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# A New Intercell Transformer for Interleaved Converters

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## Keywords

«Interleaved converters», «Intercell transformers», «Modified supply», «Core losses», «Hybrid Integration»

## Abstract

This paper describes a new topology of interleaved power converters using intercell transformers. A modified sequence of the voltages applied to windings is used to reduce the flux density in the magnetic core branches, consequently reducing core losses and the risk of saturating the magnetic material. Since the power density of the converter is high, a new assembling technique to construct the intercell transformers is used to allow easy cooling of the magnetic core branches which have higher magnetic flux. Experimental measurements confirm the topology operation and the flux reduction obtained with the modified supply.

## Introduction

Power electronics applications in the automobile and aeronautics areas require static converters to be highly performing in terms of size, robustness, efficiency and power dissipation, among others. Consequently, reducing the size of power converters nowadays is one of the main achievements desired by researchers in power electronics.

Among all forms of power integration, interleaving converters with filtered output voltage is widely studied, since the apparent frequency for the filters is “ $P$ ” times the switching frequency of each

commutation cell, where “ $P$ ” is the number of cells in parallel. Moreover, interleaving converters improve the dynamic behavior [1].

Traditionally, a static converter consists of an arrangement of elementary discrete components (power semiconductors, capacitors, magnetic components, integrated circuits, cooling device, interconnections). Static converters occupy a significant volume, which increases as the converted power increases. The assembly of the various elements requires a series of mechanical and thermal operations (screwing, fastening, soldering), which weaken the system miniaturization and automation of production. A different approach to the packaging design of static converters is necessary [2-4].

Power integration goes with technological requirements for static converters since it provides volume reduction, increase of efficiency, reliability, modularity and cost reduction. An important volume of the converter is occupied by the passive components used in the output and input filters. So, in order to increase the power density by reducing the passive components size, the integration of those components in a module is necessary.

A good manner of integrating passive components is making use of *integrated magnetic component*. This approach is based on the use of a single core to produce various magnetic components (inductors and transformers). In the literature, this technique was employed for different topologies of DC/DC converters (Forward and Cuk converters). It allows the reduction on the number of components and also to cancel out the common mode ripple, reducing core losses and size [5,6].

The impact of a passive component is not only measured by its own volume but also by its disposition in the converter which facilitates, or not, the cooling. In most of the converters, only 55% of the available volume is used [7]. Rearranging those components might increase the power density.

In a classical converter structure, active components have a direct physical contact with a heatsink. Passive components, which usually have lower losses, make use of different methods of heat evacuation (convection and radiation). This kind of construction turns out to be very bulky and so the idea of an integrated heatsink is presented as a solution to this problem [8]. Both passive and active components have a direct physical contact with a single heatsink which makes the thermal conduction the main phenomenon of heat evacuation.

### **Converter of the future**

Based on the current state of packaging, projections on the future of the converter were made [2,8]. It is a single module containing all the components of the converter and mounted on a heatsink. In this structure, passive components are implemented with specific technologies of electromagnetic integration. The active components are made with technologies similar to the active power modules existing these days. The cooling function of this module is optimized and it must ensure that the maximum temperature of the components is not exceeded. The control and diagnosis functions are implemented inside the module.

In this form, the converter takes advantage of a strong compactness and it represents a great challenge of power electronics. To arrive at such a “product”, it is necessary to achieve the maximum level of integration of each component of the converter.

### **Hybrid integration and converter architecture**

Multilevel converters have advantages which can achieve certain goals of integration:

- An increase in the number of levels available at the converter output, reducing the amplitude of steps of the switched voltage and the current ripple,
- An increase of the apparent frequency of output current or voltage, which will reduce the size of the output filter.

Among the structures of multilevel converters, topologies based on interleaved cells have the advantage that it can be directly generalized with regards to the topology and the control [9].

Depending on the association of the switching cells, two topologies are distinguished: series multicell converters and parallel multicell converters.

From the rise of low voltage/high current applications (e.g. Voltage Regulator Module, Uninterruptible Power Supply, Fuel cells, Automobile), multicell parallel converters were selected to be part of a study about hybrid integration.

