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The Numerical Simulation Study of the DC Compensated Choke for the DC/DC Buck Converter

Abstract. The paper presents the structure of an output filter used for a DC/DC buck converter. The problem with an output filter in the DC/DC converters is that the L inductor works with a high DC bias current for standard solutions and thus causes a significant increase in the core cross-section and a total weight of the choke. The proposed solution bases on a choke structure with split coils that creates opposed fluxes in the core and, as a result, cancels their DC component. This, in turn, allows to build a choke with a better utilized and lighter core. The proposed solution of the DC compensated choke is shown in the circuit simulation of the DC/DC buck converter and FEM simulations of the choke model. All results have been confirmed in laboratory experiments.

*Streszczenie. Artykuł przedstawia strukturę filtra wyjściowego użytego w przekształtniku DC/DC obniżającym napięcie typu „buck converter". Głównym problemem występującym w filtrach dla przekształtników DC/DC jest to, że w typowych rozwiązaniach indukcyjność L pracuje z dużym prądem podmagnesowania DC. Jest to bezpośrednim powodem znacznego zwiększenia przekroju poprzecznego rdzenia i całkowitej wagi dławika L. Zaproponowane rozwiązanie bazuje na strukturze dławika z rozdzielonym uzwojeniem, które tworzy w rdzeniu strumienie przeciwne, a w rezultacie powoduje wzajemne kasowanie ich składowych stałych DC. To, z kolei, pozwala na stworzenie dławika, który posiada lżejszy, lepiej wykorzystany rdzeń magnetyczny. Działanie zaproponowanego dławika ze skompensowaną składową stałą DC jest przedstawione w symulacjach obwodowych przekształtnika DC/DC obniżającego napięcie typu „buck converter" oraz symulacjach polowych FEM modelu dławika L. Wyniki symulacji zostały potwierdzone badaniami laboratoryjnymi. **Badania symulacyjne dławika ze skompensowaną składową DC do przekształtnika DC/DC typu buck converter**.*

Keywords: DC/DC buck converter, DC bias, DC choke, FEM simulations.
Słowa kluczowe: przekształtnik DC/DC typu buck, podmagnesowanie DC, dławik DC, symulacje FEM

Introduction

The growth in Power Electronics is motivated not only by different types of topologies and control strategies but also by a new design of components. Inductive components, among others, proved their huge significance for a compact and efficient converters design. Some research is still being done aiming to develop new materials but thanks to new computer-aided simulation tools the improved construction can be proposed.

The DC/DC buck converter has been selected as a sample of a power electronics converter where an inductive component is of huge importance. The output filter composed of L and C components is the required part of its topology. There is a problem, however, with a high DC bias in the current flowing through the L choke (Fig. 1b). As a consequence, we need to cover the unnecessary costs due to the oversized core cross-section, not mentioning the energy losses.
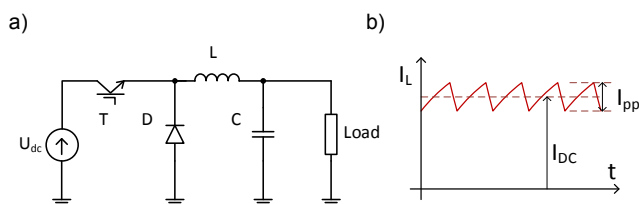

Fig.1. The equivalent circuit of the DC/DC converter (a), and DC and AC current components of the inductor (b)

The simplest solution to implement could seem the air-core choke (Fig. 2a) but, at the same time, it is the least popular one owing to the bulky and costly design. Quite a common solution, however, is the choke with the ferromagnetic core presented in Fig. 2b. The core has the air gap to prevent the core saturation. This design is a little bit smaller in comparison with the first one and definitely cheaper because it is made of a smaller amount of expensive copper used for windings and some amount of the relatively cheaper ferromagnetic iron for the core. The presented solution, however, shows a high DC-bias, which causes the oversizing of a core cross-section.

