them allows stepping the battery voltage level either up or down, according to motor drive modes of operation.

The first chosen topology is derived directly from the traditional buck-boost scheme by introducing a dual switch-diode power module as shown in Fig. 1. The IGBTs  $S_1$  and  $S_2$  are never operated at the same time, being the switch  $S_2$  always off during motoring operation, whereas the switch  $S_1$  is kept off continuously whenever the regenerative braking operation is commanded. For the transition from  $S_1$  switching operation to  $S_2$  switching operation a delay blanking time between the gate signals of the two switches is used, in order to avoid a cross-conduction current through the converter output capacitor and the two switches.

The layout of the second topology being considered in this study is accomplished by means of the cascade of a step-down converter with a step-up one, as shown in Fig. 2. In motoring operation,  $S_1$  is switching whenever stepping-down of the battery level is needed, whereas  $S_2$  is operated

as a step-up switch while  $S_1$  is permanently in the on state. On the other hand,  $S_3$  and  $S_4$  are modulated in a similar manner but during braking operation.

The converter topology shown in Fig. 2 allows driving in a separate fashion a single switch for each particular condition of operation. In this way, precise regulation of the output voltage can be achieved, as the duty-cycle is allowed to range from 0 to 1 both in step-up and step-down modes of operation. A natural drawback of the buck-boost cascade form is that both switches and power diodes are duplicated with respect to the converter arrangement shown in Fig. 1.

Both the proposed converter topologies require one inductor and two electrolytic capacitors. However, it is shown later on that for a given current ripple the buck-boost cascade topology requires an inductor having reduced size in comparison with the size of the inductor needed in a conventional bi-directional buck-boost topology.

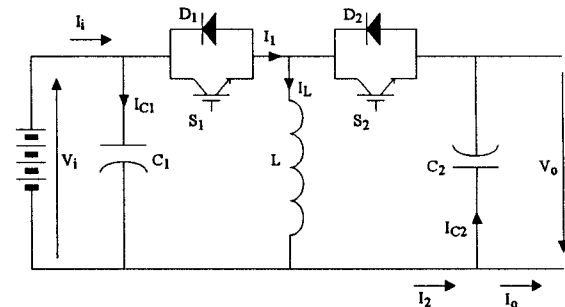


Fig. 1. Bi-directional buck-boost converter

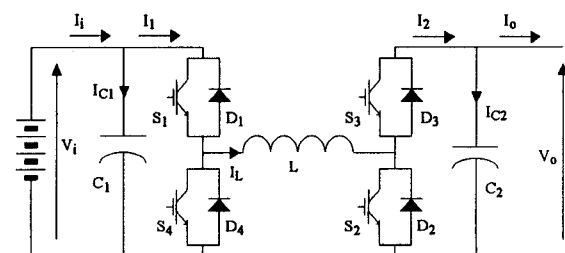


Fig. 2. Bi-directional buck-boost cascade converter

Each of the proposed converter topologies was early investigated by means of Matlab models to represent modes of operation. However, in order to base comparison on experimental results, two similar 20 kW water-cooled converter prototypes were constructed and tested by using a suitable battery-fed dc motor drive test rig. Each one of the converter prototypes was constructed by using third-generation IGBT power modules rated 1200 V, 200 A, ferrite core inductor rated 420  $\mu$ H, 80 A, input and output capacitors rated 5600  $\mu$ F, 450 V. IGBTs switching frequency is 15 kHz and converter control strategy is accomplished by means of an INTEL 80C196KC microcontroller.

## II. CONVERTER MODES OF OPERATION

### A. Bi-Directional Buck-Boost Converter

In motoring operation the buck-boost converter circuit states are shown in Figg. 3a and 3b respectively when the switch  $S_1$  is on or off. When the switch  $S_1$  is in conduction state, the battery and the output capacitor  $C_2$  supply energy respectively to the inductor  $L$  and to the machine load. When the switch  $S_1$  is off, the diode  $D_2$  is direct biased and the output capacitor  $C_2$  and the load receive energy from the inductor. Thereby, the voltage  $V_o$  at the output capacitor terminals can be regulated accordingly with the motor speed by adjusting the duty-cycle of the switch  $S_1$ .

