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Kevin Guépratte, David Frey, Pierre-Olivier Jeannin, H. Stephan, Jean-Paul Ferrieux. Fault Tolerance on Interleaved inverter with Magnetic couplers. APEC 2010, Feb 2010, Palm Springs, United States. pp.1817 à 1824. hal-00461380

HAL Id: hal-00461380

<https://hal.science/hal-00461380>

Submitted on 4 Mar 2010

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Fault Tolerance on Interleaved inverter with Magnetic couplers

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Abstract- *The paper focuses on a new control strategy for improving the availability of power electronic converters based on interleaved structures. By using this strategy, the power electronic converters can continue to work (with reduced output power) in case of power component failure. The paper describes how to adapt the magnetic output filtering structure for this original control strategy. This structure is based on a monolithic coupler or a coupling transformer. Which are usually employed to minimize in a significant way the mass of the converters. They are normally sized to work with a fixed number of phases. Our control strategy induces new constraints on magnetic component, especially saturation problems. To reduce this problem some extra switch are added. Finally an experimental Power electronic converter driven by an FPGA is presented with the experimental results. It shows some experimental results with a 6 phases converter who work with 5 or 4 phases, to simulate one or two converter leg breakdown.*

Index Terms-Power converters, Interleaved, Power efficiency

I. CONTEXTE, INTRODUCTION

The reliability is one of the challenges for power electronic converters. For high critical systems, the key point is to keep the electronic converter working even in case of breakdown of a power switch component. Due to its modular structure, an interleaved converter offers naturally the possibility of redundancy. This paper presents an original control strategy that uses this advantage for improving the operational availability and therefore the fault-tolerance. This fault tolerance implies the capacity to limit the impacts of the defaults.

If this original control strategy is used without any special adaptation of the power electronic structure, it will lead to saturation of the magnetic core of the interleaved converter. Part 2 will show the specific constraints on the magnetic device in these structures. It will show how power electronic structure has been adapted to take into account this phenomenon of magnetic saturation.

In order to validate the approach, an experimental setup has been built. Part 3 presents the demonstrator and experimental results on 4 and 6 cells single phase 115V-17A inverter. The control part of this power electronic converter is based on an FPGA.

II. POWER ELECTRONICS STRUCTURES

This part presents various power electronic structures which are used. In this paper, we are interested in interleaved structures, they can be carried out into simple or multilevel [2] [5]. Interlacing brings many structures of filtering making it possible to decrease the global volume of the converter. This structure of filtering will also have a significant impact on the phase currents of the converter.

A. Interleaved structure.

This structure is composed of different paralleled cells. The driving signal of each cell is phase shifted. This structure allows to reduce by a factor N (N is the number of cells) the output current ripple and increases the apparent switching frequency by the same factor ($N \cdot F_{\text{switching}}$) [6]. For a defined output ripple frequency, the interleaved structure needs a smaller switching frequency than traditional power converters. Another advantage is that the output power is distributed between the different cells. This allows reducing the current rating of the different transistors. The switching and conduction losses are therefore smaller than for classical structures.

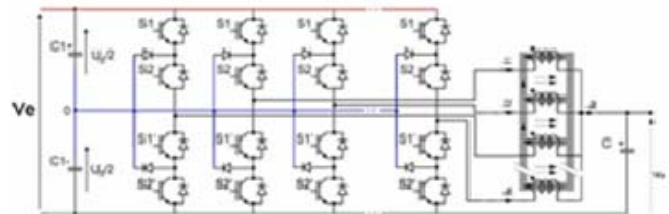


Figure 1: Interleaved structure

B. Magnetic filtered output voltage

In interleaved converters with filtered output voltage, the filters represent an important part of the converters weight. To solve this problem, it is necessary to find the best compromise between the weight of the input and output filters and the weight of power electronic elements.

The classical solution uses independent inductors as shown on Figure 4. This method imposes a very important weight and the magnetic device conception is therefore crucial. Multi-level and/or interleaved structures allow interesting opportunities.

