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A Non-isolated DC-DC Converter with InterCell Transformer for Buck-type or Boost-type Application Requiring High Voltage Ratio and High Efficiency

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Abstract

In this paper, a non-isolated DC-DC converter for applications requiring high voltage ratio and high efficiency is developed. The topology is based on a non-standard association of commutation cells [1],[2], and we introduce a magnetic coupling of all phases to further improve the converter efficiency and increase the power density. The coupled and uncoupled inductors solutions will be discussed with a focus on the reduction of losses and weight of the magnetic component. To illustrate the benefits of the proposed structure two experimental setups have been implemented. A 4kW converter for aerospace application with two independent inductors introduces the operation of the topology, the high voltage converter ratio and the high efficiency capabilities of the converter. A second experimental setup is used to validate the use of a compact 8-phase InterCell Transformer instead of uncoupled inductors.

1. Context

Many applications require high efficiency non-isolated DC-DC converter with a high voltage ratio (**Fig. 1**). These applications are presented in all industrial domains ranging from hundred watts to hundred kilowatts for both stationary and mobile applications; for example typical Point of Load (POL) converters for Telecom and End Server or Storage applications using low electrochemical voltage source components such as battery or storage system composed of a fuel cell and a water electrolyzer. In all these cases, the converter voltage ratio is around 10 or more, and it is difficult to obtain a high efficiency because the switching cell has to switch the current of the low voltage side (highest current) and the voltage of the high voltage side.

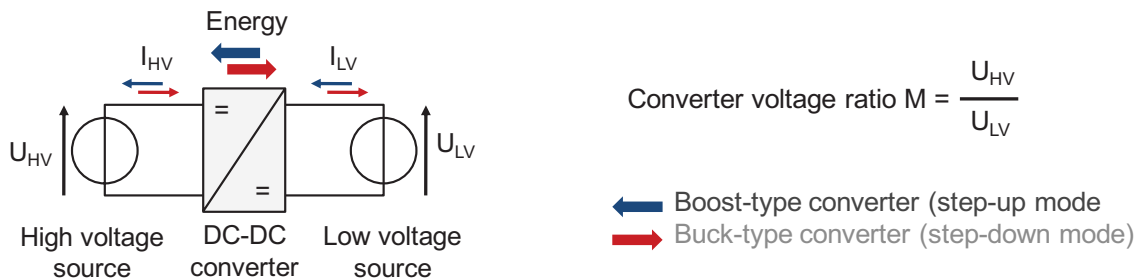


Fig. 1: Simplified schematic of a typical DC-DC bidirectional current converter where the voltage sources are working either as a voltage generator or as a load according to the direction of the energy transfer. The energy flow defines the mode of operation: boost-mode (U_{LV} : voltage generator, U_{HV} : load) or buck-mode (U_{LV} : load, U_{HV} : voltage generator). The converter voltage ratio is expressed as the ratio of the high voltage U_{HV} to the low voltage U_{LV} .

2. Scope of the work

The resistance of semi-conductors and inductors limits the efficiency in all converters, but this is even more striking when the voltage conversion ratio is high because the apparent power of the commutation cell is very high compared to the output power. In addition, in case of a boost converter these resistances even limit the output voltage that can be reached and in practice it is difficult to raise the output voltage above ten times the input voltage.

Typical solution involve cascaded converters or isolated converters with an impedance matching transformer that allows using duty cycle closer to 1 but reduces efficiency, increases cost, volume and complexity of the system.

In this paper a non-isolated DC-DC converter with high efficiency and high converter ratio is presented. An InterCell Transformer (ICT) is used instead of independent inductors which brings a reduction of losses and weight of the magnetic component. Two experimental setups allow discussing of the benefits of the structure and the use of coupled inductors.

3. Proposed converter

As will be shown below, high efficiency is antagonistic with a high voltage converter ratio due to the high difference existing between the commutated power and output power in the commutation cell. As shown in **Fig. 2**, the proposed converter is composed of a non standard association of elementary commutation cells where the power is shared in a more favorable way at high conversion ratio than with a conventional converter.

