Letters

Optimized Switching Sequence for Multiphase Power Converters Under Inductance Mismatch

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***Abstract*—Multiphase power converters allow to reduce semiconductor stress and to improve total ripple characteristics, when compared to a single-phase converter. Semiconductor stress is reduced by dividing the total current among the N parallel-connected converters or phases. Furthermore, total ripple amplitude is reduced and its frequency increases to N times the switching frequency by interleaving each phase current ripple, which lessens the requirements on the total current filtering. These improvements, however, are detrimented mainly by mismatches among the phase inductors value, leading to different ripple amplitudes among phases. As a consequence, when compared to the ideal case, total ripple amplitude is increased, ripple cancellation points are lost, and switching frequency component and its $N-1$ harmonics are generated. This letter proposes a method to mitigate this problem by selecting the phase switching sequence, in converters operating in the continuous conduction mode, which minimizes the switching frequency component and its harmonics in the total ripple. The proposed method efficiently finds the proper switching sequence for any number of phases, by using a previously presented current ripple characterization as the objective function for the optimization procedure. Simulations validate the proposal and show the improvement, when compared to another strategy present in the literature, which uses the switching sequence modification principle.**

***Index Terms*—Current ripple, genetic algorithms, multiphase power converters, switching sequence.**

I. Introduction

MULTIPHASE power converters consist in the parallel connection of N equal converters, in such a way that the total current i_T is divided among N paths or phases. When compared to a single converter, multiphase converters reduce switching and conduction losses, by dividing total current among phases, and improve total current ripple (Δi_T) characteristics, which include amplitude reduction and frequency increase to N times the switching frequency f_s, by interleaving each phase current ripple [1], [2].

However, the aforementioned features can be affected by various practical implementation factors, such as tolerances and parasitic elements on the converter passive and active components. In this sense, series voltage drop on switching devices and inductor parasitic resistance could produce mismatch on the mean current among phases [3]. Nevertheless, this effect, as well as the nonideal phase shift produced by delays on switching devices and drivers, can be mitigated by means of control techniques [2], [4], [5]. Furthermore, inductance value tolerance produces differences on each phase current ripple amplitude, which impacts on the total current ripple characteristics [6], [7]. In this condition, switching frequency component f_s and its $N-1$ harmonics are not cancelled in Δi_T. As a consequence, if the filter designed for the ideal case is used, the voltage ripple amplitude is increased in the common point among phases. This problem becomes more significant as the number of phases increases, where the minimum expected frequency is Nf_s.

The effect of mismatch among phase inductors values can be reduced by means of two different approaches. First, phase shift among phases can be modified from the ideal value $2\pi/N$, as proposed in [8]–[10]. Second, the switching sequence can be modified in order to reduce the vectorial sum of f_s component and its harmonics, as proposed in [7].

The first strategy aims at modifying the instantaneous phase shift among phases in such a way that the f_s component and selected harmonics are cancelled on Δi_T. As this procedure is performed by continuously modifying the phase shift, no transients are generated; therefore, it can be used as an online correction. Consequently, this strategy is attractive in such cases where significant changes in the inductance value are expected when varying the operating point; or in asymmetric converters where different input voltages are present in each phase. However, it requires a high computational effort, particularly for systems with high number of phases, as it involves solving a system with $N-1$ nonlinear equations to eliminate $(N-1)/2$ harmonics in Δi_T. Additionally, when applied to symmetric converters where small phase-shift correction magnitudes are required, the improvement is limited due to measurement errors and signal delays [9], [10].

The second approach is very attractive for applications that require high number of phases, such as [2], [11], [12]. This principle is based on the fact that, as Δi_T depend on the relative position between phases ripple, there is an optimal switching

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sequence that minimizes harmonic content. Due to the transient generated when modifying the switching sequence, this strategy is more suitable for an offline correction. Therefore, it is limited for the cases where the inductance ratio among phases do not change significantly with the operating point, such as in applications that use gapped inductors [13]. In them, this approach improves the Δi_T characteristics without requiring modifications on the current control or affecting its stability or dynamic behavior. However, complexity for the optimal sequence determination increases with the factorial of N, and no closed expression exists to calculate the optimal sequence analytically [14], [15].

In order to reduce the computational cost, a method that shifts 180° the phases with closest ripple amplitude has been presented in [7]. The switching frequency component is, therefore, reduced, and the implementation is simple. Nevertheless, cases with an odd number of phases cannot be optimized and, as only the f_s component is considered, the obtained switching sequence is not always optimal.