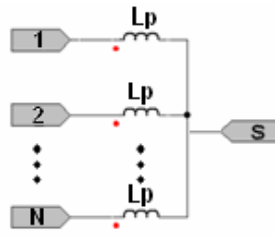


Figure 2: Filtered output voltage with independent inductors [10]

In this structure, the currents ripple in each inductance keep large amplitude and its ripple frequency remains unchanged, Figure 3. If we want to decrease the response time of the converter with a lower inductance, the current ripple is strongly increased inside each inductance. Therefore, the losses due to a larger current amplitude will increase the inductance losses.

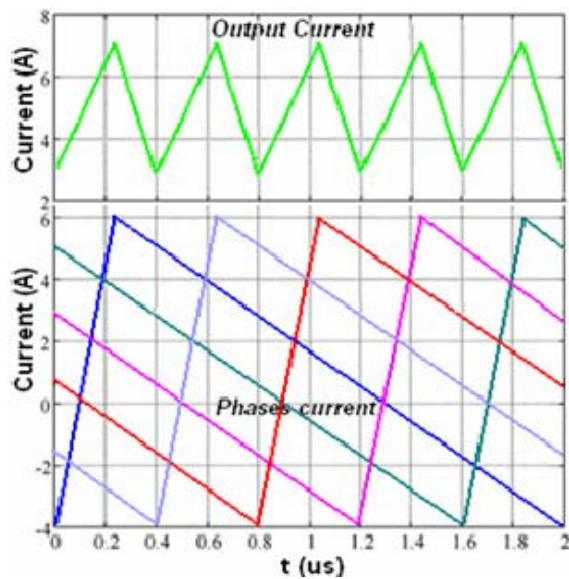


Figure 3: Current on independent inductors

These principal disadvantages can be overcome by using coupled inductances. There are several possibilities to realize **improved magnetic devices**. Two of the classical structures are presented below.

- Monolithic coupler [7] [8], which uses only one magnetic core Figure 5.
- Coupling transformers between the different output phases of the interleaved converter. On Figure 6, the cyclic cascade structure is presented [9]. Note that other coupling strategy using transformer can be used, like showed in Figure 16.

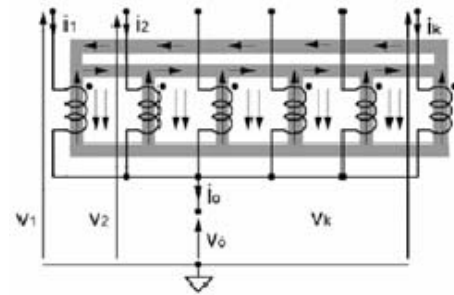


Figure 4: Interleaved structure with monolithic coupler [11]

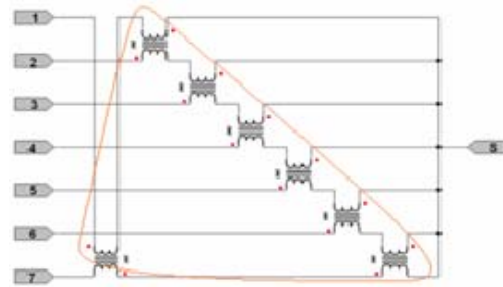


Figure 5: Interleaved structure with coupling transformers

Recent studies [4] showed that these structures generate a low output current ripple on the various converter phases, Figure 6. These currents have a ripple frequency N time the switching frequency. Thus, a faster response time can be reached without sacrificing the converter efficiency.

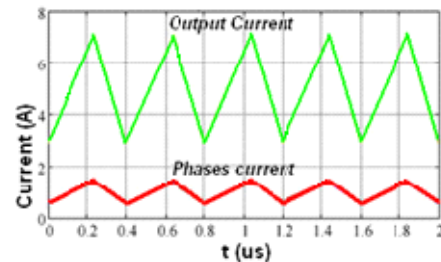


Figure 6: Current in coupled inductors

The choice of the output filtering structure must be made according two requirements: the magnetic losses and the capability of functioning with a variable number of cells. To minimize the magnetic structure and to reduce the losses, it is important to choose an output filtering structure that permit to keep a symmetrical distribution of magnetic flow in all the parts of the magnetic circuits.