The so far known solution in literature consists in using a permanent magnet (PM) for the reversed DC-bias flux [1], [2], [3], which, however, only partially solves the problem (Fig. 2c). That is why, the new structure of the output filter with a self-compensation of the DC flux has been proposed in this paper in order to resolve the issue with the DC bias (Fig. 2d).
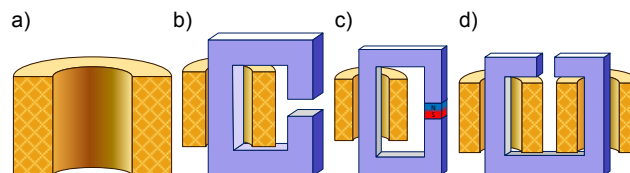

Fig.2. The comparison of the DC biased chokes: the air-core (a), the air-gapped ferromagnetic core (b), the PM reversely biased ferromagnetic core (c), the DC-bias compensated inductance (d)

The structure of the DC compensated LCLC filter

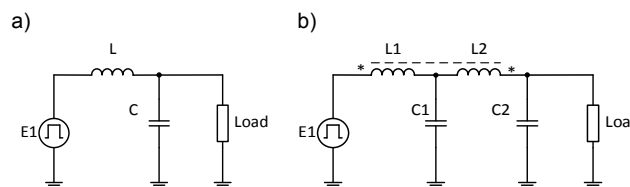The equivalent circuit of a classic LC filter and the DC compensated LCLC one are shown in Fig. 3.

Fig. 3.The basic LC filter topology (a) and the proposed modification of the LCLC (b)

The initial behaviour of a new filter has been proved by circuit simulations made with the LT-Spice simulation software. Fig. 4 below presents the simulation results of the DC/DC buck converter operation with the proposed LCLC filter. Parameters of the LCLC filter components are given in Table 2. Inductances L_1 and L_2 are reversely coupled with coupling coefficient equal 0.5. Both inductances conduct the same DC current component and both capacitors conduct the identical AC current component (Fig. 4a). The output

voltage is effectively filtered (Fig. 4b). The buck converter works with 10 kHz switching frequency and 0.66 duty cycle.
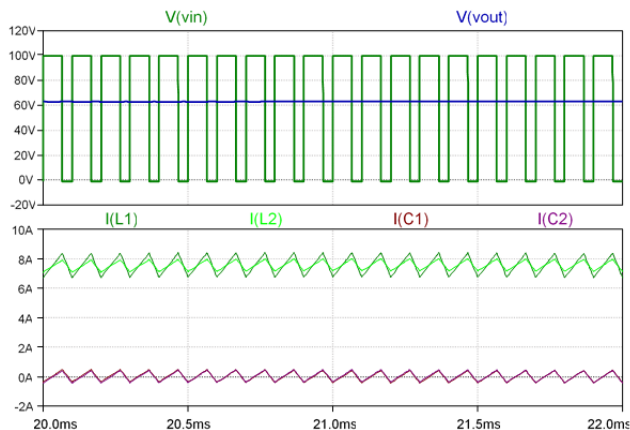

Fig.4. Input voltage, filtered output voltage (a) and currents of the two coupled inductances and capacitors in the LCLC filter (b)

In Fig. 5 the bode plots of the proposed LCLC filter (L = 1.82 mH, C = 15 µF, k = -0.5) are compared to the reference LC filter (L = 1.82 mH, C = 22 µF). Parameters have been selected in such a way so as to get the best matched response. It proves that both the LCLC and the LC behave in the same manner in the same operation point.
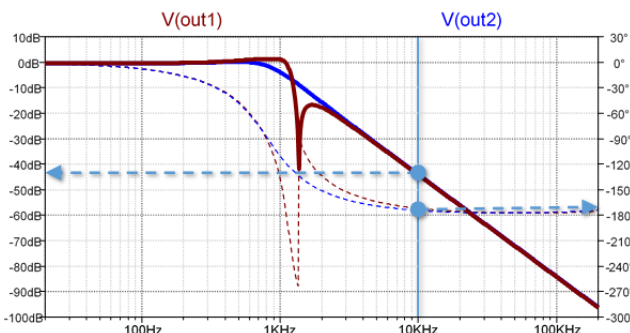

Fig.5. Bode plots of the proposed LCLC filter (Vout1) and reference LC filter (Vout2) – at f = 10 kHz, gain = -44 dB, phase = -172°

Numerical modeling of the coupled inductors

The entire filter designing process has been supported by simulations. Firstly, to verify the general idea, simple circuit simulations have been made in the LT-Spice. Then, in order to design the inductive components of the filter with the required parameters a simulation based on the Finite Element Method (FEM) has been made using the Comsol Multiphysics 4.3b software. Finally, applying the newly designed inductors, the circuit-FEM model of the converter with the entire output filter and a load has been made. Accuracy of these models has then been verified against the measurement results.

