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Optimal Multi-Phase Coupled Buck Converter Architecture Dedicated To Strong Power System Integration

N. Bouhalli*, E. Sarraute*, T. Meynard*, M. Cousineau*, E. Labouré†

*Université de Toulouse, LAPLACE, CNRS, INPT, ENSEEIHT, 2 rue Charles Camichel, BP 7122- 31071 Toulouse Cedex 7, France

†Ecole Normale Supérieure de Cachan, SATIE, 61 av du Président Wilson, 94235 Cachan Cedex, France

Email: nadia.bouhalli@laplace.univ-tlse.fr

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[6] or is based on the introduction of intercell transformers [7] and [8].

Abstract

Magnetic coupling is a very promising concept to be applied in interleaved power converter in a context of power electronics integration. However, several possible architectures using parallel and/or series intercell transformers can be chosen. It must be found which architectures have to be used when the number of phases increases. In the first part of the paper, a model of magnetic coupler is proposed. This model is used to analyze and compare different magnetic coupling configurations used in interleaved Buck converters in order to find the best configurations (efficiency and complexity). It is based on a harmonic analysis of a multi-phase balanced system. In the second part, an optimal modified sequence of phase order is proposed to enhance performances of configurations in order to find the best. Finally, an experiment validation is presented.

1 Introduction

Interleaved converters are widely employed in various applications such as automotive 42/14V systems and Voltage Regulator Module (VRM) (low voltage and high current). The well known advantage of this system is an increase of the apparent frequency of the current applied across the input and output filters; associating 'q' identical commutation cells fed by interleaved control signals (equal duty cycles, phase-shifts = $360/q$). The apparent frequency for the filters is 'q' times the switching frequency. In addition, an improvement of dynamic behaviour can be obtained in interleaved converters [1].

Two main solutions can be applied to interconnect interleaved commutation cells: by means of either uncoupled/independent inductors (Fig. 1) or intercell transformers (Fig. 2). By the first mean of interleaving, the increase of frequency concerns only the input filters and the output capacitor but the phase current is at the switching frequency 'f'. By the second mean of interleaving, also the apparent frequency of the current of phases is multiplied by 'q' [1–6]. Magnetic coupling in multiphase converters is realized on a monolithic magnetic core

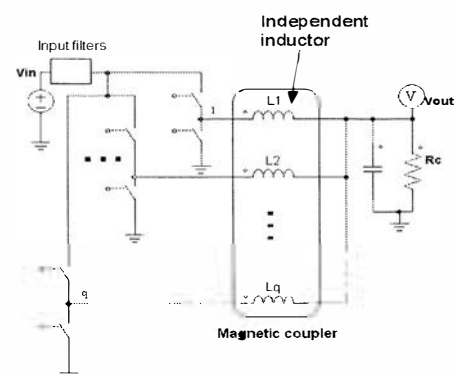


Figure 1: Interleaved converter using independent inductors

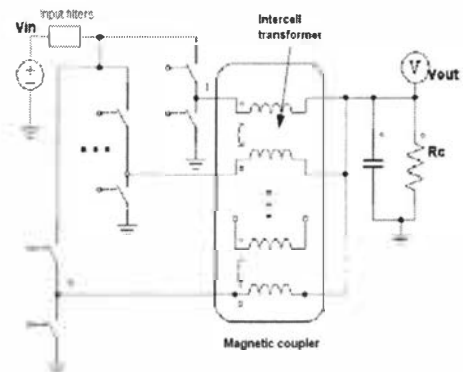


Figure 2: Interleaved converter using intercell transformers

In this paper, an analytical model of q-phase coupled Buck converter using intercell transformers is described in section 2. This model is based on a harmonic analysis of a multi-phase balanced system. In section 3, it is used to analyze and compare several coupling architectures using intercell transformers [8]. In part 4, the properties and limitations in the case of supply by a regular voltage system are described, so, an optimal modified sequence of phase order [9, 10] is proposed to enhance performances and finally experimentally tested.