Consequently, a methodology that allows performing the phase-ordering procedure in such a way that the Δi_T characteristics could be directly evaluated is required. In this sense, the previously presented current ripple characterization [6] provides the means for the evaluation of each switching sequence, which enables using more efficient optimization procedures such as metaheuristic methodologies [16].

This letter proposes a method to efficiently determine the switching sequence in converters operating in continuous conduction mode (CCM). The proposed method is capable of considering the f_s component and its $N-1$ harmonics in the optimization procedure, and it can be used in converters with any phase number. This is accomplished by using the previously presented current ripple characterization [6] as the evaluation function for the optimization procedure. The proposed method has been evaluated throughout simulations. It has also been compared against the ideal and worst cases; as well as with the other optimization method based on the same principle. It is shown that the proposed method allows to obtain similar results as the ones obtained in the ideal case, where no mismatch among phases inductor is present.

II. PROPOSED METHOD

The aim of the proposed method is to find the optimal switching sequence for any number of phases, without requiring the test of all possible cases. As previously stated, the switching sequence modification principle produces transients in the total current when the sequence is changed. Therefore, the proposed method is intended for offline corrections. Furthermore, current ripple characterization [6] will be used as the evaluation function for each switching sequence. For the purpose of the switching sequence determination, genetic algorithms will be used as optimization procedure, since they enable the efficient search of a global solution in a complex optimization problem [16], [17].

Genetic algorithms are adaptive methods that generate solutions based on the evolutionary ideas of natural selection and survival of the fittest. In this algorithm, a population of potential solutions, named chromosomes or individuals, evolve throughout successive iterations, named generations. In each generation, the fitness of every individual in the population is evaluated by assigning a score that depends on how it adjusts to the searched solution. The score is determined using a cost function also named objective function. Evolution throughout successive generations is carried out using genetic operators such as crossover and mutation. Crossover creates offspring from the combination of information provided by two individuals of the current generation. The more the individual adjusts to the problem, the more chances it has of combining its information with another individual, and therefore, spread its genetic material to future generations. Conversely, mutation is a low-probability genetic operator that randomly alters individual's properties before introducing them in a new generation. Mentioned operators have different roles within the algorithm: as crossover tends to improve average quality of the population by exploring known solution spaces, mutation allows to search new unexplored spaces while avoiding local minima. In order to preserve the solutions that properly adjust to the cost function, a certain amount of the fittest individuals, named elite, get to the next generation without suffering changes.

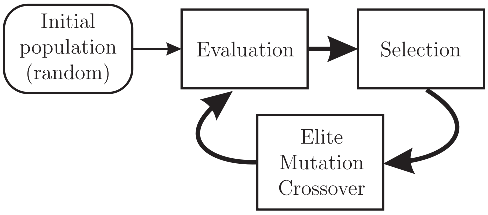


Fig. 1. Genetic algorithms flow diagram.

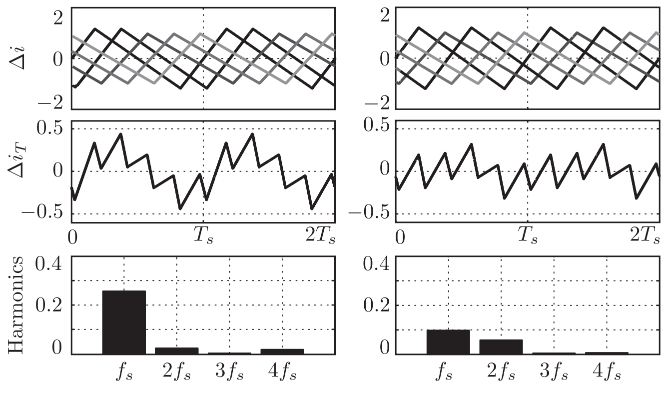
Fig. 1 shows the block diagram of a genetic algorithm. It starts with a randomly created population, generally much smaller than the total possible cases. This initial population is scored according to the results obtained from the cost function. Based on the scores, a selection of the individuals that create the next generation is made. A new evaluation returns the population to the original size by choosing the fittest individuals. The algorithm continues until a termination criterion is reached.

The following sections detail the problem modeling, the objective function, the genetic operators, and the termination criterion aforementioned.

A. Modeling and Codification of the Problem

Potential solutions for the problem are modeled using a set of parameters known as genes so that they compose the chromosome or individual. As the switching sequence determination is an ordering problem, each individual consists of an ordered array that contains each phase ripple amplitude.