This paper aims to show the development of a high power converter which must be compact, with a high number of parallel interleaved cells. It employs the topology of intercell transformers based on standardized cores which are easy to cool. Also, we show how core losses in intercell transformers can be reduced using a degree of freedom specific to multicell parallel converters.

## Interleaved Converter

A traditional interleaved converter consists of several identical commutation cells with the outputs interconnected through separated inductors as shown in Figure 1. The major drawback of this topology is the large ripple of the phase current flowing in the inductors [10]. This leads to high conduction losses in the switches, high copper losses in the inductors and increased core losses (high induction ripple through the main core at the switching frequency).

The other solution is based on the introduction of coupling transformers (or intercell transformers) [1,11-14] that are built by association of elementary transformers (separate transformers) or realized on a monolithic magnetic core (monolithic transformer). A theoretical study, principally dealing with associations of separate transformers is proposed in [11].

The general property of intercell transformers is to generate a virtual chopped voltage which is the average of the voltages provided by the converter cells, as shown in [15]. In steady state the average value of the output voltage is equal to the average value of any of the voltages (all the average values of the supply voltages must be identical). Further, the output voltage presents reduced THD (cancellation of all harmonics except those multiples of  $P$  times the switching frequency).

The voltages applied to windings can be permuted in order to reduce the fluxes in some branches of intercell transformers [15]. Also, discrete transformers can accomplish the same electrical performances as the monolithic intercell transformers [16]. Thus, we will show how to join discrete transformers in order to find the optimal flux reduction in the joint branches.

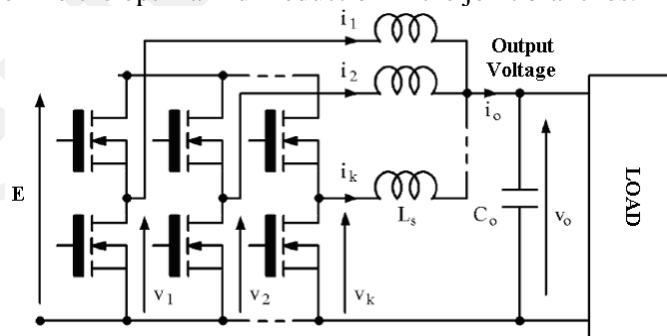


Fig. 1: Traditional interleaved converter

### Reduction of the fundamental flux

If we glue together two magnetic circuits, the flux on the joined legs will be summed and the reduction of the flux will be increased if the flux circulating in these legs are equal in magnitude and have opposite signs. Considering the fundamental flux whose amplitudes are equal, we will search the phase conditions leading to the best flux reduction.

Firstly, let's distinguish two distinct types, among the magnetic circuits commonly used: single-net magnetic circuits (e.g. "UI", "UU", and "CI") and double-net magnetic circuits (e.g. "EI", "EE").

These circuits can be joined along two axes and therefore in four different manners (Figure 2). Like this, we observe that, in order to cancel the flux in the joined legs, we must have initial flux in phase for the cases a), b) and c), and the flux with 180 degrees of phase difference for the case d).