Whenever a braking command is issued, the switch  $S_1$  is turned off and, after a fixed blanking time interval, the switch  $S_2$  is turned on to allow the reversal of the power flow. Thereafter, the switch  $S_2$  is operated at constant switching frequency and variable duty-cycle in order to keep at the desired value the braking current flowing in the battery. When the switch  $S_2$  is on, the battery receives energy from the capacitor  $C_1$  while braking energy is being stored in the inductor  $L$ . By turning off the switch  $S_2$  the battery and the capacitor  $C_1$  receive energy from the inductor  $L$ .

### B. Bi-Directional Buck-Boost Cascade Converter

In this converter arrangement only the switch  $S_1$  is operated to accomplish motoring operation with stepping down the battery voltage. The diode  $D_2$  is always reverse biased and  $D_3$  is direct biased along the entire period of operation. As shown in Figg. 4a and 4b, when the switch  $S_1$  is on the battery supplies energy to the inductor  $L$  and to the load, whereas with the switch  $S_1$  being in the off state the diode  $D_4$  is direct biased and the load receives energy from the inductor.

In motoring operation the step-up mode of operation is needed at the higher motor speeds. The switch  $S_1$  must be always on and  $S_2$  is operated with variable duty cycle

according to motor speed. The switches  $S_3$  and  $S_4$  are steadily off and the diode  $D_4$  is reverse biased.

Circuit states of the cascade converter in motoring step-up conduction mode are shown in Figg. 5a and 5b respectively when the  $S_2$  is on or off. When the switch  $S_2$  is on, the battery supplies energy to the inductor while the load receives energy from the capacitor  $C_2$ . As the switch  $S_2$  is off, the diode  $D_3$  is direct biased and load and output capacitor receive energy from the inductor.

Whenever a braking command is issued, the switch  $S_3$  is turned on just after a fixed blanking time interval to allow the reversal of the power flow. Thereafter two condition of braking operation can occur depending on the instantaneous voltage levels of both the battery and the dc motor e.m.f. If the motor e.m.f. is greater than the battery voltage, the converter operates as a step-down converter. Hence, the switch  $S_3$  is operated at constant switching frequency and variable duty-cycle, while  $S_1$ ,  $S_2$  and  $S_4$  are permanently off. The diode  $D_4$  is always reverse biased and  $D_1$  is direct biased along the entire switching period. As the e.m.f. value goes below the battery voltage, the converter operates in step-up condition. Then, the switch  $S_3$  is always on and the switch  $S_4$  is operated with variable duty cycle; the switches  $S_1$  and  $S_2$  are steadily off.

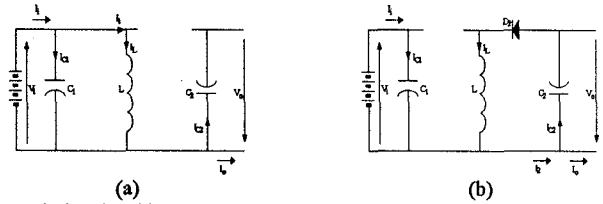


Fig. 3. Bi-directional buck-boost converter in motoring mode of operation: (a) switch on, (b) switch off

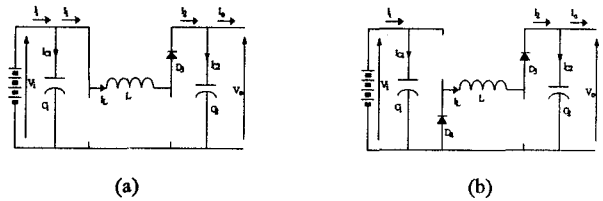


Fig. 4. Bi-directional buck-boost cascade converter in motoring step-down mode of operation: (a) switch on, (b) switch off

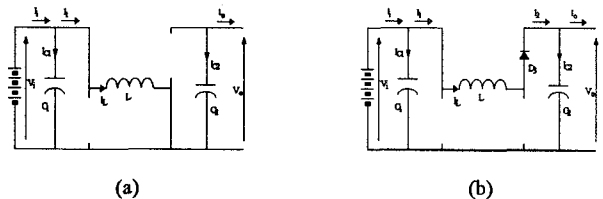


Fig. 5. Bi-directional buck-boost cascade converter in motoring step-up mode of operation: (a) switch on, (b) switch off

