

Interleaved Buck Converter with Coupled Inductors as Auxiliary Bias-Current Source for Controllable Magnetic Devices

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Abstract

This paper presents an Interleaved Buck Converter with Coupled Inductors as a DC-Bias Current Source for Controllable Magnetic Devices, the modular interleaved Buck system supplies a low-ripple current for the auxiliary DC-bias winding of a controllable inductor with different biasing winding disposition in relationship with the main operating flux of the inductor. A 4-phase interleaved Buck converter system was built and inductance measurements were made for different operating current values of the DC-bias and the main operating currents; the system is integrated by 2-phase modules of magnetically coupled interleaved Buck converters, showing the modularity and scalability of the proposed DC-bias source. Experimental results show that similar results are obtained with the proposed system in comparison with a DC voltage source in series with a large inductance; although at a lower volume and weight.

1 Introduction

For power electronic applications, volume and weight are essential physical parameters. Passive magnetic devices typically are one of the bulkiest and heavy components within the system. In this regard, controllable magnetic devices can be an opportunity to reduce the power electronic converter weight and volume and therefore the application's overall size, weight and cost.

Magnetic devices can be controlled actively by a DC current carrying auxiliary winding. The DC-bias current flows through the additional auxiliary winding which is wound on or introduced to the core material and saturates the entire magnetic core or segments of it [1]. For an inductor, this effect of controlled saturation of the core would result in a different value of its inductance depending on the DC bias-current magnitude and the associated generated flux, leading to what can be determined as a controllable inductor; therefore using controllable magnetic devices enables an additional variable to improve the application design, such as to extend the ZVS range in soft-switching converters or resonant converters, using the same magnetic core for the magnetic element, leading

to an opportunity for volume, weight and cost reduction of the power processing stage [2].

Nevertheless, and regardless of the selected DC-bias winding configuration for the controllable inductor, the required auxiliary DC-bias current has to be provided by an additional DC current source. This external and independent DC current source would have to be as compact in size and weight as possible as not to offset the benefits achieved by the volume and weight reduction of the controllable magnetic device and therefore of the entire system; as well as the extra degree-of-freedom in terms of controllability of the system. Literature in this area does not mention or shows this aspect of the area of controllable magnetic devices in high-frequency power electronics applications; a Thyristor control unit has been reported for low-frequency applications such as in [5]. Nonetheless for high-frequency power electronics applications, one solution would be to use a variable DC voltage source with a very large inductance in series, providing a constant low-ripple DC current. Unfortunately this solution would result in a heavy and bulky system, leading to an impractical implementation, specially in high-frequency systems where a compact and

lightweight solution is expected, such as in mobile, renewable energy sources or electromobility applications [6]–[8].

An alternative to this problem can be the usage of switched DC-DC converter schemes, which have been widely studied in the literature for a vast range of energy processing applications. As the system should be as simple and as compact as possible, Buck or Boost converter topologies can be considered as suitable solutions. Given that the Buck scheme presents, in the ideal case, a linear input-to-output relationship; it can be considered as an alternative to supply the DC-bias current for the controllable inductor. Nonetheless its simplicity, the Buck converter scheme has some disadvantages if high currents with low ripples are required at the output, as structurally is also integrated by an inductor and a capacitor; large passive devices are then required, increasing the system volume and weight.

This disadvantage of the conventional Buck converter scheme can be solved by increasing the switching frequency, at the expense of increasing the switching losses and the corresponding reduction in the efficiency of the system. A solution to overcome this, is to connect several Buck converters (referred as phases) in parallel in an interleaved operating scheme by phase-shifting the switching of each Buck converter by $360^\circ/p$, considering p as the number of total phases in operation, which would reduce the current levels through each Buck inductance achieving a low output current ripple and low output voltage ripple with small output capacitance values [9]. Moreover, further current ripple reduction at each phase inductance can be achieved if the phase inductances are magnetically coupled [10], reducing the demanded current ripple at the input of the converter and improving EMI [3].