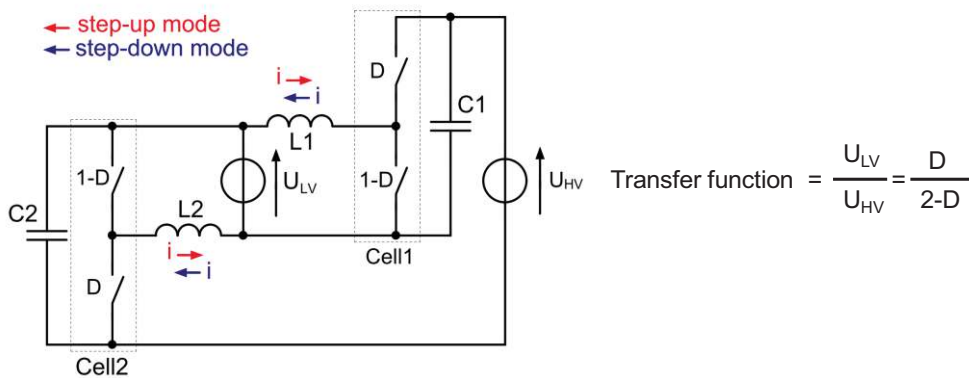


Fig. 2: Schematic of the mirror type converter
(mirror buck: step-down mode or mirror boost: step-up mode).

This structure is named mirror converter because of the symmetry observed around the low voltage source U_{LV} . The duty cycle D is defined as the duty cycle of the switches that connect the two voltage sources during a direct transfer of energy.

The converter is composed of two flying commutation cells with their decoupling capacitor and it can be seen from the circuit that we have $U_{HV} = U_{cell1} - U_{LV} + U_{cell2}$. If the control and the circuit parameters are perfectly symmetrical, the two cell voltages should be equal and we have $U_{cell1} = U_{cell2} = (U_{LV} + U_{HV})/2$. Thanks to the bidirectional current capability of the commutation cells, the converter can be used as a step-down converter (V_{LV} : load, V_{HV} : voltage generator) or step-up converter (V_{LV} : voltage generator, V_{HV} : load). The low voltage current I_{LV} and the high voltage current I_{HV} are respectively defined as the currents in the low voltage source U_{LV} and the high voltage source U_{HV} .

4. High converter ratio

Figure 3 illustrates the high voltage conversion ratio capability of the converter compared to a classical buck/boost converter. For low values of the duty cycle, the voltage conversion ratio tends to be twice the voltage conversion ratio obtained with a buck/boost converter. This property allows the converter to work with a lower duty cycle for a same converter voltage ratio, which reduces the current constraints on the semi-conductor and therefore the losses. For example, to interconnect a $28V_{DC}$ bus with a $540V_{DC}$ bus, the duty cycle D is equal to 5.18% for a buck/boost converter and is equal to 9.86% with the mirror buck/boost converter.

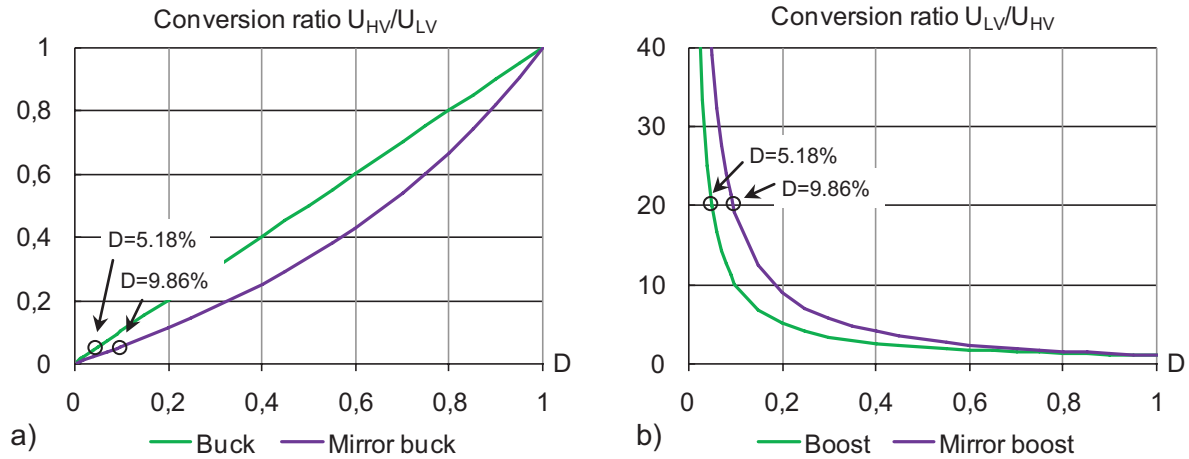


Fig. 3: Conversion ratios of standard and mirror converters a) buck mode b) boost mode.