III. DYSFUNCTIONS MODE

A. Dysfunctions of power electronic components

In case of dysfunction, the power electronic components can be in two different states: on or off. The on-state is generally (for MOSFETs or IGBTs) a result of the power component chip fail. The chip can't be controlled anymore and stays on. The off-state can be the result of different kind of troubles. If the current is too high, it can induce the destruction of the internal connections of the power module or a melting down of the power components. Another reason can be the destruction of the driver which isn't able anymore to turn on the transistor. This two types of dysfunction will induce the loss of an inverter leg which is the connected at the input of the magnetic structure.

B. Dysfunctions on coupling filters

The first studies of the "magnetic couplings" are based on transformer whose windings are connected like shown on Figure 5. The individual transformers have two windings and are produced with standard cores. This configuration makes it possible to transfer energy between each phase.

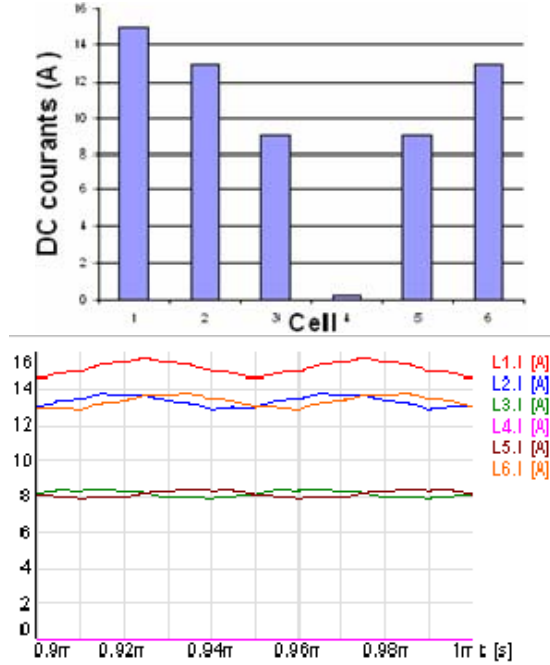


Figure 7: Simulated distribution of the DC part of the current in each winding, for a converter with 6 cells. In this structure the cell 4 is unused.

To operate, the connection of the transformers should be a closed loop. When a cell is not in use, the current can not circulate in the phase anymore. So the loop between all the transformers is open. This implies that the AC part of the current will be the same from one phase to another, but the DC part will be different [12], due the transformer (Figure 7). These current unbalances will have a significant effect on the magnetic field in the magnetic cores. Note that simulated

waveforms presented on Figure 7 do not take into account saturation phenomenons. These phenomenons can be observed on experimental waveforms on Figure 9.

In real case, the magnetic device will saturate and induce converter break down. Figure 8 presents time domain waveforms for the inverter with coupling transformers. The converter work with 6 stages and you can observe the current ripple bubble generate by the interleaved structure.

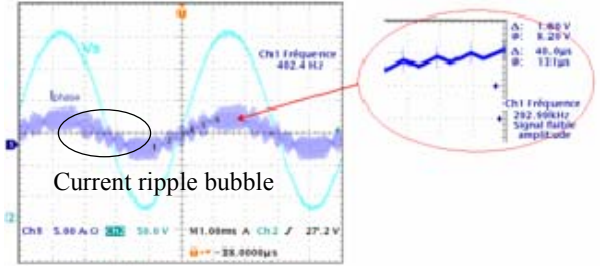


Figure 8: Experimental inverter waveforms with monolithic filter and 6 cells

If one phase breaks down, there will be only 5 phases left (on the six the total converter), therefore the magnetic core will saturate, Figure 9. This figure was realised with reduce voltage, at the beginning of core saturation. Along this point, observations are very difficult. In this waveforms we can observed the current ripple bubble, it means that AC currents are transmit between the different phases in work.