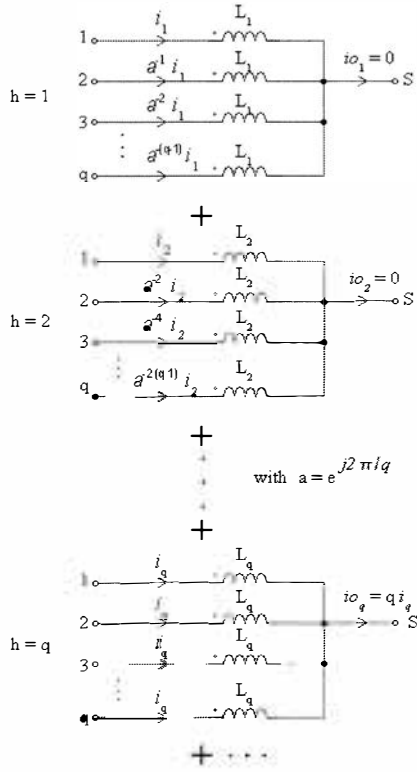


Figure 3: Harmonic model of magnetic coupler using intercell transformers

2 Modeling and analyzing of different coupling configurations

2.1 Analytical model of magnetic couplers

A q -phase coupled Buck converter using intercell transformers is shown in Fig. 2. The q -phases are fed by a q -balanced non sinusoidal voltage system that the phase shift is $2\pi/q$. This q -voltage system can be decomposed in:

- continuous component for $h = 0$ (h : harmonic row).
- sinusoidal components for $h = \alpha \cdot q$ with $\alpha = 1, 2, 3, \dots$
- sinusoidal components for other harmonic rows that are not multiple of ' q '.

Basing on this harmonic decomposition, we determine the equivalent symmetrical inductances for each harmonic row: $L_1, L_2, \dots, L_q, \dots$. Then, we define an analytical model of magnetic coupler. Based on this principle, the magnetic coupler shown in Fig. 2 is modeled by the correspondent symmetrical inductances in the different harmonic rows (Fig. 3). From Fig. 3, in a symmetrical system, ideally the output current, $i_{o_{h=1,2,\dots}}$, is zero for all harmonic rows except the harmonic rows $h = \alpha \cdot q$ when all phase currents are the same.

Analyzing currents in common mode currents and differential mode currents is useful: for the harmonic row $h = \alpha \cdot q$, we define the common mode currents and for other harmonics, we define the differential mode currents.

The common mode current ripple depends on the symmetrical inductance ' L_q ' ($h = \alpha \cdot q$). Then, ' L_q ' is the common mode inductance and the differential mode current ripple depends on the other symmetrical inductances when $h \neq \alpha \cdot q$: there are the differential mode inductances. We want the differential mode inductances to be high in order to filter the differential mode currents and we want the common mode inductances to be low to let pass the common mode current and for fast transient response while ensuring a satisfactory current ripple.

In some studied cases, when the number of parallel phases increases, the fundamental current i_1 increases in comparison with other undesirable current components. So, to filter this current component, the symmetrical inductance ' L_1 ' ($h = 1$) must be high. We introduce a new parameter: 'Effect Coupler Factor' (ECF). The ECF is equal to the ratio $\frac{L_q}{L_1}$. This new factor shows the aptitude of the magnetic coupler to filter the differential mode current and let pass the common mode current. The lower ECF , the better magnetic coupler.

2.2 Different coupling configurations

Several possible architectures using parallel and/or series intercell transformers can be chosen [8]. It must be found which architectures have to be used when the number of phases increases in a context of power integration. In this part, four magnetic coupling architectures are presented.

- Combinatorial cascade configuration (Fig. 5)
- Combinatorial parallel configuration (Fig. 6)
- Cyclic cascade configuration (Fig. 7)
- Cyclic parallel configuration (Fig. 8)

Using the analytical model, in the case of a regular voltage system supply that is shown in Fig. 4, for each coupling architecture, the symmetrical inductances L_1 and L_q corresponding respectively to harmonic rows $h = 1$ and $h = q$, are expressed by the inductance L and the mutual inductance M of each intercell transformer. In table I, are shown the different characteristics of these four configurations.