The frequency-domain simulation model description

Coupled inductors have been designed using a two-dimensional simulation model solved in the frequency domain. In this type of analysis the Stationary Solver has been implemented to find the solution to a steady-state problem. Analysis has been made for the frequency of 10 kHz using the model based on the AC/DC Comsol Multiphysics 4.3b interface and the Magnetic Field module (mf). The analysed geometry consists of 6 domains: nanocrystalline core, coil domains and the surrounding air, as shown in Fig. 6. The assumed thickness of this 2D geometry is 20 mm.
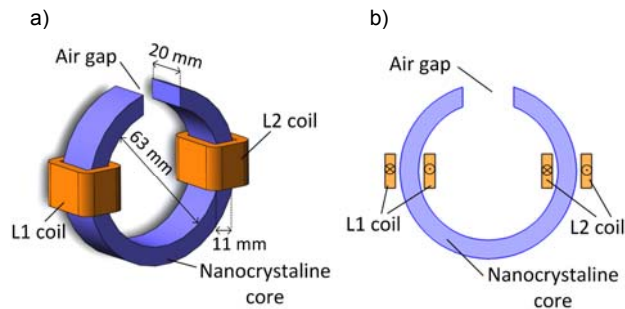

Fig.6. Geometry of the filter coils: a 3D view (a) and its 2D representation for the simulation (b)

As it can be observed in Fig. 6, only windings on the edges of the core are included in the model. Therefore, to get the same ampere-turns for the simulated device and for the constructed one, the effective turns number has been increased.

Properties of materials used in the simulation are presented in Table 1.

Table 1. Material properties of the model domains assumed in simulations

	Air	Copper	Vitroperm 500F
Electrical conductivity σ	1 [S/m]	$5.998 \cdot 10^7$ [S/m]	1 [S/m]
Relative permeability µ$_r$	1	1	38000
Relative permittivity ε$_r$	1	1	1

Windings are assumed to be made of copper. The nanocrystalline Vitroperm properties have been assigned to the core domain. Constant permeability is a good approximation as the B-H characteristic of Vitroperm has a very good linearity in the area far below the saturation 1.2 T [4] and inductors are intended to operate in this region.

Both coils are modelled using a homogenized approach that does not explicitly consider each turn of the coil. That is why to model the coils the Multi Turn Coil domain (MTCD) Comsol feature is applied treating the whole domain as carrying the homogenized current that flows only in the out-of-plane direction. The mesh of the model geometry consists of triangular elements. The mesh is finer (elements are smaller) in areas of importance such as expected zones of the fast varying magnetic field. Fig. 7 shows the mesh of the whole model domain with the enlarged mesh of the inductors.
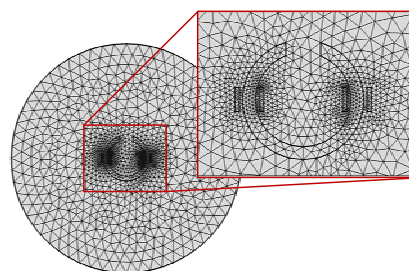

Fig.7. Mesh of the whole model domain

Inductor design based on the frequency-domain simulation results

The developed simulation model uses data of an off-the-shelf toroidal core. The selected core has been made of nanocrystalline Vitroperm because of its high permeability and high saturation flux density. This material has also good stability of parameters over a broad range of temperatures and operation frequencies [4].

Upon selecting the core, the following features should be determined to complete the design of the coupled coils with the required parameters:
- coils arrangements
- turns number
- air gap length

In order to decrease the coupling between the L_1 and L_2 coils they are arranged in a way not to cover the whole core circumference but occupy only a small section of it, as presented in Fig. 8.
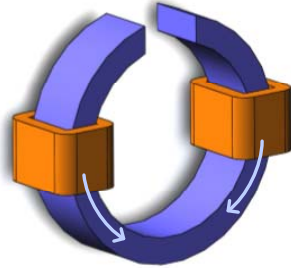

Fig.8. Coil arrangements for the flux cancellation by the mutual coupling

Simulations with the fixed air gap length prove that shifting coils closer to each other, as it is indicated by the arrows in Fig. 8, increases the coupling. The reason for this is that the magnetic flux coupled coils not only through the core but also through the air and the second type of coupling increases if coils are close to each other. As filter coils should be weakly coupled, for further analysis coils arranged as far as possible from each other have been used, as shown in Fig. 8.