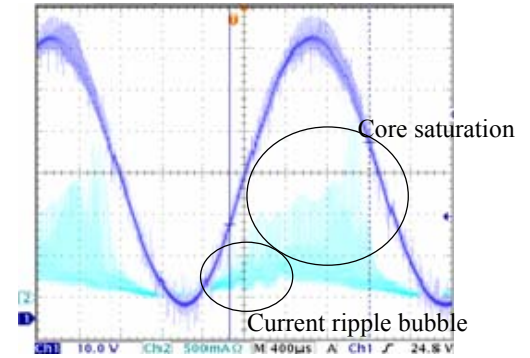


Figure 9: Experimental inverter waveforms with 5 cells in works and 1 cell not use.

C. Dysfunctions in monolithic structures

In monolithic structures, the different windings are on the same magnetic core. They have high filtering performances for a very low weight, whereas are more difficult to realise. The monolithic couplers can be produced many different ways. The most current topology is called in "scale". In this topology a problem of over sizing appear, because in some columns of the magnetic circuit there are strong concentrations of magnetic flow, Figure 10, [11] and [15].

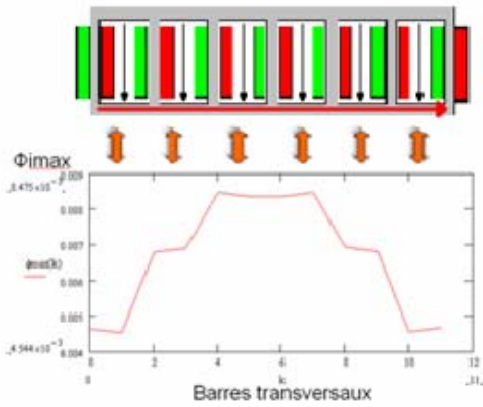


Figure 10: Distribution of the maximum induction value in a monolithic magnetic structure using a topology in “scale”.

One drawback of this structure is in the case of electrical (and magnetic) unbalances. Indeed if a winding is open, the current in this winding will be null. So the magnetic reluctance will be very low (in this leg), and the magnetic flow will pass mainly by this leg. It will change the global flow distribution in the entire magnetic circuit, and it will cause local magnetic saturation. The magnetic circuit doesn't contain an air-gap, the flow generated by each phase is totally channelled by the unused leg and each phase can then be interpreted like a simple independent inductance Figure 11. The ripple of the resulting current in each phase will be at the switching frequency and an unequal concentration of flow occurs in the magnetic circuit. It is necessary to oversize the coupler according to the tolerated number of unused legs

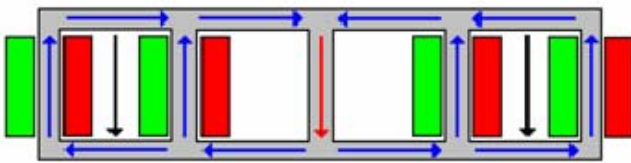


Figure 11: Flows channelled in monolithic structures with dysfunction on the central leg.

Figure 12 presents time domain waveforms for the inverter with monolithic coupling. The converter works with 6 stages and like the transformer coupling, the current ripple bubble appear.

If we use only 5 phases (instead of the six of the total converter), the magnetic filter is equivalent to five independent inductors with no air-gap. So the magnetic core will saturate, Figure 13. In these waveforms there are no current ripple bubbles, it means there is no coupling between the different phases.

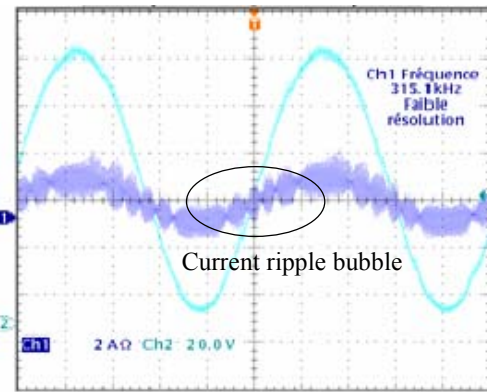


Figure 12: Experimental inverter waveforms with monolithic filter and 6 cells

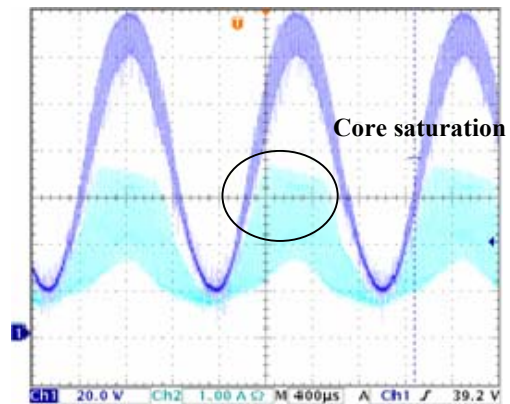


Figure 13: Experimental inverter waveforms with 5 working cells and 1 cell not in use.