In addition to the aforementioned benefits of interleaved DC-DC Buck converter with magnetically coupled inductors, the scheme can be modularized, which allows better tailoring of the system according to the particular requirements for each controllable inductor in terms of the required current levels. This paper presents a DC-bias current source for controllable inductors based on a modular interleaved Buck converter (MIBC); a 2-

module 4-phase system is presented, where each module is integrated by a 2-phase interleaved Buck converter with magnetically coupled inductors. The load of the MIBC is the auxiliary DC-bias winding of the controllable inductor, where the current injection through the DC-bias winding generates an additional magnetic flux with a selected disposition in relationship to the main magnetic flux generated by the main operating winding of the inductor.

The paper is organized as follows: Section 2 presents the fundamentals of controllable magnetic devices through DC-biasing, Section 3 presents the Modular Interleaved Buck converter scheme and the analysis of its output characteristic. In Section 4, the application of a 4-phase MIBC system as a DC-bias source for controllable magnetic devices is presented; experimental results are shown for parallel and orthogonal DC-bias winding disposition in controllable inductors and finally Section 5 presents the concluding remarks of this work.

2 Controllable Magnetic Devices through DC Biasing

For an inductor, as a two-terminal passive device consisting of a coil wound around a bobbin, the inductance of such coil is defined as the ratio of the total magnetic flux linkage ψ in the coil turns to the time-varying (AC) current i that produces the flux linkage in the coil [15]:

$$L = \frac{\psi}{i} = \frac{N^2}{\mathfrak{R}} = \frac{\mu N^2 A_c}{l_c} \quad (1)$$

As stated in Eq. (1), the inductance can also be defined in terms of the geometric and physical parameters of the coil and the material in which the coil is wound; this is the number of turns of the coil and the reluctance \mathfrak{R} of the resulting magnetic circuit. In Eq. (1), μ is the permeability of the material in which the coil is wound, N is the number of turns of the coil, A_c is the cross-sectional area of the bobbin and l_c is the mean length of the core or magnetic circuit. Therefore for a given inductor constructed around a ferromagnetic core, a change of inductance can be achieved by varying its physical dimensions or parameters or by varying the permeability characteristics of the medium/core in which it was built. The first alternative is not always

feasible for all applications, although it can be made by tap changers at the expense of increased complexity in the manufacturing of the inductor (limited also by the core and the coil former) and the integration of additional switches to perform the changes between different taps; nevertheless, changing the turns ratio would only result in discrete values in the inductance of the device. Then, the remaining alternative to modify the inductance is to change the permeability of the core in which the coil is wound; as stated in [1] one of the methods to achieve this is by changing the magnetization characteristic of the material by biasing predefined sections of the core, as $B = \mu H$ the permeability is modified, this will result in a change of the reluctance of the equivalent magnetic circuit of the inductor. The DC biasing methods are considered in this paper.

There are three methods for controllable inductors via DC-bias magnetization of sections of its core, whose pros and cons are described in [1], depending on the disposition of the DC-bias winding with respect to the main flux and/or winding:

Parallel DC-bias method: In this method the DC-bias winding is wound in the same section (although it can be branched) as the main winding, as depicted in Fig. 1, the generated biasing flux is in parallel with the main magnetic flux and can be in the same direction or opposing [11], [12]. This method is the operating principle of a magnetic amplifier [14].

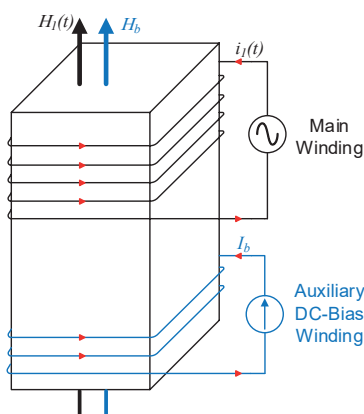


Fig. 1: Windings disposition: DC-bias winding in parallel to the main flux.