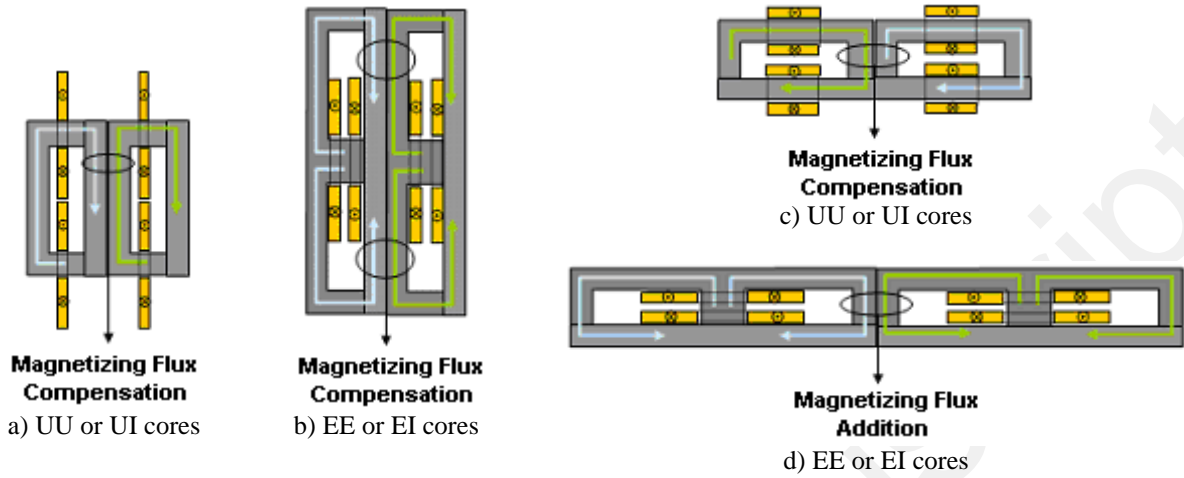


Fig. 2: Summing and compensating magnetizing flux by joining transformers together

In this way, we note that the optimal phase difference is 0 or 180°, depending if the number of nets in the magnetic circuit in the joint axis is 1 or 2.

In the intercell transformers of interest to us, we will try to find these optimal methods of joining them by considering the phase of the fundamental fluxes determined by the method described in [15].

Figure 3 shows the evolution of the reduction factor ( $\gamma$ ) of the flux in the joined columns according to the phase difference between the fundamental fluxes. In cases a), b) and c) of Figure 2, based on the assumption that the fluxes have the same fundamental amplitude,  $\gamma$  is given by the following expression:

$$\gamma = 2 \cdot \sin \frac{\delta}{2} \quad (1)$$

where  $\delta$  is the phase difference between the fundamental fluxes through the two joined branches.

### Reduction of the leakage flux

Having shown how to join the transformers to reduce the magnetizing flux in the common legs, we consider now the leakage fluxes. Take the case of transformers based on circuits EE or EI joined horizontally, as show in Figure 4. Figure 4a illustrates the lines of leakage flux associated with each coil. We can see that in this case there is a summation of leakage flux in the column.

In a single-phase transformer, coils can be swapped without changing the magnetizing flux. So, as shown in Figure 4b, after a permutation of coils of a transformer, we obtain leakage flux compensation in the column.

This aspect is very interesting in the case of intercell transformers, because the continuous components of the flux circulate mainly in the leakage reluctances. Thus, the compensation of the leakage flux results in the cancellation of continuous components of the flux.

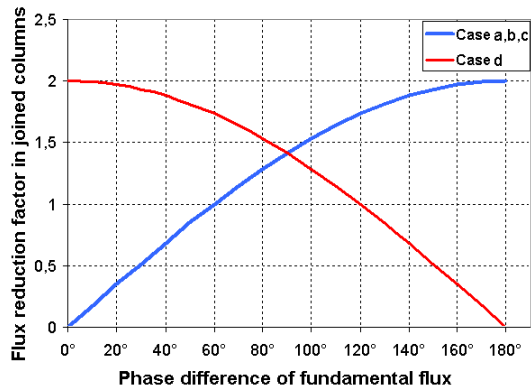
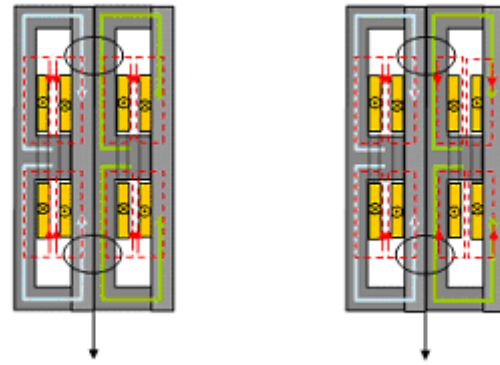


Fig. 3: Flux reduction versus phase difference



a) leakage flux addition    b) leakage flux compensation  
Fig. 4: Leakage flux reduction in EE or EI cores

## Proposed prototype

When deciding how the prototype should be done, some objectives were taken into account:

- To build a compact high power converter, containing a considerable number of interleaved cells;
- to employ a topology of intercell transformers based on standardized cores which are easy to cool;
- to carry out tests to determine the efficiency of the converter in the standard supply and modified supply;
- to minimize the length of electrical connections by the use of the modified supply.