As for the other output of the simulation, it is the number of turns that provide the required inductance. It is a kind of approximation rather than the exact number due to the simplified model which does not include the full volume of windings but as an estimation it is good enough. The ratio of the prototype turns number to the model turns number is: 1:1.5 because of the dimensions of the core.

Not the whole flux produced by the primary winding is coupled to the secondary winding. Therefore, a coupling coefficient k is defined as a measurement of the magnetic coupling between two coils $L1$ and $L2$. Its value ranges from 0 to 1, where 1 means a perfect coupling. The coupling coefficient is defined as [5]:

$$(1) \qquad k = \frac{M}{\sqrt{L_1 L_2}}$$

where M is the mutual inductance of the coupled coils and $M = M_{21} = M_{12}$.

To determine the parameters of the coupled coils consider a two-winding transformer with an ac current source i_1 connected to the primary winding and an ac current source i_2 connected to the secondary winding as presented in Fig. 9.
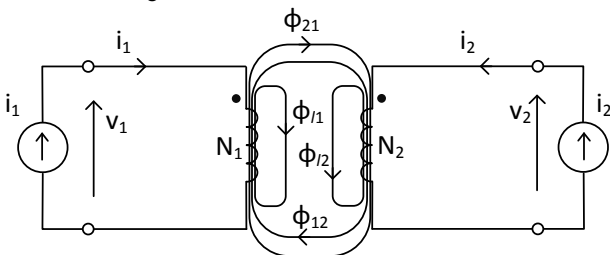

Fig.9. Two magnetically coupled coils driven on both sides by the ac current sources i_1 and i_2

For the linear transformer we obtain the magnetic flux in the primary winding induced by currents i_1 and i_2:

$$(2) \qquad \phi_1 = \phi_{l1} + \phi_{21} + \phi_{12} = \phi_{11} + \phi_{12}$$

This flux results in the voltage v_1 across the primary winding [5]:

$$(3) \qquad v_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$

The task for the frequency domain simulation is to find the air gap length that provides the required coupling between coils. In order to analyse the coupling factor a set of frequency domain simulations with different gap length have been made. During these simulations coil currents i_1 and i_2 have been set to 0 A or 1 A standing for the open or short winding case respectively.

Fig. 10 shows the result of a single step of this analysis – a detailed plot of magnetic flux density in the core with the 21 mm long air gap if the L_2 coil is powered by 1 A and the L_1 coil is open.
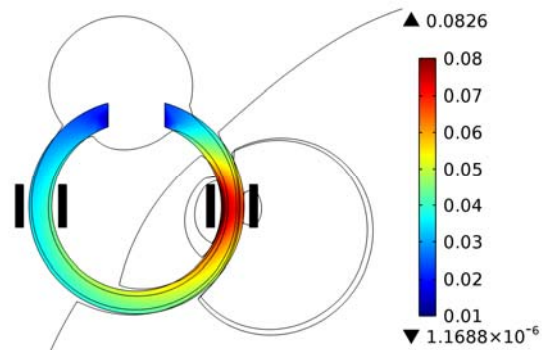

Fig.10. The magnetic flux distribution [T] in the core and in the surrounding air if L_2 coil is powered by 1 A alternating current with the frequency of 10 kHz; air gap length: 21 mm

For each gap length and each combination of coil currents the coils voltage has been computed. This, in turn, has been used to the computed inductances L_1, L_2, M and the coupling coefficient k (according to equations (3) and (1)). Fig. 11 presents the coupling coefficient as a function of the air gap length in the core.
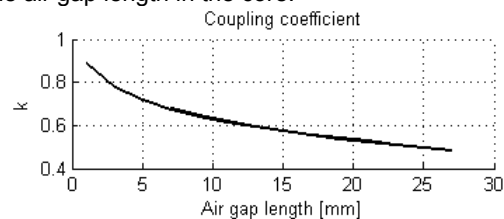

Fig.11. The coupling coefficient k as a function of the air gap length for the analysed coils

Based on the simulation results presented in Fig. 11 the air gap length that provides the required $k = 0.5$ for the analysed coil configuration as 23 mm has been determined.