5. Semiconductor voltage and current stresses

Another advantage of this topology is that the constraints applied to the switches of the proposed structure are reduced compared with a buck-boost converter. As summarised in **Tab. 1**, the reduction of the constraints are more important at very low duty cycle, i.e. high difference between the converter input voltage and output voltage.

Switches	Voltage constraint U_{MAX}		Current constraint ⁽²⁾ I_{MAX}	
	D	1-D	D	1-D
Buck/boost	U_{HV}	U_{HV}	I_L	I_L
Interleaved ⁽¹⁾ buck/boost	U_{HV}	U_{HV}	$I_L/2$	$I_L/2$
Mirror buck/boost	$U_{HV}/(2-D)$	$U_{HV}/(2-D)$	$I_L/(2-D)$	$I_L/(2-D)$

Tab. 1: a) Maximum current and voltage constraints (1) Interleaved buck/boost with two commutations cells i.e. same power than the mirror buck/boost (2) I_L : current in the inductor

6. Experimental results with uncoupled inductors

The purpose of this setup is to illustrate the benefits of using the mirror topology instead of using the standard buck converter. To do this, a comparison is done with a high difference between the input voltage and the output voltage, i.e. a low duty cycle.

The compared converters are used to feed a 4kW/28V load from a DC bus equal to either 270V or 540V (these are the two voltage levels evaluated for a High Voltage (HVDC) aircraft bus).

The proposed structure (**Fig. 4a**) is compared to an interleaved buck converter (**Fig. 4b**) with the same available output power so that each converter uses 2 commutation cells.

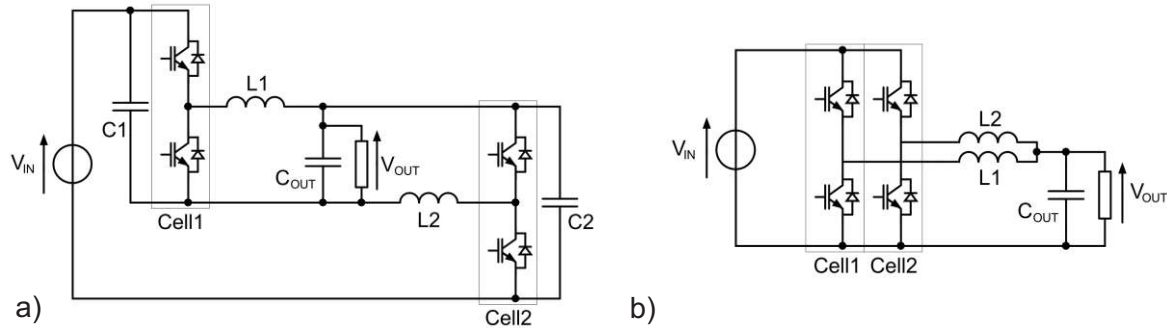


Fig. 4: a) Structure of the mirror buck b) Structure of the interleaved buck converter.

6.1. Experimental set-up

As shown in **Fig. 5**, the compared converter are developed with two three-phase inverters using 600V IGBT modules (Fuji Electric 2MBI300U2B-060) controlled in open loop by a DSP-FPGA board (TMS320C6713 Texas Instruments, ALTERA ACEX EP1K100QC208-2). Each phase is connected to a 80A/250uH inductor. The switching frequency is 15.63kHz. The converter output is connected to a resistive variable load which is not shown in the figure.

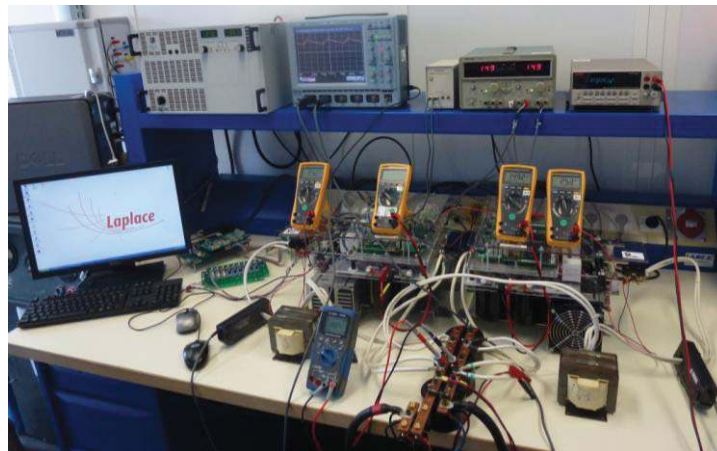
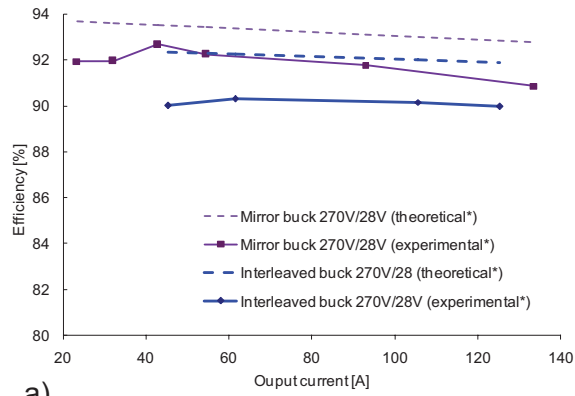