DC-bias winding in parallel to the main flux: If the DC-biasing winding is embedded through the core

(through a hole or several), as shown in Fig. 2, the resulting biasing flux is orthogonal to the main magnetic flux and inhomogeneous; changing the reluctance of the branch with no coupling effects with the main winding.

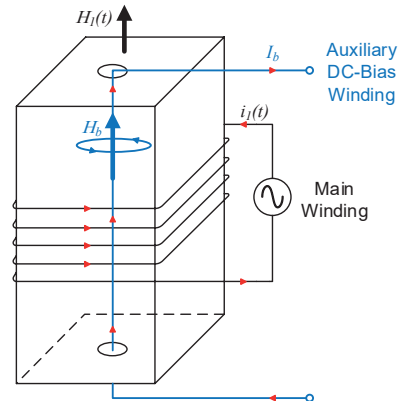


Fig. 2: Windings disposition: DC-bias winding in parallel to the main flux.

DC-bias winding orthogonal to the main flux: For this alternative the DC-biasing winding is orthogonal to the main flux also through the core, as shown in Fig. 3, the resulting biasing flux as the effect of a Virtual Air Gap (VAG) [5].

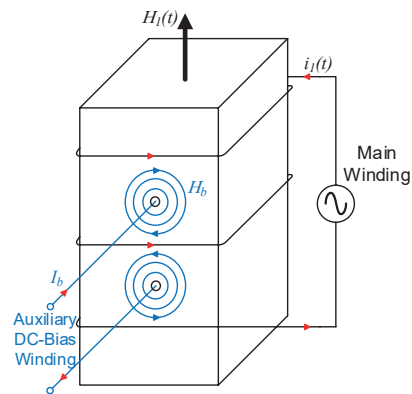


Fig. 3: Windings disposition: DC-bias winding orthogonal to the main flux.

Regardless of the selected biasing method to achieve a controllable inductor with a given core geometry, a ripple-free DC current must be supplied through the biasing winding. This task is not addressed in the literature as part of the solution, and for laboratory set-ups is usually achieved by a commercial constant DC current source of a DC voltage source in series with a large inductance. However, for compact power electronic applications

with limitations in size and weight, this would not be feasible as the required DC current source or even just the smoothing series inductance may be bulkier and heavier than the entire power electronics system, specially for high frequency applications such as portable devices and/or electromobility. This paper presents an alternative solution for a modular and compact low-ripple DC-bias current source for controllable magnetic devices based on magnetically coupled interleaved Buck converters as exposed in the following section.

3 Modular DC-bias Current source based on Interleaved Buck Converters

The proposed DC-bias current source for controllable magnetic devices is based on 2-phase magnetically coupled interleaved Buck converters modules (IBC) as shown in Fig. 4, the modules are connected in parallel at the input and output stages. The phase-shift between each module is $360^\circ/p$, with p as the total number of phases in the system and the phase-shift between the phases of a module is 180° .

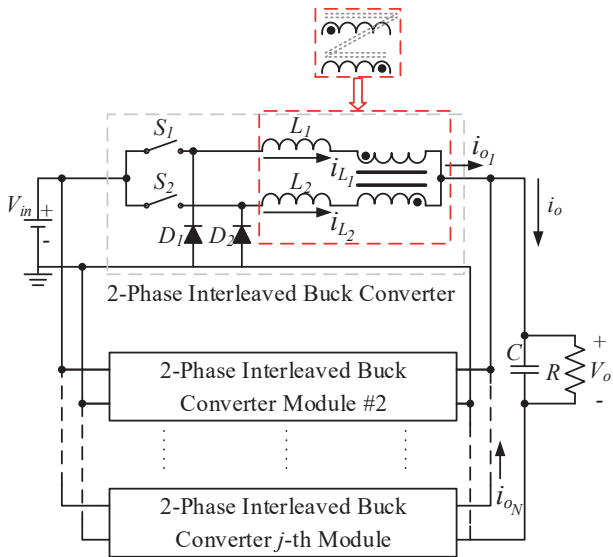


Fig. 4: DC-bias source based on Modular Interleaved with magnetically coupled Buck converters.