For high power tests, the opposition method was considered (Figure 8). The advantage of this method is well known: it allows the components of the converter to achieve their rated operation point without using a rated charge and a voltage source which accepts the active power of the system.

As a result, it was decided that converter would have 12 cells, allowing to operate in two modes: 12 cells in parallel or “6x6” (opposition method).

### Topology of intercell transformers

The intention to carry out tests using the opposition method has focused our choice to a topology of intercell transformer with a horizontal symmetry (see Figure 5). It is a topology based on vertical planar cores, containing superposed coils placed on the vertical columns and made with foil conductors.

In this topology, the six transformers located on one side of the axis of symmetry can operate independently of the six transformers located on the other side.

For operation near the rated operation point of the converter, an overheating can occur on wound columns, due to copper and core losses. To facilitate cooling in these columns, layers of air (or non-magnetic material) were thought-out. The fact of introducing these layers of air, separating the wound columns into two parts, does not change the operation in the output of the converter and it does not change the main fluxes.

The columns are joined (as explained in the last section) and it was observed that it leads to a reduction in total core losses. Also, it reduces copper losses since it reduces the length of each turn. However, there is a trade-off between the reduction of losses and the possibilities of cooling.

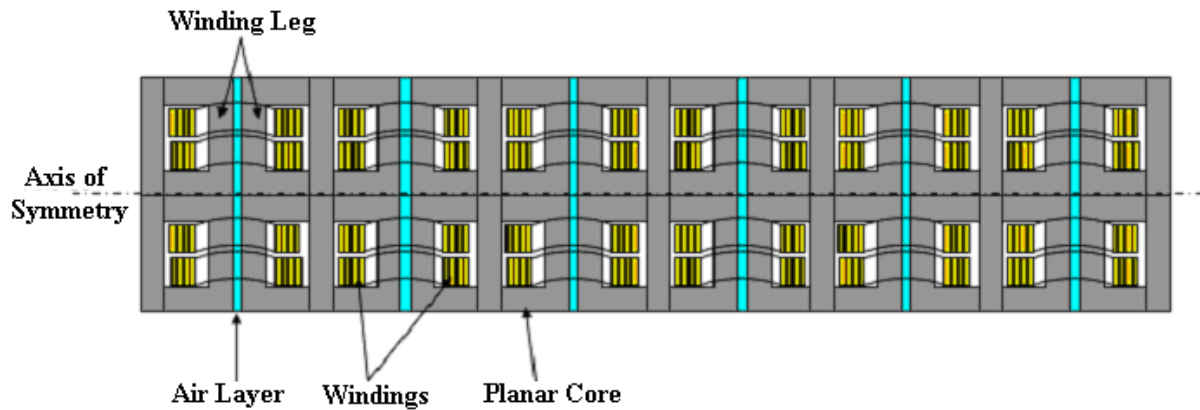


Fig. 5: Intercell transformer topology with horizontal symmetry

The phase sequences of the converter operating on 12 cells in parallel will not be shown here for the purpose of simplifying the explanation of the converter. Figure 6 shows the phase sequence of the standard supply when the converter is operating in the opposition method. Figure 7 illustrates the optimal permutation of the phases which leads to the lower core losses, as explained in [15].

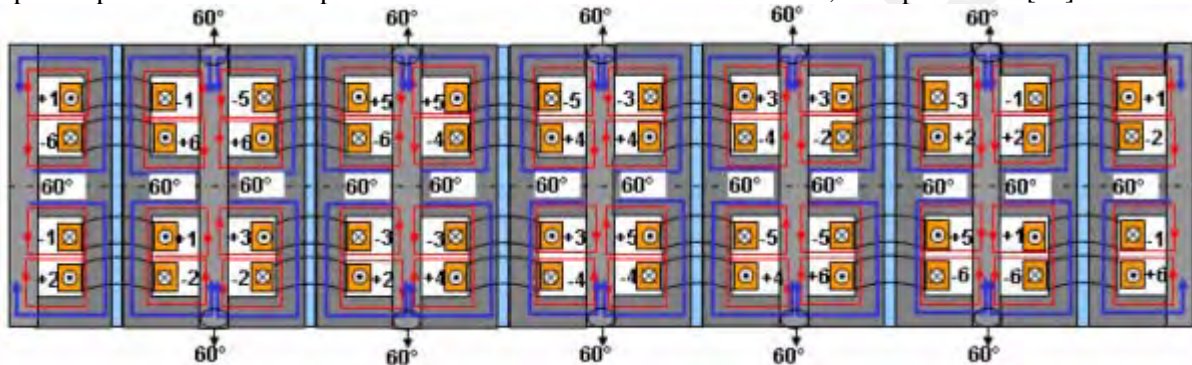


Fig. 6: Intercell transformer operating in “6x6”. Phase sequence in standard mode