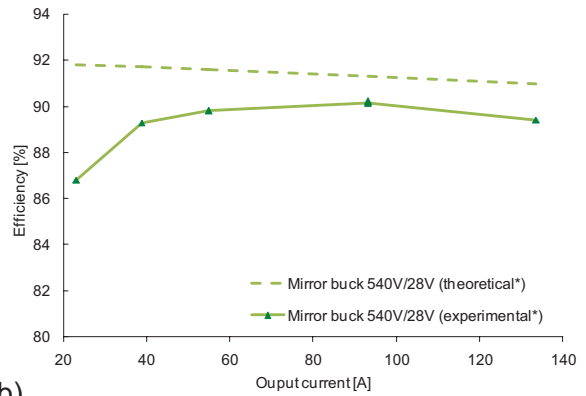
Fig. 5: Experimental set-up used for the first evaluation test.

6.2. Results

The goal of the experiment is to compare the efficiency between the mirror buck converter and the interleaved buck converter with parts available in the laboratory and switches are not optimized to maximize the efficiency. Theoretical plots take into account only the losses in the semi-conductors. The experimental efficiency is the ratio between of measured converter output power to the measured input power.



a) (*)Theoretical means "based on the estimation of switch losses only", experimental means "based on output power/input power measurement".



b) (*)Theoretical means "based on the estimation of switch losses only", experimental means "based on output power/input power measurement".

Fig. 6: Theoretical and experimental efficiency of the mirror buck and interleaved buck converters using the same 600V IGBT: **a)** $V_{IN} = 270V$ to $V_{OUT} = 28V$, **b)** $V_{IN} = 540V$ to $V_{IN} = 28V$

As shown in **Fig. 6a** the mirror buck converter has a better efficiency compared to a classical buck converter.

It can also be seen that results are quite good with a bus equal to 540V (**Fig. 6b**) i.e. the output voltage is around 20 times lower than the input voltage. The efficiency of the buck converter is not represented with a 540V voltage bus because the 600V IGBT cannot handle this voltage. With the mirror buck converter, the voltage applied to the switches are $(28+540)/2=284V$ which is far below the voltage limits of a 600V IGBT.

As with series converter, sharing the voltage constraints among the switching cells can be used in order to improve the converter efficiency or reach a high output voltage greater than the voltage rating of the switches. Using components with a lower voltage rating improves the converter efficiency because the performances of semi-conductors are generally inversely proportional to the breakdown voltage of the switches.

As show in **Fig. 7**, interleaved techniques (the control signals of commutation cell are phase shifted of 180°) increase the input and output current frequency which reduces their ripples and allows reducing the size of the output capacitor. Nevertheless, interleaved pattern do not change the current in the inductors and does not bring any benefit in term of losses in the inductors and in the commutation cells.

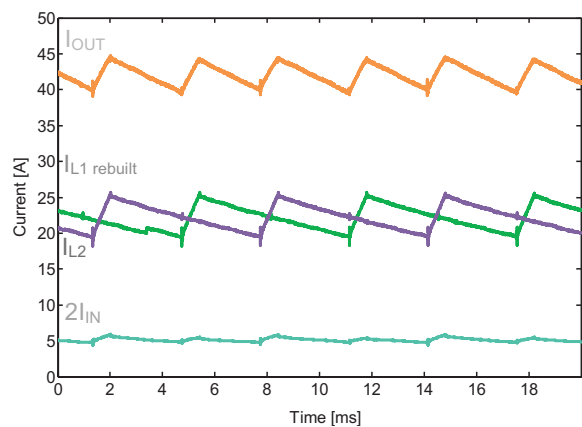
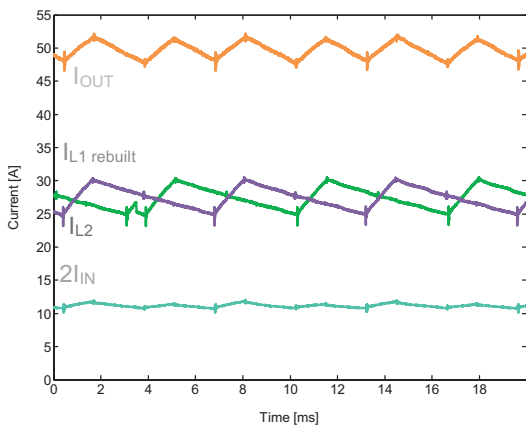