IV. FAULT TOLERANCE AND CONTROL STRATEGY

In the paper [3], a method offers an interesting solution to increase the converter efficiency for output power much lower than its nominal value. The idea is to use only a part of the cells, so that each cell always works close to its nominal power as shown on figure 2 and 3. This solution is particularly interesting and can be adapted to ensure the converter operation with 1 or 2 legs out of order.

In the case of coupling filter, the iron section does not depend of the number of phases. The equation (2) always guaranteed a constant iron section even if the number of operating cells varies. So for magnetic flow saturation considerations, there is no need of increasing the switching frequency. However it can be interesting to modify the switching frequency to maintain the output switching frequency constant. This induces that the switching frequency of each cell changes, depending on the number of cells used. The **table 1** shows the switching frequency of each cell versus the number of cells used.

$$S_{fer} = \frac{E}{8 \times N_{spire} \times B e_{max} \times f_{min}} \quad (2) \quad [18]$$

N of active cells	1	2	3	4	5	6
Switching frequency of each cell (kHz)	292	146	97	73	58	48

Table 1 : Switching frequency of each cell versus the number of cells used

The increase of the interleaved cell number with the output power induces a reduction of the switching frequency of each switch. Therefore the switching losses are reduced and the global efficiency will be higher.

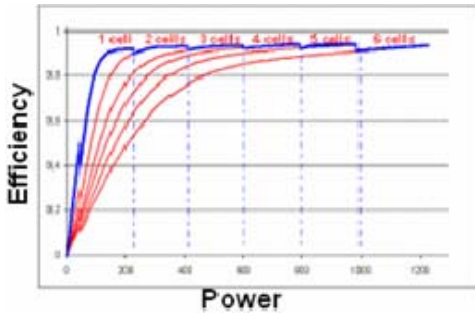


Figure 14: Efficiency optimization (blue), efficiency on variable cells (red).

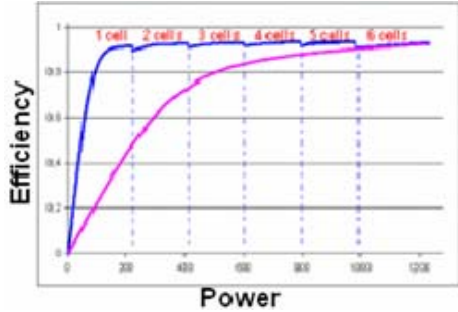


Figure 15: Efficiency optimization (blue), efficiency on classic inverter (red).

In case of control strategy for increase efficiency, all cells will not work simultaneously. To ensure the same lifetime and limit the constraint on the power transistors, the working time of each cell should be equal. A solution is to equalize the operating time of each output phase by making a circular bearing system of the cells. Of course, in case of dysfunctions the problem is different. The aim is to ensure the converter work until its repair.

In the case of the interleaved structure with filter, it is necessary to ensure that the current can always pass through the different magnetic circuit. This should be done even if some converter cells are shut down. A solution consists in short-circuiting the phases of the magnetic coupler as presented on Figure 16.

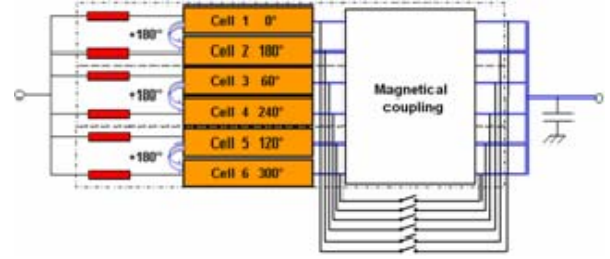


Figure 16: Additional switching to short-cut the unused phases of the magnetic output filter.