The magnetic coupling approach of the converter in Fig. 4 is made considering a two winding coupled inductor as an ideal transformer with inductances in series at each winding; this approach allows to

optimize each element, this is, each inductor and the transformer for the operating conditions [13].

To analyze output current characteristic of the system in Fig. 4, a 4-phase system as depicted in Fig. 5 is considered, although this is not a limitation and can be extended to a higher number of total phases p . As a simplification, but not as a limitation, losses are neglected and the inductances are considered as: $L = L_1 = L_2 = \dots = L_p$. For a Buck converter scheme it is known that $V_o = DV_i$.

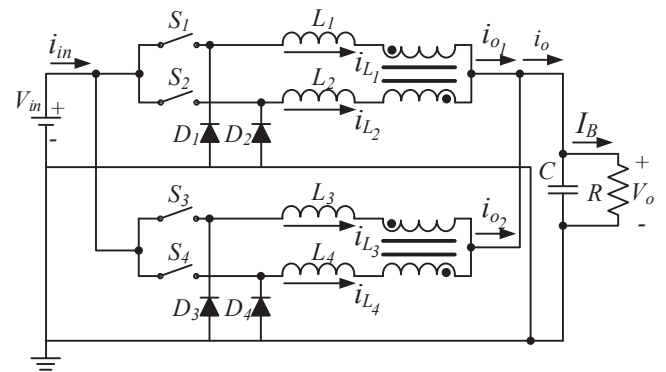


Fig. 5: 4-phase Interleaved Buck Converter.

From the corresponding analysis of the system in Fig. 5, for each D/p time segment, the output current ripple Δi_o can be obtained as:

$$\Delta i_o = \frac{V_i}{L} (k - pD) \left[D - \frac{(k - 1)}{p} \right] T_s \quad (2)$$

where V_i is the input voltage, L is the phase inductance, D is the duty cycle, $T_s = 1/f_s$ is the switching period of the phases, p is the total number of phases of the system and $k = 1, \dots, p$. The relative output current ripple as a function of the duty cycle from Eq. (2) is depicted in Fig. 6.

It can be observed from Fig. 6 that as the number of phases increases, the amplitude of the output current ripple Δi_o decreases; while also presenting p zero-value points equally spaced by D/p intervals. Considering that the inductor current ripple $\Delta i_{L_{Buck}}$ and output current ripple $\Delta i_{o_{Buck}}$ for a conventional one-phase Buck converter is given by:

$$\Delta i_{L_{Buck}} = \Delta i_{o_{Buck}} = \frac{V_i}{L} D (1 - D). \quad (3)$$

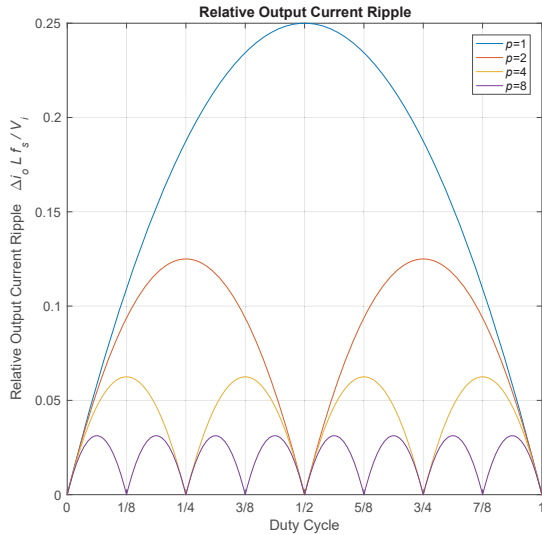


Fig. 6: Relative output current ripple for different number of phases.