As an example, for an eight phase converter, the individual $I_1 = (A1\ A2\ A3\ A4\ A5\ A6\ A7\ A8)$ represents the case in which L_1 phase inductor associated ripple precedes L_2 phase inductor associated ripple, and so on. On the other hand, in the individual $I_2 = (A2\ A1\ A3\ A4\ A5\ A6\ A7\ A8)$, L_1 and L_2 ripples order is reversed in such a way that $A2$ amplitude precedes $A1$ amplitude.



(a) (b)

Fig. 2. Phase Δi and total Δi_T ripple with ($N-1$) harmonics for two different switching sequences, for a $N = 5$ converter.

Due to the nature of the problem, individual composition is attached to restrictions that guarantee its validity. First, every individual should comprise the ripples amplitudes of all phases. Second, no repeated amplitudes are allowed within the same individual. These restrictions can be taken into consideration in two different ways.

1) By penalization of invalid individuals, assigning poor fitness value, and therefore, preventing reproduction.
2) By using appropriate forms of genetic operators so that they always produce valid individuals.

For the purpose of this letter, the second strategy is adopted in order not to waste computational effort for the generation and evaluation of invalid individuals.

B. Objective Function

The objective function, defined as $f_{\text{fit}}(I_j)$, returns an indicator of the individual I_j fitness according to the chosen optimization criterion. In this case, the aim is to minimize the filtering requirements in the phases common connection point by modifying the switching order. As in the ideal case the first nonzero component is Nf_s, minimizing the peak-to-peak current ripple implies minimizing the frequency components f_s to $(N-1)f_s$, as it can be determined from [6]. Therefore, a suitable evaluation function should provide the peak-to-peak current ripple as a function of the individual phase ripple amplitudes and position, for a given operating point.

As an example, individuals I_1 and I_2 that produce Fig. 2(a) and (b), respectively, can be compared. As it can be seen, the harmonic content, and therefore, the peak-to-peak current ripple amplitude is smaller in the situation depicted on Fig. 2(b). Therefore, the evaluation function should indicate that I_2 individual is fitter than I_1, i.e.

$$f_{\text{fit}}(I_2) < f_{\text{fit}}(I_1). \tag{1}$$

In [6], a Δi_T characterization method has been presented for interleaved converters operating in CCM. This characterization calculates the peak-to-peak Δi_T amplitude, among other total ripple characteristics, as a function of the number of phases N, duty cycle D, and phase ripple amplitudes. This method calculates the Δi_T positive and negative peaks, associated to phase x, defined as P_+^x (2) and P_-^x (3), respectively. Peak-to-peak ripple amplitude is, therefore, determined by computing said peaks for $x = 1$ to $x = N$, and selecting the extreme values, as shown in (4).

$$\begin{aligned} P^x_{+(D)} = & \sum_{k=0}^{N-1} A_{(x-k)} \left[1 - \frac{2k}{(1-D)N}\right] + \\ & + \sum_{k>N(1-D)}^{N-1} A_{(x-k)} \left[\frac{2k}{(1-D)DN} - \frac{2}{D}\right] \end{aligned} \tag{2}$$

$$\begin{aligned} P^x_{-(D)} = & -\sum_{k=0}^{N-1} A_{(x-k)} \left[1 - \frac{2k}{DN}\right] - \\ & - \sum_{k>N\cdot D}^{N-1} A_{(x-k)} \left[\frac{2k}{(1-D)DN} - \frac{2}{(1-D)}\right] \end{aligned} \tag{3}$$

where $A(x)$ is the current ripple amplitude of phase x and D is the duty cycle.

$$f_{\text{fit}}(I_j) = \max\left(P_+^x\right) - \min\left(P_-^x\right). \tag{4}$$

The necessary phase ripple amplitudes to obtain the Δi_T characteristics can be obtained through measurements of the steady-state phase current ripple. However, inductors value, and thus, phase ripple amplitude, may vary according to average current due to magnetic core nonlinear response [13]. For this reason, the ordering method is appropriate whenever the ratio between inductors value does not change significantly with the average current, such as converters with gapped inductors or applications with reduced average current variation.

C. Crossover Function

Crossover function exchanges information between two individuals of the current generation, named parents, so as to create a new individual, named offspring. Since Δi_T is affected by phase relative order and not by their absolute position, then order crossover function is attractive due to its simplicity and effectiveness [18]. The mentioned crossover function takes a phase subsequence of one of the parents and preserves the relative order of the second one.