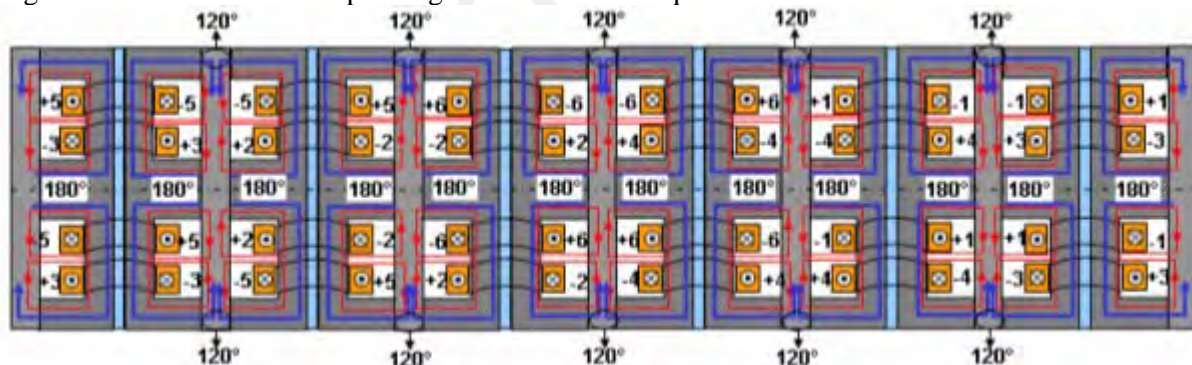


Fig. 7: Intercell transformer operating in “6x6”. Phase sequence in permuted mode

## Experimental Setup Description

The converter is designed for operation in 300V/144A and switching frequency equal to 50kHz. It comprises twelve cells, each cell with two switches Infineon SKW30N60HS as shown in Figure 8.

For both types of operation (12 cells in parallel or “6x6” in the opposition method), the control board must generate control signals corresponding to standard and permuted supplies. The correspondent control was implemented in a FPGA.

The control board allows the setting of the following parameters: switching frequency, dead time, duty cycle of one converter and the duty cycle difference between converters 1 and 2.

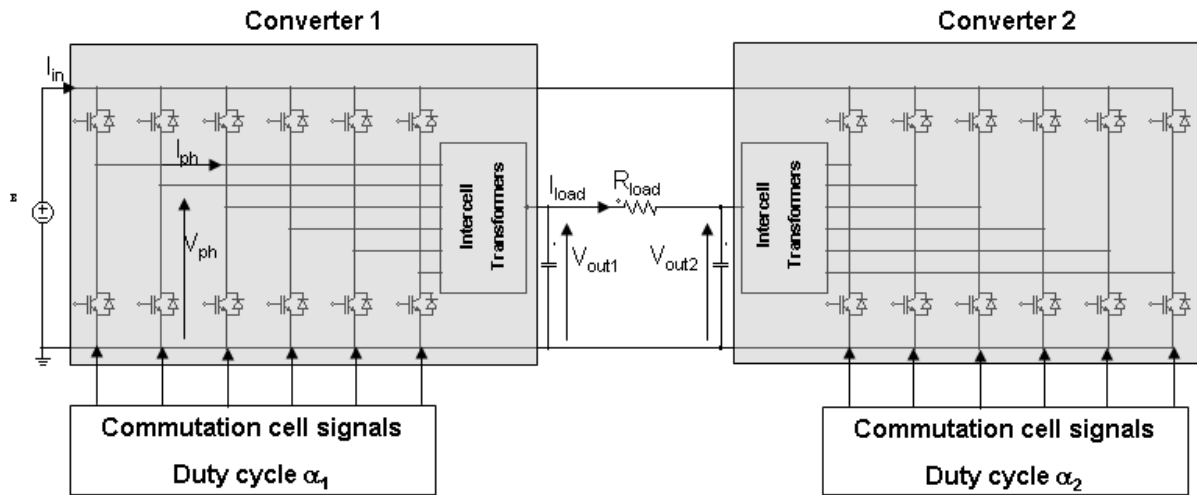


Fig. 8: Interleaved converters operating on the opposition method (6x6)