The main problem is the coupling between the phases. With this method, we can ensure to keep coupling even in case of dysfunctions. In practice, the coupling between phase n and output will generate additional losses. However, in case of reduced power this solution ensures a good compromise. The principal disadvantage of this system is the number of additional semiconductors required. The components must be controlled at turn on and turn off, be bidirectional in current and voltage. Several configurations of semiconductor devices can then be adopted (see Figure 17).

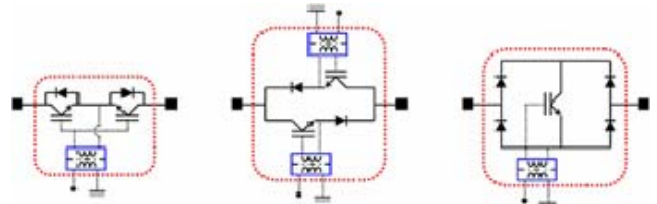


Figure 17: Switch semiconductor configuration with Transistors base.

In case of dysfunction, in order to insure a continuity of operation, the defective cell must be disconnected. To disconnect an invert arm, 3 switches are requested (red elements on Figure 18).

Many different technologies are available to insure this disconnection. Fuse technique [14] are generally found in literature, but power semiconductors can either be use. The advantages of semiconductors are that they can be electrically controlled, and they can be faster than fuse. With this flexibility and rapidity they will limit the disturbance due to the loss of one element.

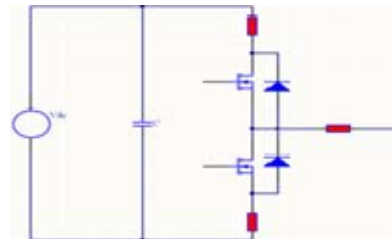


Figure 18 : Cell and switches (in red) in order to disconnect the cell

This solution (Figure 16) works with both monolithic and coupling transformers structures. However physical phenomenons are different.

In case of coupling transformers, the short circuits on defective phase insure the continuity of current loop into the transformer (see Figure 5). The Figure 19 shows the example of the loss of phase 4, in this case the short circuit of phase 4 insures that current of phase 3 and 5 will be magnetically coupled.

The DC courant will be also equitably distributed into all the magnetic structure Figure 19 (b). This figure does not take into account the magnetic loss, in the real case this short circuit of phase 4 will introduce some extra losses.

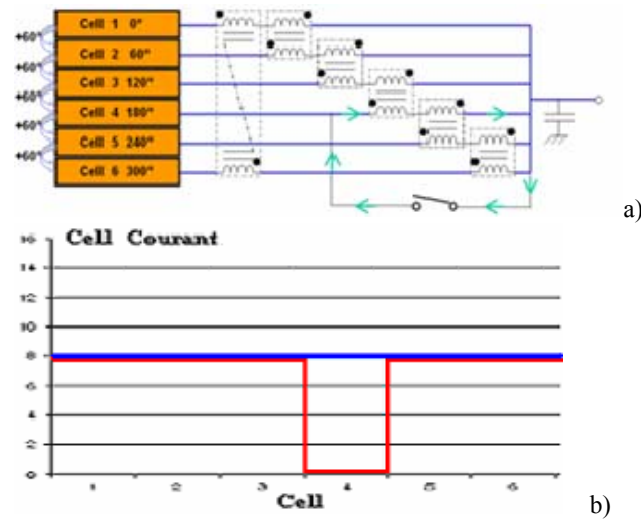


Figure 19: (a) Example of 6 cell structure with short-circuit component on cell 4. (b) In blue, courant into the different winding. In red, current going out each winding.

Figure 20 presents time domain waveforms of the inverter with transformer couplings. It shows the current ripple of the six-cell converter with dysfunction on one cell. On Figure 20, the converter works with 5 cells. One of the six cells is short-circuited and the FPGA (control circuit) has changed the phase shift. With one cell less, the courant ripple increase of a sixth. To keep it at the same level of a converter using 6 interleaved cells, we can increase the switching frequency like it is showed on table 1.