Fig. 7: Currents in the mirror converter **a)** $V_{IN} = 270V$ to $V_{OUT} = 28V$ and $P_{OUT} = 1390W$, **b)** $V_{IN} = 540V$ to $V_{OUT} = 28V$ and $P_{OUT} = 1182W$

7. Coupled inductors

The parallel multi-cell approach is used to handle a high current requirement or in order to reduce the total conduction losses. The control signals of commutation cells are interleaved (phase shift of $360/n$ with n being the number of commutation cells). The average current on the low side is equally shared in each independent inductor. Thanks to interleaving, the low current ripple I_{LV} is reduced (maximum divided by n^2) and I_{LV} has a frequency equal to n times the switching frequency, which allows reducing the value of the low voltage capacitor. This solution allows working with high current but the current ripple in the inductors is still high and each independent inductor adds volume to the system. Using InterCell Transformer allows reducing the volume of the magnetic component (volume of 8-phase ICT is reduced by a factor of roughly 2 compared to 8 independent inductors). With an InterCell Transformer the low voltage current is the same as with independent inductors. Copper losses in the windings and conduction losses in the semi-conductors decrease because of the reduction of the AC component of the current in each phase. Core losses in the magnetic component are also reduced because of the reduction of the flux swing in some regions of the core. The total losses of the magnetic component are reduced and that is one of the reasons that allows reducing its size.

8. Experimental results with coupled inductors

The aim of this experiment is to validate the replacement of uncoupled inductors by an InterCell Transformer. As shown in **Fig. 8**, a 3kW mirror boost converter 15V to 150V with 8 phases has been implemented. The converter used is composed of 8 legs and the 8 phases are connected to an InterCell Transformer. In each commutation cell, the control switches are realized with 3 IGBTs in parallel; the non-controlled switches are composed of 3 diodes in parallel.

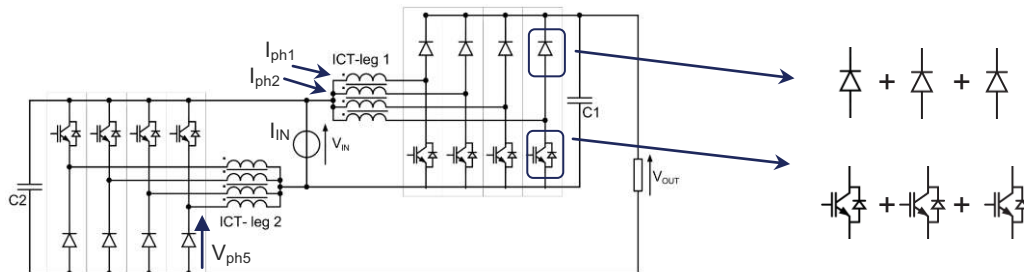


Fig. 8: Schematic of the mirror boost converter implemented.

8.1. Experimental setup

In order to validate the use of an InterCell Transformer with a mirror topology, tests have been made using by reconfiguring an 8-cell interleaved buck converter available in the laboratory [3]. The converter is controlled in open loop by a FPGA board ALTERA DE2-115. Each phase uses 600V devices and is connected to the InterCell Transformer designed for $400V_{pkpk}$ square voltage operation (**Fig. 9**). The control signals of each commutation cell are phase shifted of 45° ($360^\circ/8$) and the phase order is determined to minimize the flux in the magnetic core [4]. The switching frequency is 20 kHz. A 10kW variable load is connected to the converter output.