Figure 9 shows the prototype as it was defined in the preceding paragraphs. Note that the circuit drivers and decoupling capacitors are placed on the bottom side of the PCB (on the top side there are the intercell transformers).

To facilitate cooling on the wound columns, copper drains were placed on each vertical face (see Figure 9). These copper strips can drain the heat from the ferrite to the heatsink.

The magnetic cores are subject to a compressive force in order to realize the contact between different magnetic cores. As a result of rising temperatures, the phenomenon of thermal expansion can occur inside the ferrite. To compensate for these thermal expansions, strips of silicone rubber were thought-out.

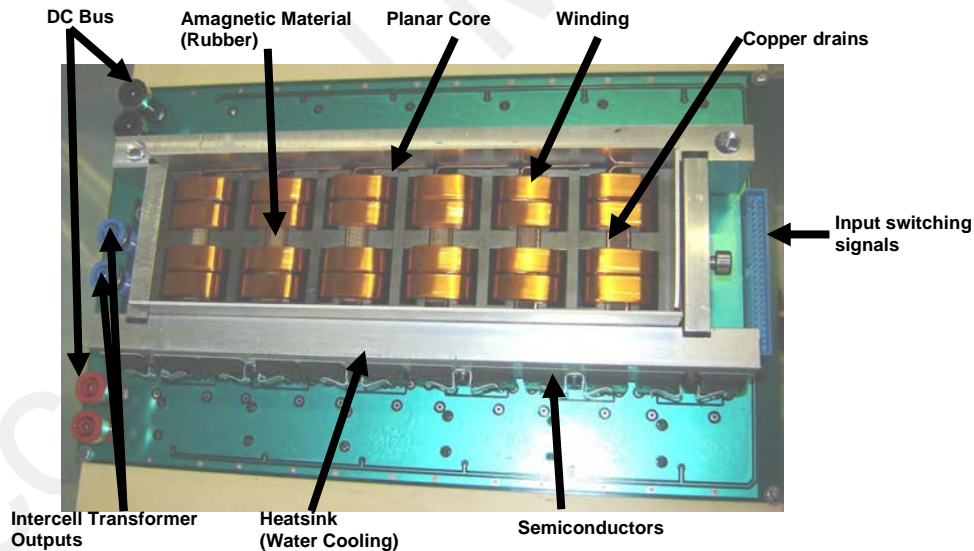


Fig. 9: Prototype of the interleaved converter with intercell transformers

## Experimental Results

The objectives of the experimental measurements are: verify the operation of the converter, show the reduction of magnetizing current obtained with permuted supply and measure total losses of the converter in permuted and standard modes.

Currents of two phases of the first converter are presented in Figure 10. The converters work in the permuted mode. The tests were performed in open-loop. By the waveform of the each phase current, we can see an increase in the apparent frequency (which corresponds to a characteristic of intercell

transformers). The continuous components of the phase currents are balanced. The difference between the alternative components of each current is due to the superposition of the magnetizing currents.