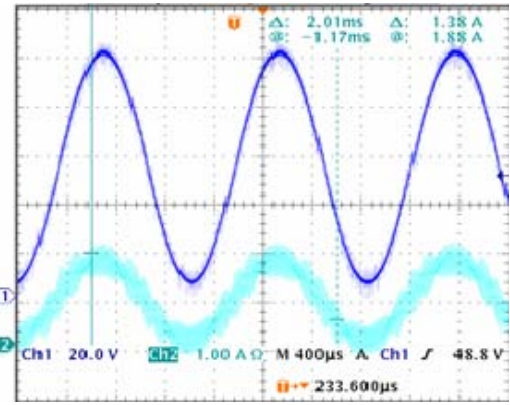


Figure 20: Experimental inverter waveforms with 5 cells

In the case of monolithic transformer, the explanation is based on flow analyze.

$$V = N \times \frac{d\Phi}{dt}$$

$$\text{If } V = 0 \text{ also } N \times \frac{d\Phi}{dt} = 0 \Rightarrow \frac{d\Phi}{dt} = 0$$

Based on Faraday's law, these equations show that flow variation is proportional to the voltage of the winding. If this voltage is null, there will be no flow variation. Therefore if a phase is broken, our system will close the switch on the corresponding winding; also the flow must be equilibrating between all other windings. Indeed, a current appear (Figure 22) that insure that the flow on the unused winding is null

In a real, case, due to unperfected coupling between windings, a stray inductance allows a way for the flow even on the short circuit winding. It will cause some extra losses.

If we connect in short-circuit the unused or broken phases, a courant appear on the unused winding, Figure 22. The flows will take another way and will not use the arms in short-circuit.

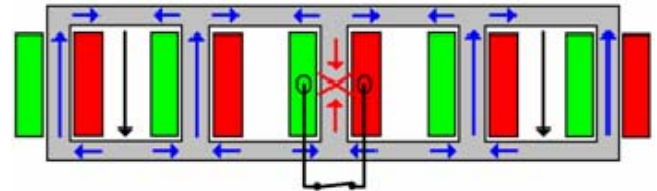


Figure 21: Circulation of flow in a coupler with 5 cells. 3 cells are used and short-circuit on the un-used phase.

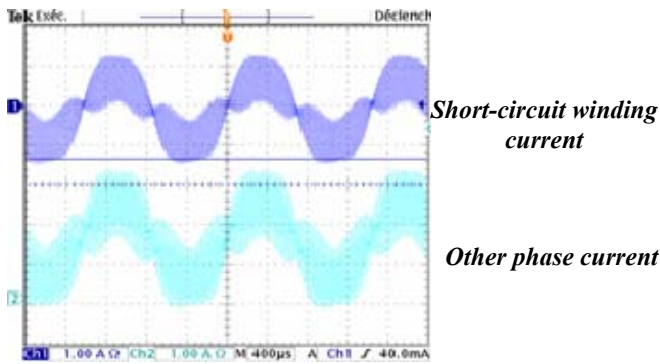


Figure 22: Experimental inverter waveforms with 2 cells and short-circuit.

For reduce iron section it can be use different phase shift between each cells, tables 2 & 3. Choose a phase shift as near as possible 180° between all adjacent winding (Table 3); allow reducing the flow on common iron section.

0	$2\pi/6$	$4\pi/6$	$6\pi/6$	$8\pi/6$	$10\pi/6$
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Table 2 : Standard phase shift

0	$4\pi/6$	$8\pi/6$	$2\pi/6$	$10\pi/6$	$6\pi/6$
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Table 3 : Permute phase shift

But phase shift between two phases vary versus the number of cell, and are more or less far from 180° . It result that an odd number of phase is better for volume reduction. The Figure 23 shows the iron losses for different cells number, the losses are directly proportionally to volume.