### III. COMPARISON BETWEEN THE PROPOSED TOPOLOGIES

In order to develop a comparison between the above discussed converter topologies, theoretical expressions of the currents flowing through the converter components were worked out. Plots of duty cycle, current ripple and rms value as function of the ratio  $V_o/V_i$  between the converter output and input voltages are shown in Fig. 6 through Fig. 12. These plots refer to converter operation assuming as reference input voltage  $V_i = 180\text{V}$ , reference output current  $I_o = 35\text{A}$ , switching frequency  $f_s = 15\text{kHz}$  and are based on the use of an inductor having  $L = 420\mu\text{H}$ .

If the duty cycle of the switch in the buck-boost converter is indicated as  $D_b$ , and  $D_{cd}$  and  $D_{cu}$  are the duty cycles of the working switch in the buck-boost cascade topology respectively during step-down and step-up mode of operation, the output voltage  $V_o$  can be calculated as:

$$V_o = \frac{D_b}{1-D_b} \cdot V_i \quad 0 < D_b < 1 \quad (1)$$

$$V_o = \frac{D_{cd}}{1-D_{cu}} \cdot V_i \quad \begin{cases} 0 < D_{cd} < 1 \text{ \& } D_{cu} = 1 \\ D_{cd} = 1 \text{ \& } 0 < D_{cu} < 1 \end{cases} \quad (2)$$

Consequently, the duty cycle expressions as function of voltage ratio  $V_o/V_i$  are:

$$D_b = \frac{V_o/V_i}{1+V_o/V_i} \quad 0 < D_b < 1 \quad (3)$$

$$D_{cd} = \frac{V_o}{V_i} (1-D_{cu}) \quad D_{cu} = 0; V_o < V_i \quad (4)$$

$$D_{cu} = 1 - \frac{D_{cd}}{V_o/V_i} \quad D_{cd} = 1; V_o > V_i \quad (5)$$

Fig. 6 shows that in the step-down mode of operation the duty cycle  $D_b$  of buck-boost topology is always lower than the duty cycle  $D_{cd}$  value required in buck-boost cascade topology. On the other hand, the  $D_b$  is always greater than  $D_{cu}$  in step-up conduction mode. This fact results in greater current ripple and rms value in a number of converter components as shown later on.

Full theoretical expressions of inductor current ripple, inductor, capacitors and power semiconductor components rms current are presented in the Appendix. Fig. 7 shows that the ripple of inductor current in p.u. respect to the output current is greater in buck-boost converter than in buck-boost cascade one. This difference is particularly remarkable when the output voltage level is close to the battery voltage value. Also, for a given value of the ratio  $V_o/V_i$ , the rms value of the inductor current is higher in bi-directional buck-boost topology.

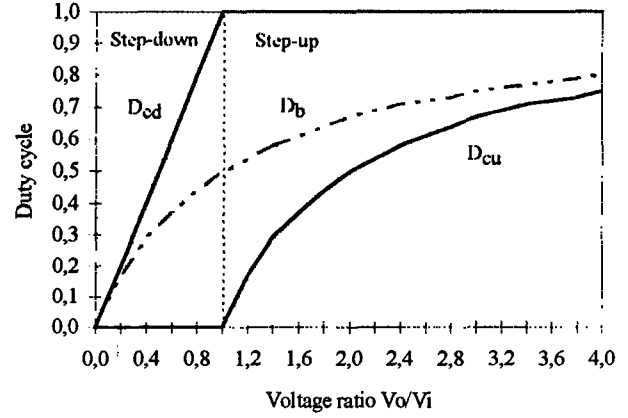


Fig. 6. Duty cycle versus  $V_o/V_i$  of buck-boost (dashed trace) and of buck-boost cascade (line trace)

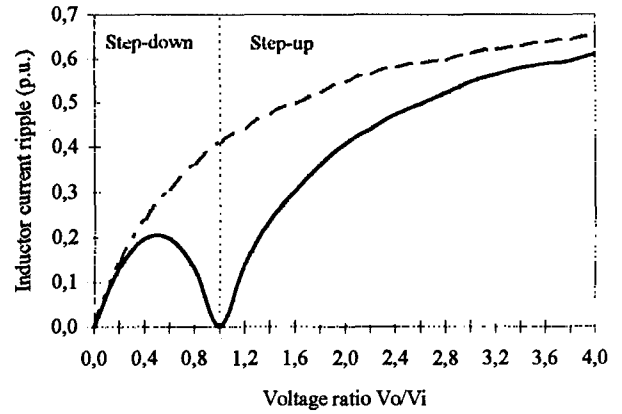


Fig. 7. Inductor current ripple versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