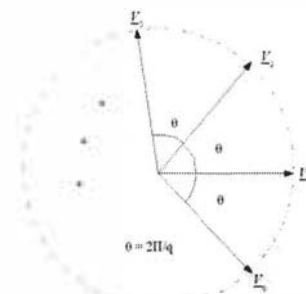


Figure 4: Supply by a regular voltage system: phase shift principle

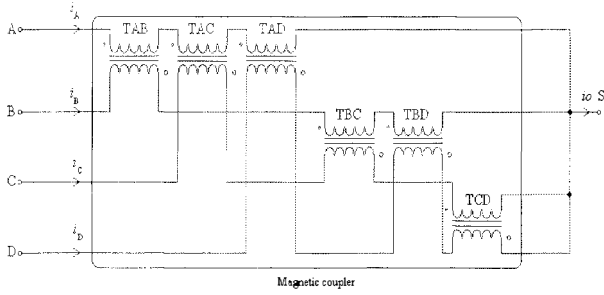


Figure 5: Combinatorial cascade configuration

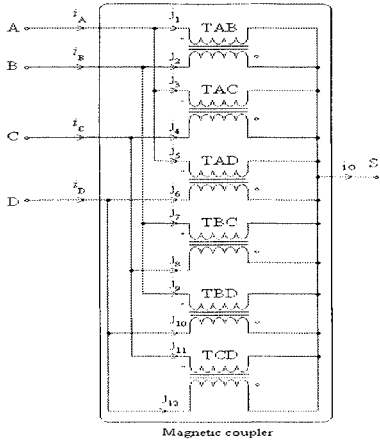


Figure 6: Combinatorial parallel configuration

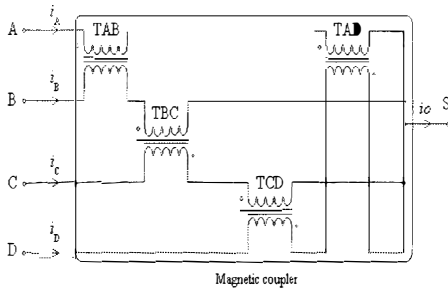


Figure 7: Cyclic cascade configuration

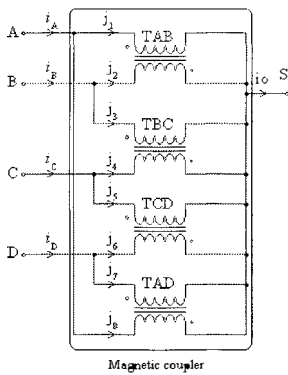


Figure 8: Cyclic parallel configuration

Coupling configurations	p	L_1	L_q
Combinatorial cascade	$\frac{q(q-1)}{2}$	$(q-1)L + M$	$(q-1)(L-M)$
Combinatorial parallel	$\frac{q(q-1)}{2}$	$\frac{L^2 - M^2}{(q-1)L - M}$	$\frac{L^2 - M^2}{(q-1)(L+M)}$
Cyclic cascade	q	$2(L - M \cos(\frac{2\pi}{q}))$	$\frac{1-k}{1 - k \cos(\frac{q-1}{2} \cdot \frac{2\pi}{q})}$
Cyclic parallel	q	$\frac{L^2 - M^2}{2(L + M \cos(\frac{2\pi}{q}))}$	$2(L - M)$

Table I: Coupling configurations characteristics (p: number of intercell transformers, q: number of parallel phases and L: the inductance)

3 Comparative Analysis

The model presented in (2.1) is used to analyze these architectures in aspects of efficiency and complexity. In table II are compared the total number of intercell transformers p, the ratio L_q/L and the Effect Coupler Factor ECF respectively for the four magnetic coupling configurations of multi-phase Buck converter for a given intercell transformer: $k = 0.99$ (k : the coupling factor). In a best configuration, p must be low, L_q/L increases by increasing the number of parallel phases, thus enhance the dynamic performance of the system, minimize the size of magnetic components and reduce current ripple. Also, the ECF should be as low as possible to filter undesirable signals and to pass the common mode currents at the frequency $q.f$.