As an example, considering parents P_1 and P_2, a selection of two random cut points is made. This is marked by "|," in the following equation:

$$\begin{aligned} P_1 &= (A1\ A2\ |A3\ A4\ A5|\ A6\ A7\ A8) \\ P_2 &= (A3\ A4\ |A2\ A5\ A1|\ A6\ A8\ A7). \end{aligned} \tag{5}$$

The resulting O_1 offspring is created as follows. First, amplitudes inside the cut points of parent P_1 are copied to the offspring, keeping their original order and position

$$O_1 = (\_\_\ \_\_\ |A3\ A4\ A5|\ \_\_\ \_\_\ \_\_). \tag{6}$$

Then, remaining phases are chosen from the second parent P_2, starting from the second cut point and omitting phases already present in O_1 ($A3$, $A4$, and $A5$ in this case).

$$O_1 = (A2\ A1\ |A3\ A4\ A5|\ A6\ A8\ A7). \tag{7}$$

Additionally, different individuals from the same parents can be created by reversing the order of the parents.

D. Mutation Function

Mutation function modifies the genes of a randomly chosen individual, before introducing it in a new generation. Mutation is carried out by reversing the order of two phases, in order to create a new ordering that explores other solution spaces avoiding local minima convergence. For example, from P_1 individual, O_1 is generated by reversing phases $A3$ and $A7$, as shown in the following equations:

$$P_1 = (A1\ A2\ \underline{A3}\ A4\ A5\ A6\ \underline{A7}\ A8) \tag{8}$$

$$O_1 = (A1\ A2\ \underline{A7}\ A4\ A5\ A6\ \underline{A3}\ A8). \tag{9}$$

E. Termination Criterion

Considering that genetic algorithms search the most appropriate ordering by iterating successive generations, it is necessary to have a criterion that indicates the convergence to a solution. Many criteria have been introduced in the literature to determine the end of the iterative process such as: maximum error bound, maximum number of generations, or relative improvement between one generation and the previous ones [19].

First, in the case of phase ripple ordering, it is not possible to establish a maximum error bound. This is the result of not knowing in advance the expected maximum or minimum Δi_T for a given inductance mismatch. Second, defining the termination criterion as the maximum number of generations is not practical, since it is possible to carry out more iterations than required or to stop the process before obtaining an optimal solution. Finally, if relative improvement between one generation and the previous ones is chosen as a termination criterion, it is possible to reach an adequate solution when no change occurs during a certain number of generations.

In this case, the relative improvement throughout generations is the most-suitable criterion, as it allows to define the stop point without knowledge on the error bounds or the risk of overdimensioning the number of iterations. It is important to point out that, through this methodology, the mutation plays the important role of avoiding early convergence to suboptimal switching sequences [20].

III. PROPOSED METHOD EVALUATION

In order to validate the proposed method, simulation tests have been carried out on the circuit simulator NL5. For the simulations, it is assumed that the phase shift is set to the ideal $2\pi/N$ by the appropriate driving signals generation [2], [11], [21]. Furthermore, simulations take into consideration the main inductor and filter practical parameters, such as capacitor's equivalent series resistance (ESR) and equivalent series inductance (ESL), and inductor's series resistance. Additionally, inductance value tolerance is set to ±10%, which is a typical tolerance in gapped or planar inductors [6], [7]. The converter parameters are listed in Table I.

TABLE I
SIMULATED CONVERTER PARAMETERS

Description	Value
Switching frequency, f_s	50 kHz
Input voltage, V_i	100 V
Output voltage, V_o	30 V
Load resistance, R_L	350 mΩ
Filter capacitance, C_L	10 μF
Filter capacitor's series resistance, ESR_{C_L}	40 mΩ
Filter capacitor's series inductance, ESL_{C_L}	20 nH
Nominal phase inductance, L_n	100 μH
Inductor's series resistance, ESR_L	10 mΩ
Phase inductance tolerance	±10 %

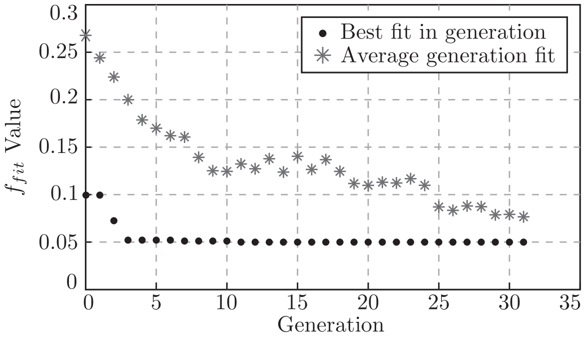


Fig. 3. Best and average fit of each generation, corresponding to the $N = 8$ converter.