The maximum values of Eqs. (2) and (3) for the output current ripple are given as:

$$\frac{d\Delta i_o}{dD} = 2k - 1 - pD \quad (4)$$

$$\frac{d\Delta i_{o_{Buck}}}{dD} = 1 - 2D \quad (5)$$

Solving for the duty cycle D at which the maximum value of Eqs. (4) and (5) is obtained, the output current ripple reduction ratio (RR) for a p -phase IBC can be defined as:

$$RR = \frac{1}{p} \quad (6)$$

The reduction ratio at the output current i_o also results in a reduction of the output voltage ripple ΔV_o at the load; then, the required capacitance C value for a p -phase IBC is reduced also by a factor of p as:

$$C = \frac{(k - pD) \left[D - \frac{(k-1)}{p} \right]}{8pDL(\Delta V_o/V_o)f_s^2} \quad (7)$$

for $k = 1, \dots, p$ and p as the total number of phases of the system.

From the presented analysis and obtained results, a DC-biasing source based on a Modular IBC

presents a feasible alternative for a current source for controllable magnetic devices; as higher DC-bias currents are required, the number of total phases of the IBC system can be increased with decreasing current ripple at the output, which in turn would result in smaller required output capacitance values, as the first output voltage harmonic is located at pf_s . The application of a Modular IBC for a DC-bias source for controllable magnetic devices is presented in the next section.

4 Experimental Results

For the 4-phase IBC system depicted in Fig. 5, the application as a DC-bias source for controllable magnetic devices is as shown in Fig. 7. The parameters for the MIBC in Fig. 7 are listed in Table 1.

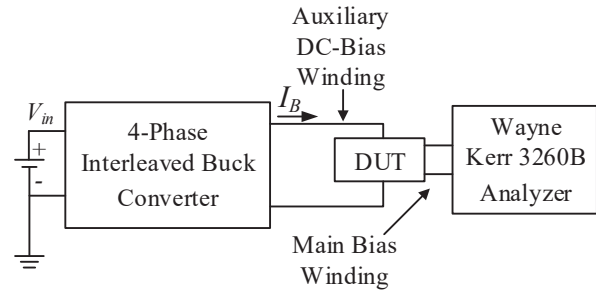


Fig. 7: DC-bias source for controllable magnetic devices based on a 4-phase IBC system.

Tab. 1: DC-bias source system parameters.

Parameter	Value
Number of phases, p	4
Maximum Input voltage, V_i	15 V
Maximum Duty Cycle, D	1/4=0.25
Maximum Average output current, I_o	20 A
Inductance, $L_{1,\dots,4}$	100 μ H
Resistance, R	150 m Ω
Capacitance, C	2.2 μ F
Switching frequency, f_s	100 kHz

The Device Under Test (DUT) in Fig. 7 is an inductor with a DC-bias winding, the inductance measurements are performed by a Wayne-Kerr 3260B LCR analyzer under different main winding current levels, all inductance measurements are taken at 100 kHz operating frequency in the main

winding. In order to evaluate the performance of the proposed system, for each of the controllable inductors in the following section, reference measurements are taken using a DC current source integrated by a DC voltage source in series with a smoothing inductance. The results are presented for an open-loop system.

4.1 DC-bias winding in parallel to the main flux

The controllable inductor with a DC-bias winding in parallel to the main flux is integrated by two UR64/40/20 cores of 3C90 material, the DC-bias winding is disposed in parallel to the main flux through the core in the two largest vertical branches as depicted in Fig. 8.

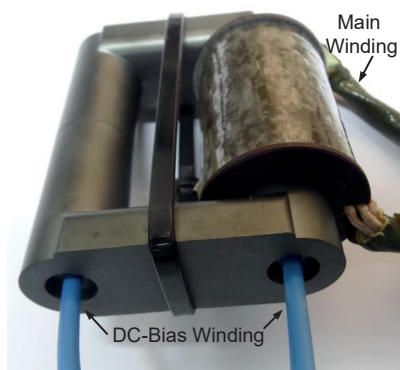


Fig. 8: UR64/40/20 core inductor with DC-bias winding in parallel to the main flux.