Fig. 9 shows that the combinatorial cascade configuration is the most advantageous in the aspect of a low value of ECF and a high L_q/L (Fig.10 (a)) despite of the significant number of intercell transformers to implement when the number of phases increases (Fig.10 (b)). Also, the cyclic cascade configuration is advantageous in the aspect of a low number of transformers but the ECF , in this case, is higher than in the combinatorial cascade. The combinatorial parallel and the cyclic parallel configurations are not interesting because ECF is high and L_q/L is low in these two cases. To enhance performances, a solution consists of an optimal modified sequence of voltage supply order [9].

Coupling configurations	p	$\frac{L_q}{L}$	$ECF = \frac{L_q}{L_1}$
combinatorial cascade	$\frac{q(q-1)}{2}$	$(q-1)(1-k)$	$\frac{1-k}{1 + \frac{k}{q-1}}$
combinatorial parallel	$\frac{q(q-1)}{2}$	$\frac{1-k}{q-1}$	$\frac{(q-1)k}{(q-1)(1+k)}$
cyclic cascade	q	$2(1-k)$	$\frac{1-k}{1 - k \cos(\frac{2\pi}{q})}$
cyclic parallel	q	$\frac{(1-k)}{2}$	$\frac{1+k \cos(\frac{2\pi}{q})}{1+k}$

Table II: Comparison of the coupling configurations in a regular supply mode ($k = \frac{M}{L}$: coupling factor, q: number of parallel phases, L_q : common mode inductance, L: the inductance and p: number of intercell transformers)

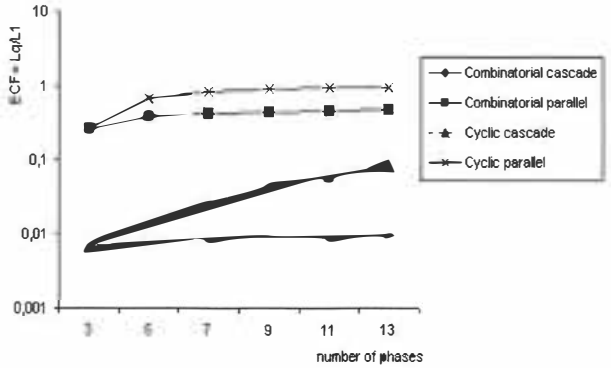


Figure 9: ECF evolution with the number of phases for the 4 coupling configurations in a regular supply mode

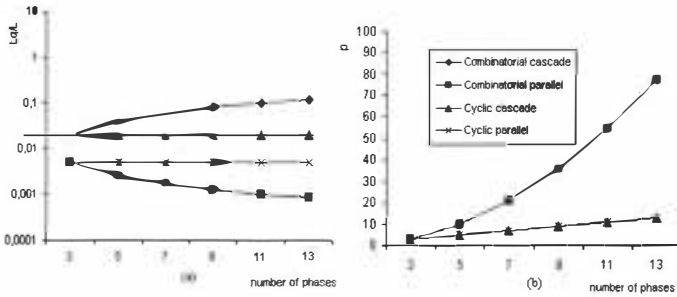


Figure 10: (a) L_q/L and (b) number of intercell transformer 'p' evolution with the number of phases for the 4 coupling configurations

4 Interest of voltage sequence permutation

In case of supply by a regular voltage system ($2\pi/q$), it was shown that the combinatorial cascade architecture is advantageous despite of the high number of transformers to implement. In aspect of number of transformers (Fig.10 (b)), the cyclic cascade is advantageous but the ECF increases with the number of phases (Fig. 9). To solve this problem, a permutation of voltage system is needed. In [9, 10], for odd number of interleaved phases, the optimal phase-shift is $\pi - \frac{\pi}{q}$. The vector diagram of Fig. 11 illustrates an example of permutation of 5-parallel phases. In this case, the optimal phase-shift between two successive interleaved control signals is $(2.2\pi/5)$.

In table III are compared the total number of intercell transformers p , the ratio L_q/L and the Effect Coupler Factor ECF respectively for the four magnetic coupling configurations of multi-phase Buck converter for a given intercell transformer: $k = 0.99$ in a permuted voltage supply system.