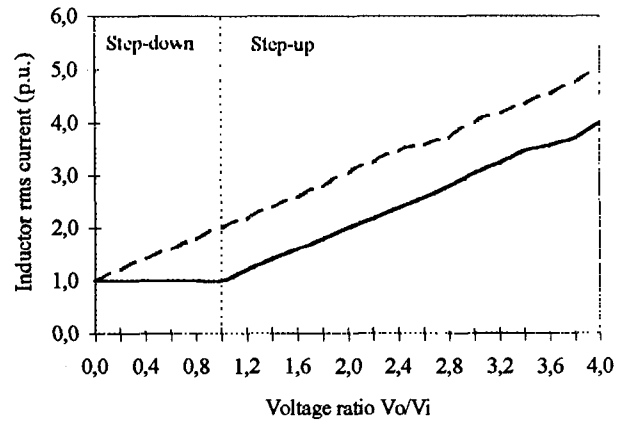


Fig. 8. Inductor rms current versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

Fig. 8 shows the p.u. value of inductor rms current ( $I_L$ ) as a function of the voltage ratio.

During step-down mode of operation, the inductor rms current of buck-boost cascade converter is nearly constant and equal to the output current value, as in any instant the inductor current is the output current too. On the contrary, in the step-up mode of operation the modulating switch being in the on state, the load is fed by the output capacitor  $C_2$  and the inductor  $L$  is connected in parallel to the input source. This results in inductor rms current which increases accordingly with the ratio  $V_o/V_i$ .

Concerning voltage ratios greater than 1, the buck-boost inductor current exceeds the buck-boost cascade inductor current of a quantity equal to the output current.

Hence, the inductor in the buck-boost configuration operates under higher electric and thermal stress, turning out in greater power losses and saturation of the ferrite core reached for a lower value of the voltage ratio  $V_o/V_i$ .

Fig. 9 and 10 show the current rms value respectively in the input and output capacitor  $C_1$  ( $I_{C1}$ ) and  $C_2$  ( $I_{C2}$ ) of both

the converter topologies being under investigation. The curves shown in Fig. 9 reveal that the input capacitor works in a similar manner in both the converters, and the rms current is always below the output current  $I_o$  along the entire ratio  $V_o/V_i$  range. On the other hand, the output capacitor is more stressed in buck-boost than in buck-boost cascade topology. As shown in Fig. 10, the output capacitor rms current is higher in the first configuration than in the second one of an average amount equal to the 1/3 of the output current. Besides at high values of the voltage ratio the output capacitor current results twice the output current  $I_o$ .

Fig. 11 and 12 show the rms current diagrams of the switch and the diode in switching mode of operation. It is again found that the buck-boost topology results in higher current stress on both switch and diode compared to buck-boost cascade. In detail, during step-up mode of operation, the switch rms current in the buck-boost configuration results nearly equal to the current in the second one added up  $I_o$ . Thus turning out in higher switching and conduction power losses in buck-boost converter.

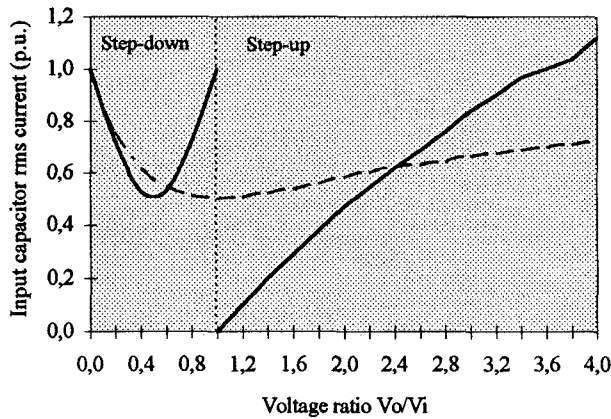


Fig. 9. Current ripple rms value of  $C_1$  versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