The genetic algorithm population size and mutation rate are selected according to [22]. In this study, it is reported that a small population size with relatively large mutation rate allows to find better solutions, while reducing the evaluation function calls. Particularly, population size is set to 50 individuals per generation, 95% of which are created by crossover function and 5% by mutations. The two fittest individuals of the population move to the next generation without changes.

The termination criterion consist on evaluating whether variations exists in the best individual along 20 generations. If no variations are detected, said individual is considered as the optimum switching sequence and the algorithm is stopped.

First an $N = 8$ converter is evaluated, so as to illustrate the evolution across generations and to compare the current and voltage ripple for different phase orderings. Fig. 3 shows the best individual fitness value, obtained by using (4), and the average population fitness value for the described converter. As it can be noted, the algorithm convergence is reached in 31 iterations. It should be pointed out that, as the population size is 50 individuals, the fitness function is evaluated at most $31 \cdot 50 = 1550$ times, out of a total of $N! = 8! = 40\,320$ possible switching sequences. The convergence is detected because the best individual does not change along 20 generations. It should be noted that the average fitness value is not monotonically decreasing. This occurs because the mutation operator is successfully exploring different solution spaces. Then, the best individual, which represents the phase switching order that

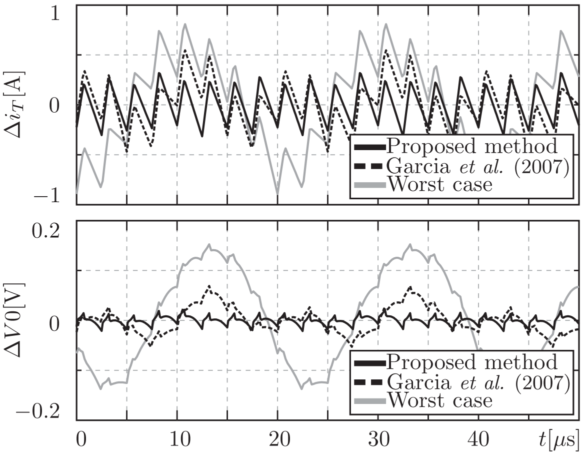


Fig. 4. $N = 8$ phase converter. Δi_T (top) and ΔV_0 (bottom) using different optimization procedures.

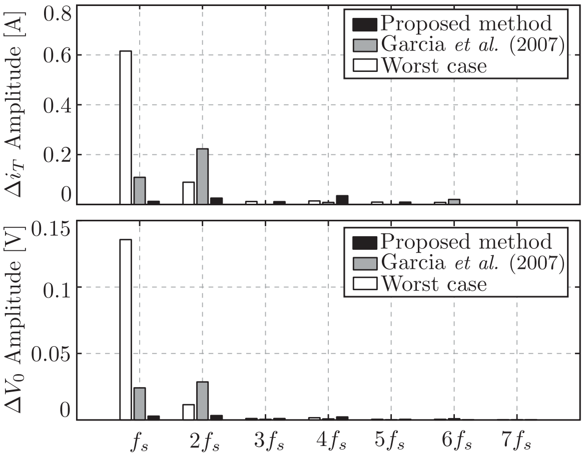


Fig. 5. $N = 8$ phase converter. Frequency components of Δi_T (top) and ΔV_0 (bottom) using different optimization procedures.

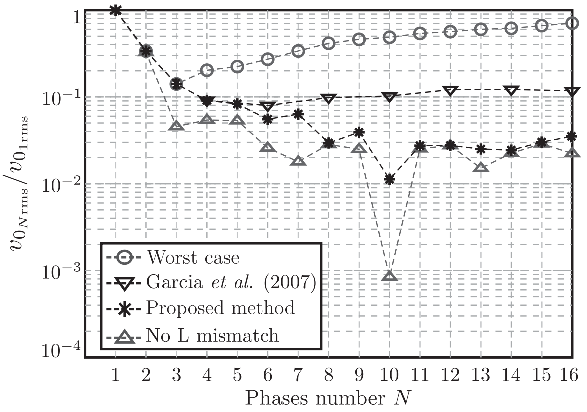


Fig. 6. Ripple attenuation as a function of N. Proposed method comparison.