In fact, by modifying the voltage supply sequence, the relationship between flux is modified. Consequently, the value of symmetrical inductances for different harmonic rows are permuted and then the Effect Coupler Factor is modified. From table III, it can be noted that the permutation solution does not affect both the combinatorial cascade and the combinatorial parallel configurations. Fig.12 shows the evolution of ECF in the permuted mode for the different configurations. It can be seen

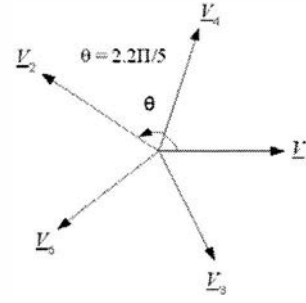


Figure 11: Permuted voltage supply system for 5 coupled phases

Coupling configurations	p	$\frac{L_q}{L}$	$ECF = \frac{L_q}{L_1}$
combinatorial cascade	$\frac{q(q-1)}{2}$	$(q-1)(1-k)$	$\frac{1-k}{1+\frac{k}{q-1}}$
combinatorial parallel	$\frac{q(q-1)}{2}$	$\frac{1-k}{q-1}$	$\frac{(q-1)-k}{(q-1)(1+k)}$
cyclic cascade	q	$2(1-k)$	$\frac{-k}{1-k \cos(\frac{q-1}{2} \cdot \frac{2\pi}{q})}$
cyclic parallel	q	$\frac{(1-k)}{2}$	$\frac{1+k \cos(\frac{q-1}{2} \cdot \frac{2\pi}{q})}{1+k}$

Table III: Comparison of the coupling configurations in a permuted supply mode for odd number of interleaved phases

the impact of the permutation solution on decreasing of the ECF in the cyclic cascade and cyclic parallel configurations. The cyclic cascade, in the permuted supply, has the lowest ECF that becomes constant when $q \geq 7$.

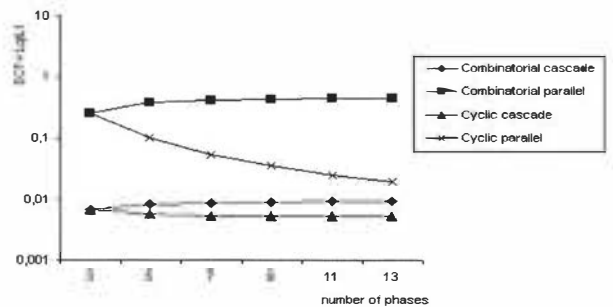


Figure 12: ECF evolution with the number of phases for the 4 coupling configurations in a permuted supply mode for odd number of interleaved phases

5 Experimental results

To validate the influence of the permutation of sequence of supply, we have tested a 5-coupled Buck converter in a cyclic cascade configuration. In the experience, $f = 250 \text{ KHz}$, $L = 10.56 \mu\text{H}$, $M = 10.54 \mu\text{H}$ and $k = 0.99$. Fig.13 and Fig.14, show the phase current waveforms respectively in the regular supply mode and in the permuted supply mode. The reduction of the fundamental current component in the second supply mode is noted. The simulation results, using the analytical model, are confirmed. With the permuted mode, the phase current ripple is reduced, which is interesting in power system

integration. It is important to see from Fig.15 and Fig. 16 that there is no impact of the permuted mode on the output current waveforms.

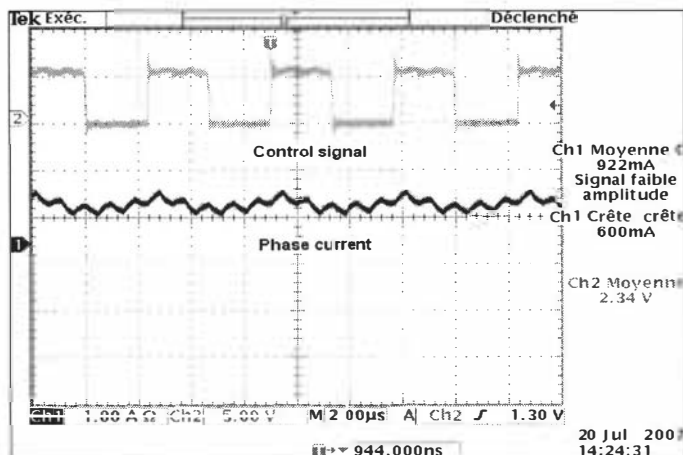


Figure 13: Phase current i in a cyclic cascade architecture in a regular supply mode for $q = 5$