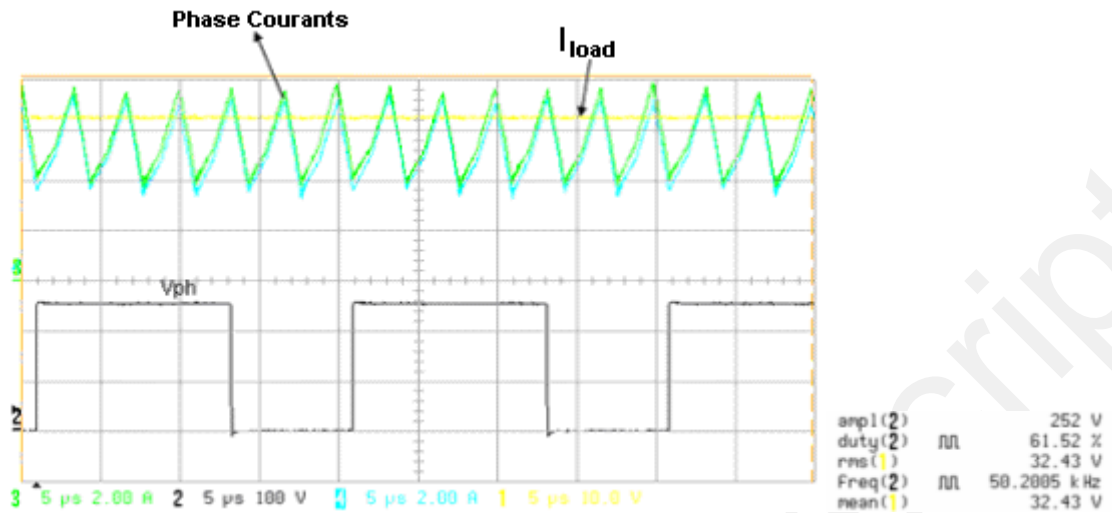


Fig. 10: Voltage and currents of one interleaved converter when  $E=252\text{V}$ ;  $I_{\text{load}}=32.4\text{A}$ ;  $F_s=50\text{kHz}$

The difference between two phase currents allows us to determine the magnetizing current. The magnetizing current of each transformer of Figure 7 has been measured under the following conditions:

$E = 200\text{V}$ ,  $F_s=50\text{kHz}$ , duty cycle of both converters equal to 40%, in permuted supply.

Figure 11 illustrates the magnetizing currents, measured and simulated with a reluctance model for 2 transformers of the same converter. They are different from one transformer to another and their waveforms are quite complex.

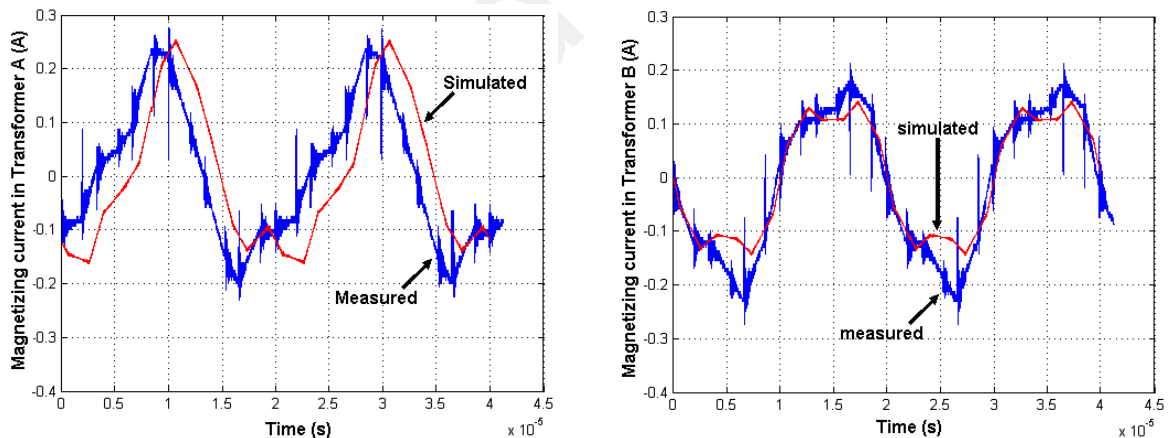


Fig. 11: Magnetizing currents in two intercell transformers of the same interleaved converter

In order to make a comparison between the permuted mode and the standard mode, the magnetizing current of one transformer was measured for each mode, using the same conditions of the converter. Figure 12 illustrates this comparison and emphasizes the reduction of magnetizing current of one transformer in the permuted mode.