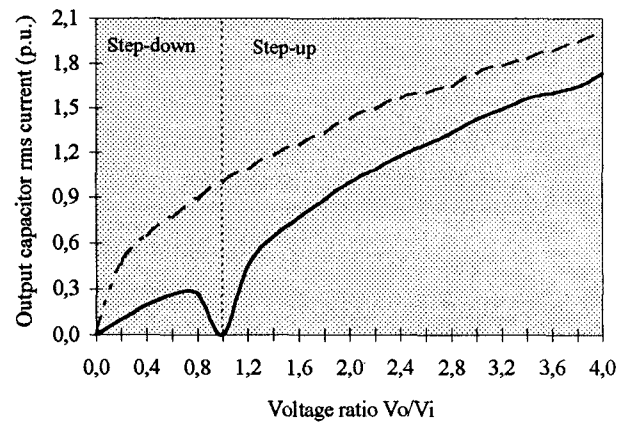


Fig. 10. Current ripple rms value of  $C_2$  versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

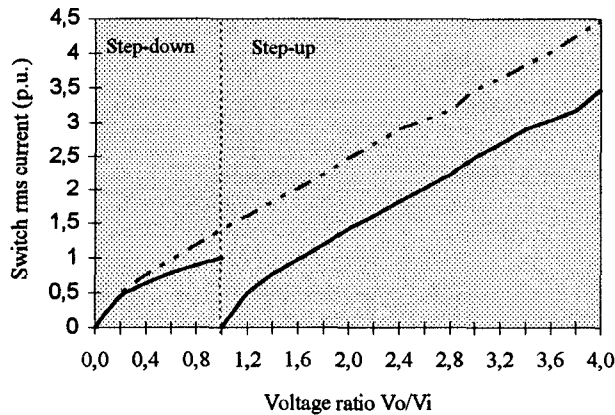


Fig. 11. Switch rms current versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

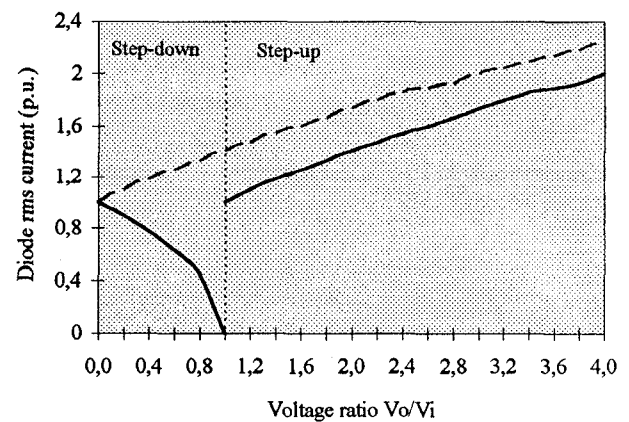


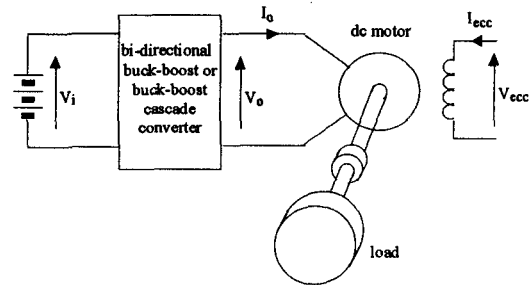
Fig. 12. Diode rms current versus  $V_o/V_i$  in buck-boost (dashed trace) and buck-boost cascade (line trace)

## IV. SIMULATION AND EXPERIMENTAL RESULTS

Concerning the two converter topologies being under investigation, computer analysis was performed by using Matlab models which describe the converter modes of operation. In addition, a test campaign was carried out by using a motor drive arrangement as shown in Fig. 13.

Waveforms of the output current  $I_o$ , inductor current  $I_L$  and output capacitor current  $I_{C2}$  in both step-down and step-up mode of operation are plotted in Figg. 15 and 16 for the bi-directional buck-boost converter and in Figg. 17 and 18 for the bi-directional buck-boost cascade converter. According to theoretical considerations, simulation results

Fig. 19, 20, 21 and 22 show waveforms achieved from experimental test campaign. Comparing experimental curves with simulation results shown in Fig. 15 through Fig. 18 it can be remarked the similarity of the waveforms and then the validation of both theoretical study and simulation models.