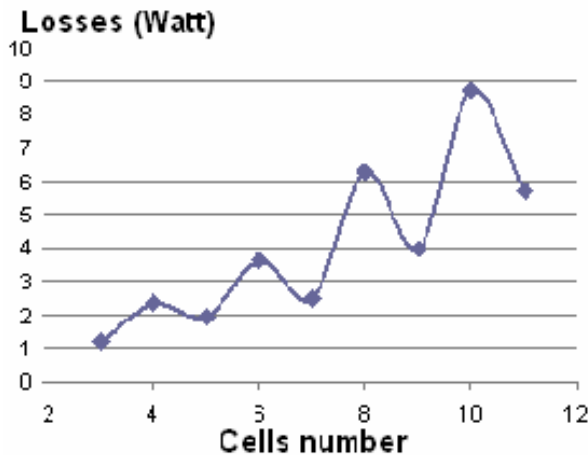


Figure 23: Iron losses for different cells number

In case of different number of phases and of various phase shifts, it can be necessary to increase switching frequency, in order to ensure a constant flow in magnetic core. In others case, some local flow saturation can appear.

V. EXPERIMENTS AND VALIDATION

Two tests benches have been developed; the first one is composed of 4 interleaved cells based on independent inductances and monolithic magnetic filters. Each cell is composed of a 3 level multi-level NPC converter. The second one is composed of 6 interleaved simple-level cells based on magnetic filters transformers. The whole system is driven by an FPGA. Figure 24 show one of these tests benches.

Each cell is able to provide a power of 400W. The global converter power is 1.6kW. The power electronic structure developed allows an auto-adaptive control. This control depends of the number of cells and the current and voltage measurements in the structure. The FPGA calculates the different control signals for each cell. The numerical structure into the FPGA is composed of a microprocessor NIOS II of Altera®.

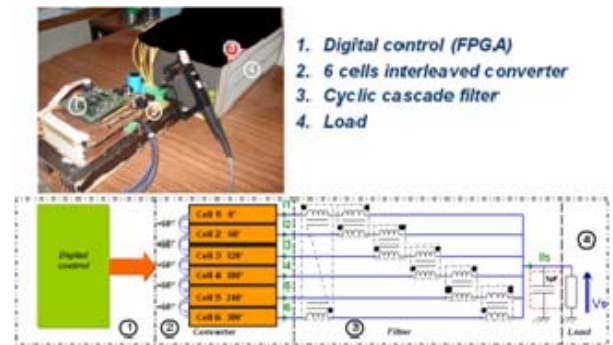


Figure 24: 6 interleaved simple-level cells based on interphase transformers.

The processor analyzes the data coming from measurements (tension and current), it adapts PWMs in real time for functioning with variable number of phases versus the measured powers. His function is also to control the output voltage of the converter. The PWM module is a high DPWM resolution according to the model developed in [17]. A USB connection is also use with software of diagnostic and system requirements.

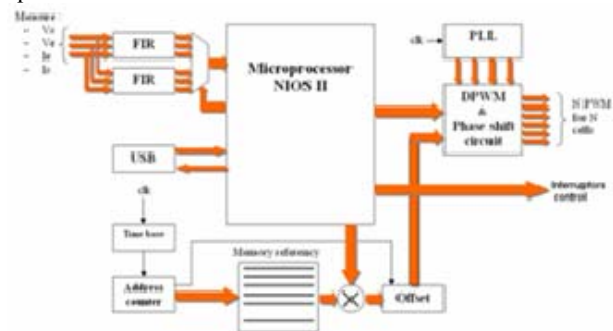


Figure 25: Numerical structure of the FPGA

VI. CONCLUSION

This paper shows an original control strategy that permits fault tolerance on an interleaved inverter with Magnetic couplers.

Part 2 presents how classical magnetic coupling Method (coupling transformers and monolithic coupler) can be used. Part 3 analyse the dysfunction mode and its effects on the coupling transformers or monolithic coupler.

Part 4 presents how power electronic structure must be adapted to take into account the fault tolerance control strategy.

Part 5 validate this approach by showing experimental setup.

Another advantage of using this control strategy is to permit the use of this kind of converter with a reduced number of phases, and so to potentially increase the efficiency.

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