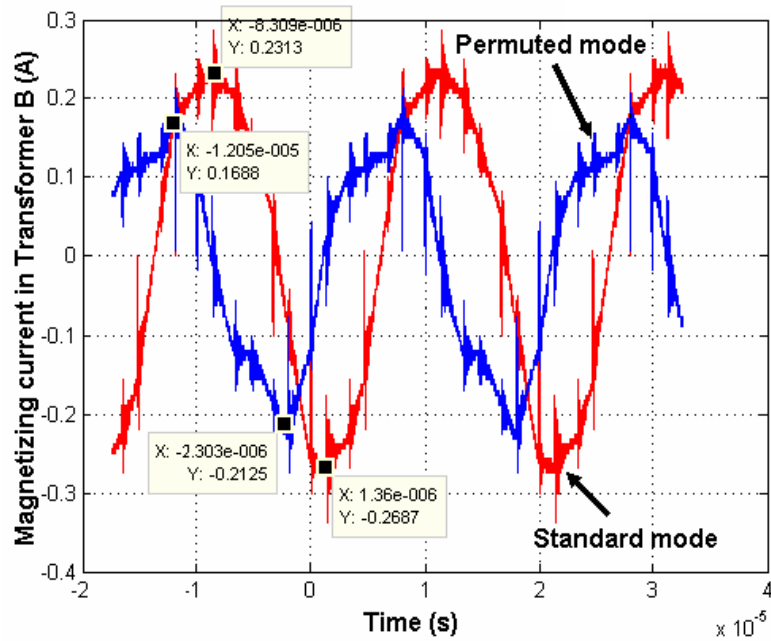


Fig.12: Magnetizing currents in the same intercell transformer in standard and permuted modes

Figure 13 shows the total losses measured in the converters (all semiconductors and intercell transformers) using the opposition method. The experimental results correspond to a given difference of duty cycle ( $\alpha_1 - \alpha_2$ ) and a fixed load resistance (the load current varies with the input voltage). There is indeed a reduction in global losses when the converters operate in the permuted mode.

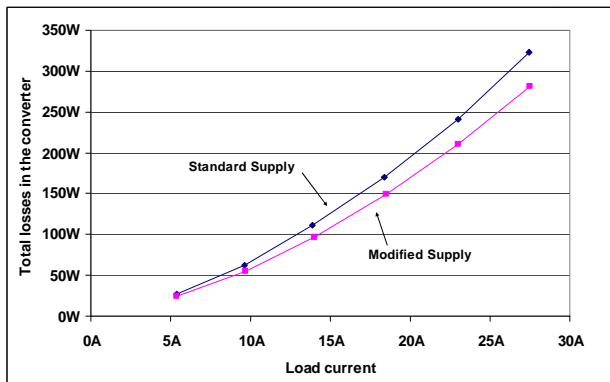


Fig. 13: Total losses of the interleaved converter versus load current

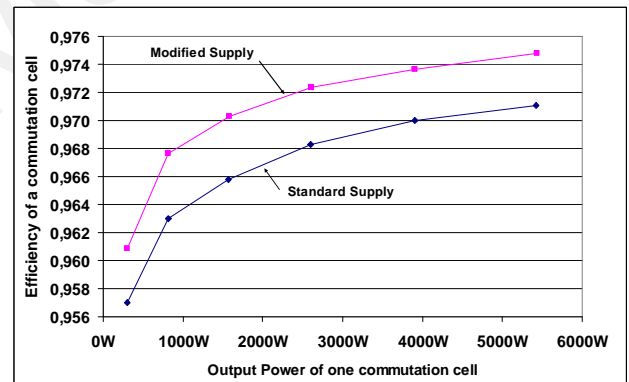


Fig. 14: Efficiency of the interleaved converter versus the output current

From these total measured losses, it is possible to estimate the efficiency of one of the converters. The comparison between the performance of one converter in standard mode and in permuted mode is shown in Figure 14. The efficiency in permuted mode is always higher than the efficiency in standard mode.

## Conclusion

We have developed a new intercell transformer to be used in interleaved power converters. We have also proposed a compact power converter prototype which makes use of intercell transformers. The permutation of the phases of supply in order to reduce core losses was presented for six interleaved cells. Experimental tests have been realized in the configuration "6x6" (opposition method). The results obtained demonstrate the reduction in total losses of the converter when the permuted supply is applied. The balance of the phase currents has been experimentally verified for the converter in the configuration "6x6".

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