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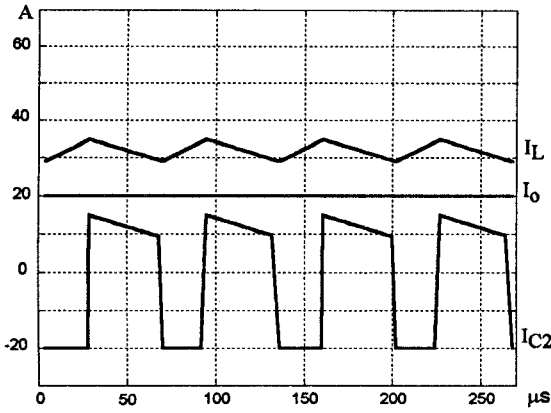


Fig. 15. Simulation results: inductor ( $I_L$ ), output capacitor ( $I_{C2}$ ) and output ( $I_O$ ) currents in buck-boost converter in step-down mode of operation (current scale 10A/div, time scale 50μs/div)

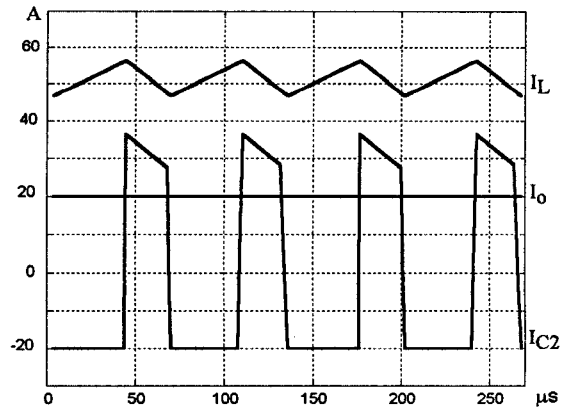


Fig. 16. Simulation results: inductor ( $I_L$ ), output capacitor ( $I_{C2}$ ) and output ( $I_O$ ) currents in buck-boost converter in step-up mode of operation (current scale 10A/div, time scale 50μs/div)

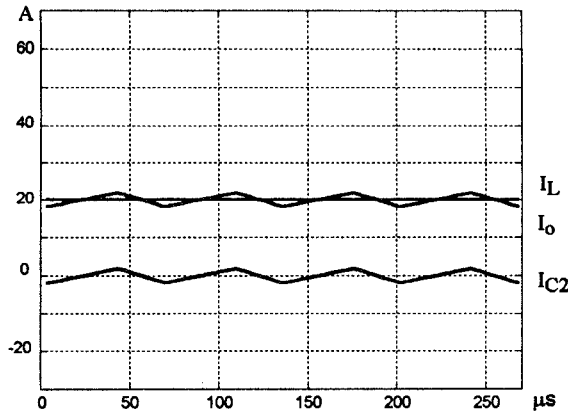


Fig. 17. Simulation results: inductor ( $I_L$ ), output capacitor ( $I_{C2}$ ) and output ( $I_O$ ) currents in buck-boost cascade converter in step-down mode of operation (current scale 10A/div, time scale 50μs/div)

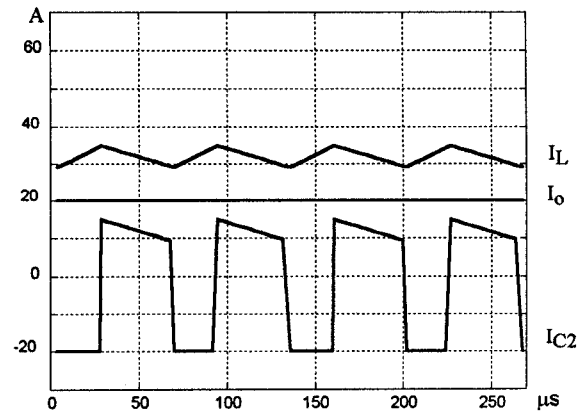


Fig. 18. Simulation results: inductor ( $I_L$ ), output capacitor ( $I_{C2}$ ) and output ( $I_O$ ) currents in buck-boost cascade converter in step-up mode of operation (current scale 10A/div, time scale 50μs/div)