A comparison between inductance measurements results are shown in Fig. 9, as stated, the reference values are taken by using a DC voltage source in series with an inductance constructed by two AMCC-80 U cores to obtain a constant ripple-free DC source and compared with the injected DC current using the proposed DC-bias source. For both cases, series inductance measurements are taken injecting DC-bias current values of $I_B = 5, 10, 15, 20$ A, and considering an operating current in the main winding from 0 to 30 A in the Wayne Kerr analyzer. In Fig. 9 solid lines correspond to the inductance values obtained with the DC source in series with the AMCC-80 core inductance, while the dashed lines correspond to the inductance values obtained with the proposed 4-phase MIBC system.

It is observed from the results in Fig. 9, that the overall main behavior of the measured inductance

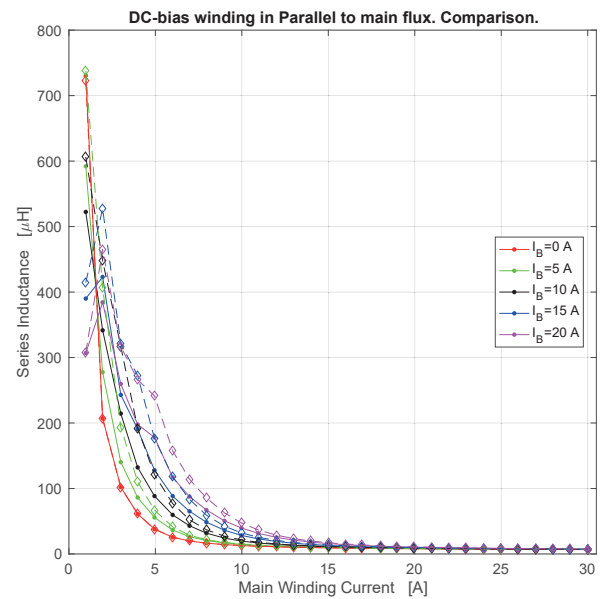


Fig. 9: Inductance measurements: DC-bias winding parallel to main flux.

is similar for the two alternatives; small differences between are observed and correspond to the DC-bias current values not being exactly the same for both, as the currents levels for both alternatives are set manually.

4.2 DC-bias winding orthogonal to the main flux

The controllable inductor with a DC-bias winding orthogonal to the main flux is constructed by two E34/14/9 cores of 3C90 material, the DC-bias winding is disposed orthogonally to the main flux through the core in several locations as depicted in Fig. 10.

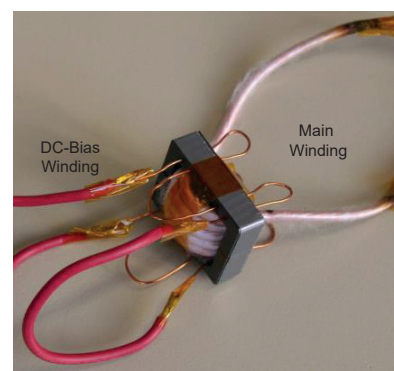


Fig. 10: E34/14/9 core inductor with DC-bias winding orthogonal to the main flux.

Similarly as for the parallel to the main winding

configuration, inductance measurements results are taken for DC-bias current values of $I_B = 5, 10, 15, 20$ A and operating current in the main winding from 0 to 30 A, the results are shown in Fig. 11.