minimize the peak-to-peak current ripple Δi_T is

$$I_B = (A3\ A2\ A4\ A8\ A6\ A7\ A5\ A1). \tag{10}$$

The optimization results on Δi_T and ΔV_0, when using switching sequences obtained with different optimization procedures, are shown in Fig. 4. Moreover, Fig. 5 shows f_s component and its first $N - 1$ harmonic amplitudes. The optimization procedures used in this test are the proposed method, the method presented in [7], and the worst switching sequence. The worst case is obtained by using the proposed method to maximize the fitness function. It should be noted that the worst case is a possible switching order if a random order with no optimization is applied.

As it can be noted, the method proposed in [7] produces a significant improvement over the worst case, mainly due to the reduction of the f_s component, even though the $2f_s$ component is increased. On the other hand, as the proposed method performs the optimization procedure by minimizing the fitness function, both f_s and $2f_s$ components are reduced. Therefore, improvements are achieved with respect to both cases. Particularly, if compared with the method presented in [7], the amplitude of the f_s and $2f_s$ components are reduced 6.37 times and 9 times, respectively.

Additionally, to evaluate the proposed method for different number of phases, RMS output voltage is evaluated for $N = 1$ to $N = 16$. In order to be able to compare the different situations, output load and filter are not modified throughout the test and the relative RMS voltage is evaluated. Relative RMS voltage is defined as the ratio between the N-phase converter RMS voltage, $v_{0_{N\,\mathrm{rms}}}$, and the single-phase RMS voltage $v_{0_{1\,\mathrm{rms}}}$.

Fig. 6 shows the relative RMS voltage, when using the proposed method and the method presented on [7] (for the cases with an even number of phases). Furthermore, the ideal case without inductance mismatch as well as the worst case are included as a reference.

The worst and ideal cases are first analyzed in order to establish the optimization boundaries. As previously stated, duty cycle remains constant for the different N, thus output voltage is attenuated by two different factors: by interleaving the phases ripples, and by the output filter. Particularly, in this ideal case and considering that the duty cycle is $D \approx 0.3$, a Δi_T cancellation point is present for $N = 10$. Moreover, it can be seen that, even though the minimum frequency is directly proportional to N, the attenuation does not increase accordingly. This occurs because the filter capacitor's ESR and ESL limit the maximum filter attenuation. Therefore, this ideal case is the best achievable case for the load and filter considered in the present tests. Conversely, worst case is obtained for each case by applying the proposed method to maximize the fitness function.

By using the previously described ideal and worst cases, different optimization procedures can be compared. As it can be seen in Fig. 6, for $N \leq 3$, different phase ordering does not modify Δi_T, as the resulting sequence is the same. Furthermore, for $N = 4$, the proposed method yields the same result as the method presented in [7]. Additionally, it can be noted that, even though the method presented in [7] effectively avoids the worst case for an even number of phases, no ripple improvements are observed when increasing the number of phases above $N = 6$. On the other hand, the proposed method is able to optimize the switching order both for even and odd N. Moreover, the obtained attenuation is close to the ideal case, particularly, for large N. As an example, for $N \geq 8$, the proposed method attenuation is between 3.3 and 9 times larger than the one obtained when using the methodology presented in [7] (whenever applicable), and between 14 and 43 times better than the worst case.

IV. CONCLUSION

One of the main advantages of interleaved power converters is the reduction in the total current filtering requirements. However, mismatches among phases inductance increase total ripple amplitude and harmonic content. In this study, a method has been presented to reduce this effect, based on the offline switching sequence modification principle. The proposed method uses a previously presented current ripple characterization as the evaluation function for the optimization procedure, which allowed to optimize the switching sequence for any number of phases N and mismatch condition, on interleaved power converters operating in CCM. The proposal has been evaluated and compared with the other method present in the literature that uses the same principle, arriving at different conclusions for different N. First, for small N, the obtained results are close to the ones obtained by using the other method. However, the proposed method is able to optimize the cases with odd N ($N = 5$ and $N = 7$). Second, if a large number of phases is considered, the attenuation obtained by using the proposed method is close to the ideal case attenuation. For example, when $N \geq 8$, the attenuation is at least 3.3 and 14 times larger than the one obtained with the other method and the worst case, respectively. Therefore, by using the proposed method, it is possible to extend the benefits present on ideal interleaved power converters to practical cases, without requiring modifications on the current control.

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