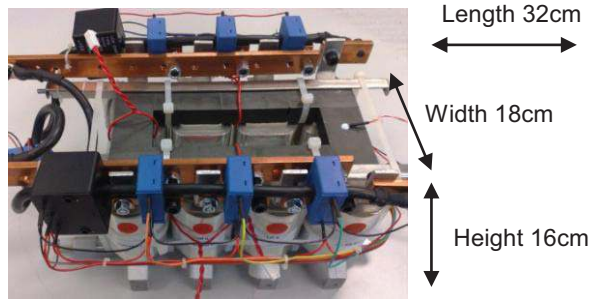


Fig. 9: Eight-phase InterCell Transformer with all its sensors

8.2. Results

The first measurements presented here involve a very low power compared to the nominal power of the InterCell Transformer. A first reason is that operation with a conversion ratio of 10 means switching ten times the power, so the output power will always be much lower than the power delivered in a buck configuration. A second reason is that the available power supply was limited to 15V/200A.

As shown measures in **Fig 10**, the input current and the phase currents have a frequency of 160kHz which is 8 times the switching frequency ($8 \times 20\text{kHz}$) and a very low ripple (the same remark applies to the output current waveform that is not displayed here).

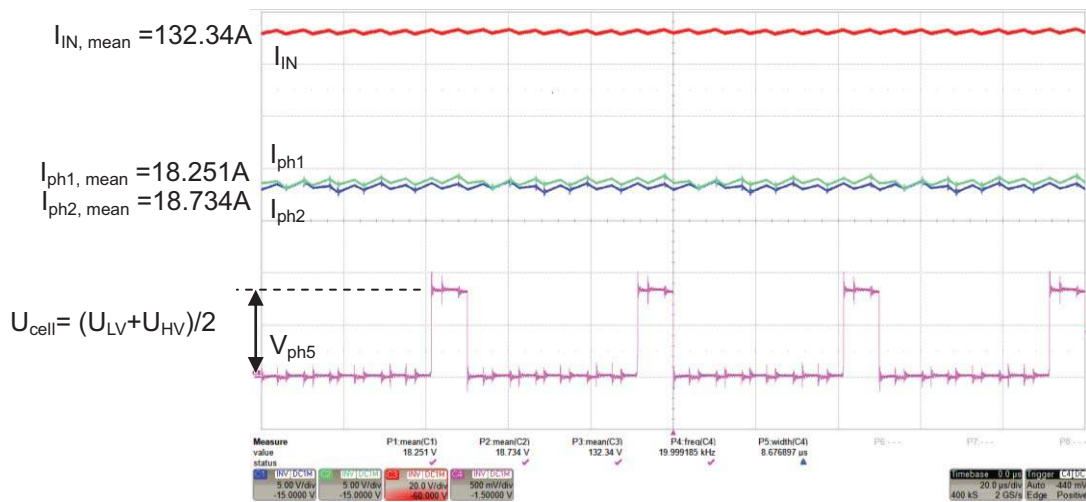


Fig. 10: Measurement of the input current I_{IN} , phases current I_{ph1}, I_{ph2} and voltage phase V_{ph5}

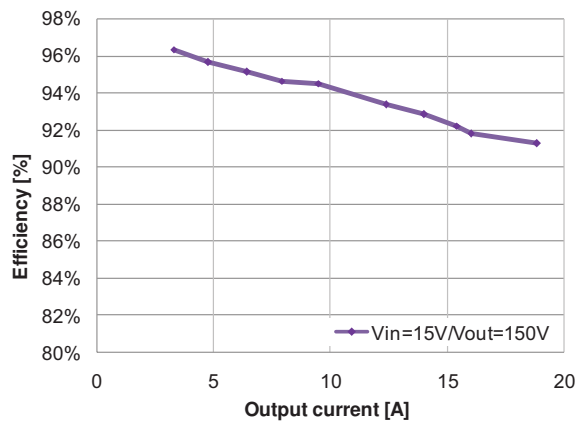


Fig. 11: Experimental efficiency of the mirror boost converter based on the ratio output power to input power measurement

The experimental efficiency is shown **Fig. 11**. These measurements are made with a commutated voltage of around 80V which is far beyond the limits of 600V IGBTs which is unfavourable for the efficiency. Efficiency at 28V input voltage should be significantly better.

9. Conclusion

The proposed structure has a better efficiency than a classical converter with a high voltage ratio. Semiconductor losses have been calculated and efficiency has been measured and compared with a classical interleaved buck in a step-down application. Theoretical analysis has shown the interest of using coupled inductors instead of independent inductors in terms of efficiency and power density. A step-up application has confirmed the feasibility of using InterCell Transformer instead of independent inductor.

10. References

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