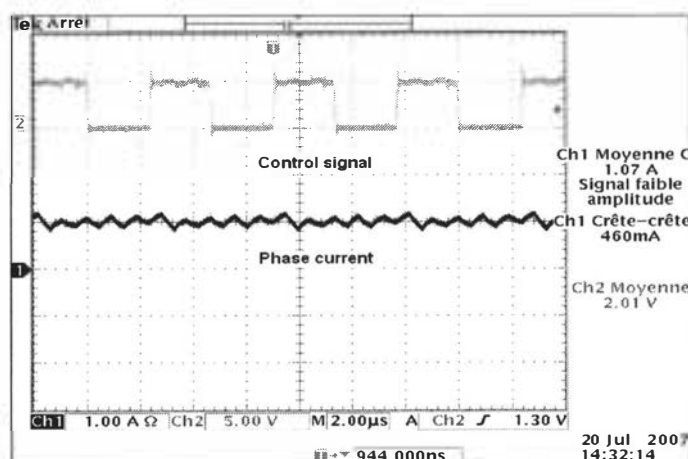


Figure 14: Phase current in a cyclic cascade architecture in a permuted supply mode for $q = 5$

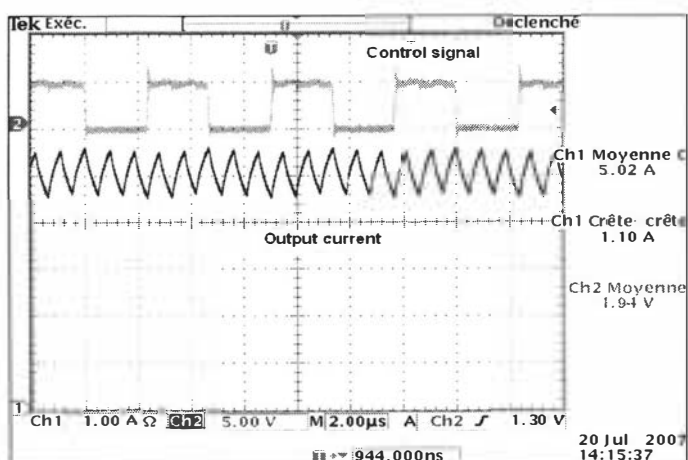


Figure 15: Output current waveform in a regular supply mode for $q = 5$

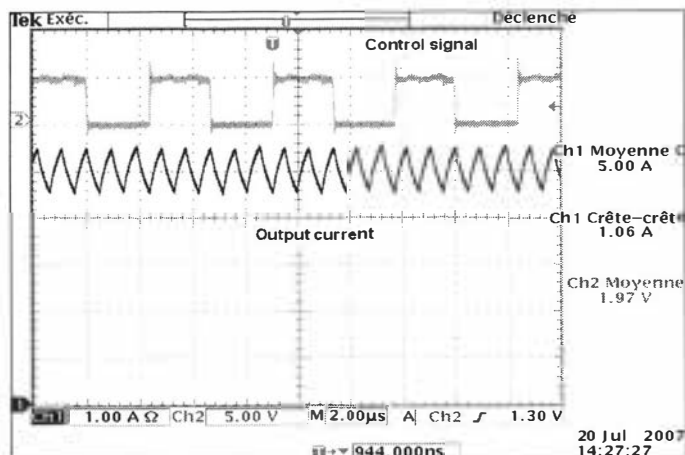


Figure 16: Output current waveform in a permuted supply mode for $q = 5$

6 Conclusion

A harmonic model of magnetic coupler has been developed and used to analyze and compare different architectures of coupling. In this paper, it is shown that with this model, some configurations of coupling are better adapted than others when the number of phases increases. The combinatorial cascade configuration seems to be well adapted for high parallelism approach despite of the significant number of transformers to implement. By the choice of an optimal sequence of phase order, the performances of the cyclic cascade configuration are enhanced. Experimental results confirm the theoretical study.

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