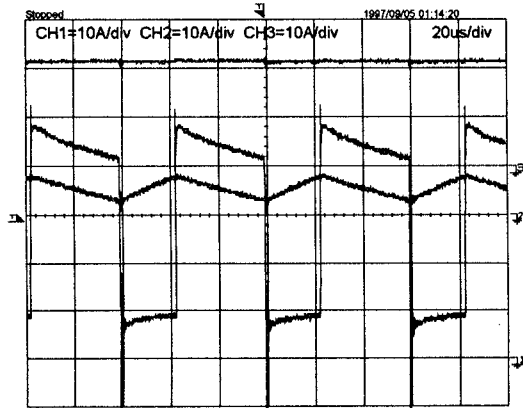


Fig. 19. Experimental results: inductor (trace 1), output capacitor (trace 2) and output (trace 3) currents in buck-boost converter in step-down mode of operation (current scale 10A/div, time scale 20μs/div)

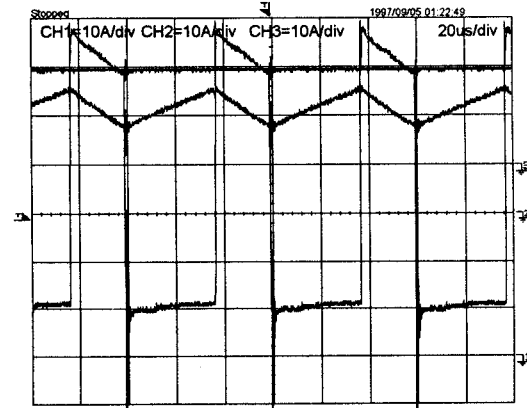


Fig. 20. Experimental results: inductor (trace 1), output capacitor (trace 2) and output (trace 3) currents in buck-boost converter in step-up mode of operation (current scale 10A/div, time scale 20μs/div)

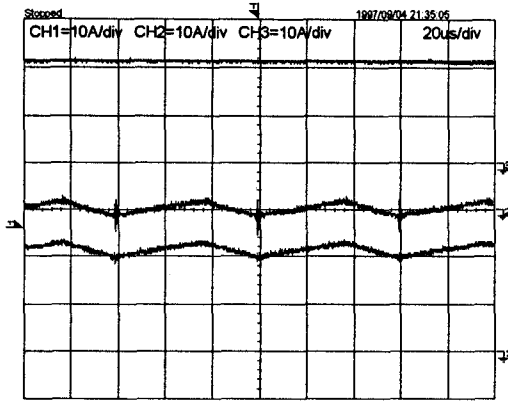


Fig. 21. Experimental results: inductor (trace 1), output capacitor (trace 2) and output (trace 3) currents in buck-boost cascade converter in step-down mode of operation (current scale 10A/div, time scale 20μs/div)

## V. CONCLUSIONS

This paper has discussed the comparison between bi-directional buck-boost converter topology and bi-directional buck-boost cascade converter topology. Simulation and preliminary experimental results were achieved by using Matlab models and by carrying out a campaign test on 20 kW water-cooled converter prototypes.

The comparison results point out that higher electric and thermal stress characterize the operation of the bi-directional buck-boost configuration with respect to the bi-directional buck-boost cascade one. In step-down mode of operation the two topologies differences are not very large, whilst in step-up mode of operation the current rms value of inductor, power switches and output capacitor, is greater of an amount, respectively equal to the output current  $I_o$  and to 1/3 of the output current  $I_o$ , in buck-boost converter with respect to buck-boost cascade converter. In conclusion, even if in the buck-boost cascade topology both switches and power diodes are duplicated with respect to the buck-boost one, reduced size inductor and capacitors can be used, thus gaining back the cost increment due to the power semiconductor components.

## REFERENCES

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- [2] Caricchi, F. Crescimbin, A. Di Napoli, M. Marcheggiani, "Prototype of electric vehicle drive with twin water-cooled wheel direct drive motors," *Proceedings of the 27th Annual IEEE Power Electronics Specialists Conference (PESC'96)*, Baveno (Italy), June 23-27, 1996.