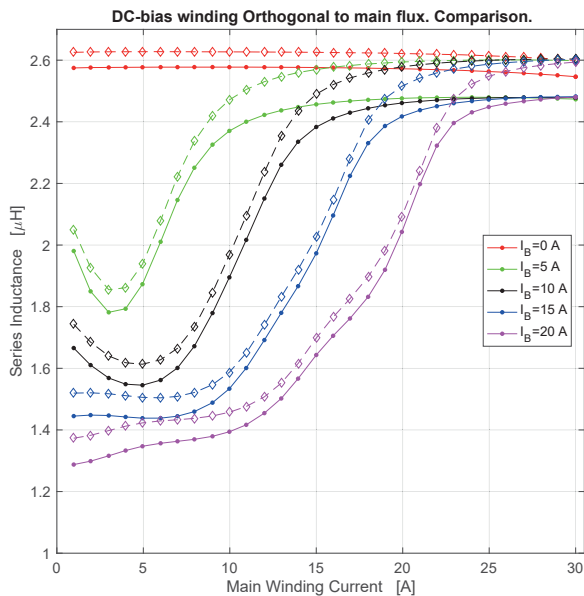


Fig. 11: Inductance measurements: DC-bias winding orthogonal to main flux.

As well as in the previous case, the solid lines correspond to the inductance values obtained with the DC source in series with the inductance, while dashed lines correspond to the inductance values obtained with the proposed 4-phase MIBC system in Fig. 11.

As a physical comparison, Fig. 12 depicts the 4-phase IBC next to the employed series inductance to obtain the constant DC-bias current source in the previous cases. It is observed that the resulting volume for the proposed system is lower, as each 2-phase IBC module measures 4.9 cm length x 4.9 cm width x 2.8 cm height. Moreover, the total weight of the 4-phase IBC system accounts for approx. 200 grs. (100 gr per 2-phase module) in comparison with the approximate 1.8 kg of the AMCC-80 core inductance, which would represent a significant reduction in weight of the system where a controllable magnetic device is required.

From the results in Figs. 9 and 11, it can be observed that the proposed Modular IBC is a feasible alternative as a DC-bias current source for controllable magnetic devices, as the supplied current through the DC-bias winding generates an

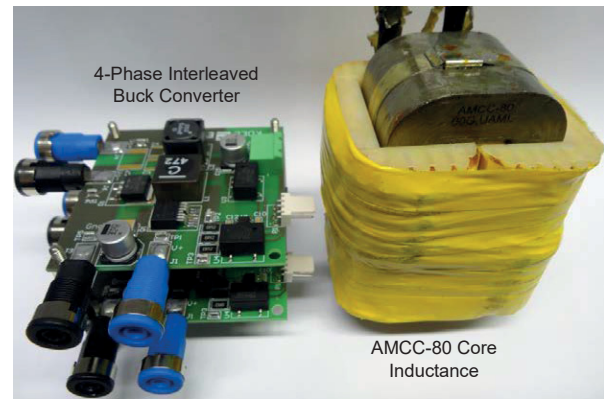


Fig. 12: Size comparison: 4-phase IBC system and AMCC-80 cores inductance.

inductance characteristic similar to the one provided by constant DC current source integrated by a DC voltage source in series with a heavy and bulky inductance. The presented solution is of a smaller total volume in comparison with the series inductance alternative but at a much lower total weight, with the added benefits of controllability and scalability of the proposed system.

5 Conclusions

This paper has presented an application of an Interleaved Buck converter with coupled inductors as a DC-bias source for controllable magnetic devices. The overall effect on the measured inductance of the controllable inductor is the same as if a DC voltage source in series with a heavy and bulky inductance is used. The presented Modular Interleaved Buck converter scheme presents a feasible alternative for the DC-biasing source in controllable magnetic devices, as the total number of phases of the system can be increased if a higher current level is required, achieving at the same time a reduced output ripple; the overall weight of the proposed DC-bias current system in comparison with the passive solution of a DC voltage source in series with an inductor can be significantly reduced while adding the controllability benefits as well as the scalability and modularity of the presented active solution. The application of the presented system for controllable magnetic devices can also be extended to the application on controllable transformers and magnetic switches.

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