## APPENDIX

Assuming  $f_s$  as the switching frequency,  $V_i$  the input voltage,  $I_o$  the output current and  $L$  the inductance value, inductor current ripple ( $\Delta I_L$ ), inductor ( $I_L$ ), input and output capacitor ( $I_{C1}$ ,  $I_{C2}$ ), power switch ( $I_S$ ), and diode ( $I_D$ ) rms current can be calculated as:

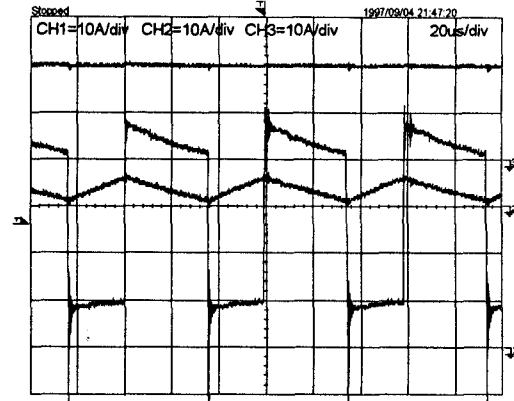


Fig. 22. Experimental results: inductor (trace 1), output capacitor (trace 2) and output (trace 3) currents in buck-boost cascade converter in step-up mode of operation (current scale 10A/div, time scale 20μs/div)

### 1) Buck-Boost Converter

$$\Delta I_{L,b} = \frac{V_i \cdot D_b}{f_s \cdot L} \quad (6)$$

$$I_{L,b} = \sqrt{\left(\frac{I_o}{1-D_b}\right)^2 + \frac{1}{3} \cdot \left(\frac{\Delta I_{L,b}}{2}\right)^2} \quad (7)$$

$$I_{C1,b} = I_o \cdot \sqrt{1-3 \cdot D_b \cdot (1-D_b)} \quad (8)$$

$$I_{C2,b} = I_o \cdot \sqrt{\frac{D_b}{1-D_b}} \quad (9)$$

$$I_{S,b} = I_{L,b} \cdot \sqrt{D_b} \quad (10)$$

$$I_{D,b} = I_{L,b} \cdot \sqrt{(1-D_b)} \quad (11)$$

### 2) Buck-Boost Cascade Converter in Step-Down Mode of Operation

$$\Delta I_{L,cd} = \frac{V_i \cdot D_{cd}}{f_s \cdot L} \cdot (1-D_{cd}) \quad (12)$$

$$I_{L,cd} = \sqrt{I_o^2 + \frac{1}{3} \cdot \left(\frac{\Delta I_{L,cd}}{2}\right)^2} \quad (13)$$

$$I_{C1,cd} = I_o \cdot \sqrt{1-3 \cdot D_{cd} \cdot (1-D_{cd})} \quad (14)$$

$$I_{C2,cd} = \Delta I_{L,cd} \cdot \sqrt{\frac{2 \cdot D_{cd} + 1}{3 \cdot (1-D_{cu})}} \quad (15)$$

$$I_{S,cd} = I_{L,cd} \cdot \sqrt{D_{cd}} \quad (16)$$

$$I_{D,cd} = I_{L,cd} \cdot \sqrt{(1-D_{cd})} \quad (17)$$

### 3) Buck-Boost Cascade Converter in Step-Up Mode of Operation

$$\Delta I_{L,cu} = \frac{V_i \cdot D_{cu}}{f_s \cdot L} \quad (18)$$

$$I_{L,cu} = \sqrt{\left(\frac{I_o}{1-D_{cu}}\right)^2 + \frac{1}{3} \cdot \left(\frac{\Delta I_{L,cu}}{2}\right)^2} \quad (19)$$

$$I_{C1,cu} = \Delta I_{L,cu} \cdot \sqrt{\frac{2 \cdot D_{cu} + 1}{3 \cdot (1-D_{cu})}} \quad (20)$$

$$I_{C2,cu} = I_o \cdot \sqrt{\frac{D_{cu}}{1-D_{cu}}} \quad (21)$$

$$I_{S,cu} = I_{L,cu} \cdot \sqrt{D_{cu}} \quad (22)$$

$$I_{D,cu} = I_{L,cu} \cdot \sqrt{(1-D_{cu})} \quad (23)$$