Numerical modelling of the LCLC filter
The output of the frequency domain simulations is the designing data of inductors with the given inductance and the coupling coefficient. This newly designed device has then been used in a complex time-domain simulation including the FEM model of the inductors and a circuit model of the inverter, load and other filter components. This equivalent circuit is shown in Fig. 12 along with splitting into

the finite element components and the discrete circuit components of the lumped circuit model.
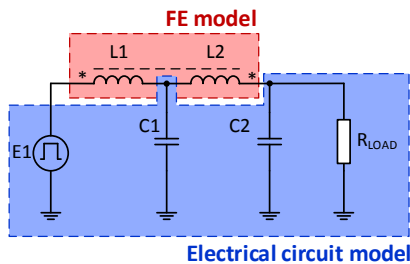

Fig.12. The equivalent circuit representing the converter with an output LCLC filter and the load with splitting into the FE and the discrete circuit components of the model

The finite element model of inductors wound in a common core is coupled with the circuit model of the inverter (represented as the voltage source E_1), other filter elements (capacitors C_1, C_2) and the load (R_{LOAD}). Coils themselves have been modelled using the MTCD like in the former model but in this case the variable current results from the electrical circuit.

Fig. 13b presents the magnetic flux density in the choke operating with 12A load current. It should be pointed out that in these conditions the maximum flux density is 0.48 T and the device operates in the linear region of the H-B characteristic.
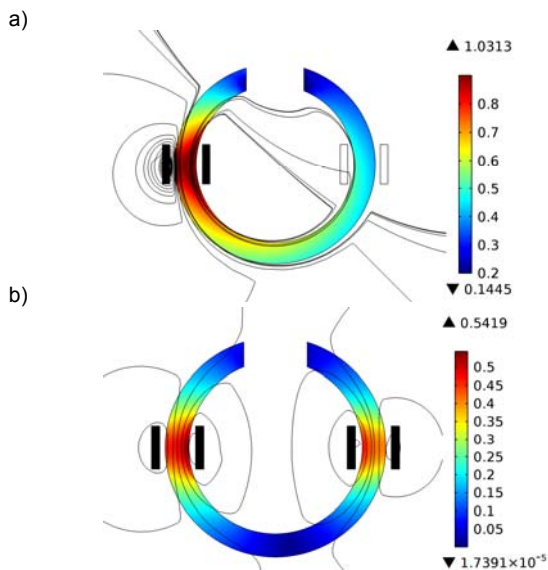
a)

b)

Fig.13. The magnetic flux density norm [T] and the flux lines in the choke without DC flux compensation operating at 12A (a) and choke with DC flux compensation at 12A (b) load current condition. Both pictures were taken at the same time instant

As the magnetic flux varies significantly during the time simulation, the proper solver configuration is of greatest importance. In general, there are two ways to control the error accumulation over the time while solving a time-dependent problem: to decrease the tolerance or to decrease time intervals. The latter one has been adopted in this case. To solve a dynamic problem the implicit time stepping scheme BDF (backward differentiation formula) has been used. Steps taken by the solver have been forced to end at the times specified by the user and the solver has been allowed to take additional steps in between these times, if necessary [6]. The idea behind has been not to allow the time stepping method to choose freely the time steps because then the user-defined time intervals have not

been considered and the resultant time step has been too large.

A combined FEM and circuit simulation with the time span of 15 ms, time step of: 1 µs and aforementioned solver settings require 1,19 GB physical memory and 1.23 GB virtual memory and take 461 s to complete. The Fully Coupled solution attribute has been used in order to solve simultaneously equations referring to Magnetic Fields and Electrical Circuit components of the model.

Laboratory measurements of the LCLC filter prototype
In order to verify all steps of the designing procedure a prototype of the LCLC filter has been constructed and tested. Parameters of the prototype are collected in Table 2 and a view of inductor is presented in Fig. 14.

Table 2. Parameters of the simulated and constructed circuit

Item	Value (simulation)	Value (measurement)
Capacitance C_1, C_2	15 µF	15 µF
Self-inductance L_1, L_2	1.82 mH	1.87 mH
Air gap length	23 mm	20 mm
Turns number	155	100
Coupling coefficient k	0.509	0.504

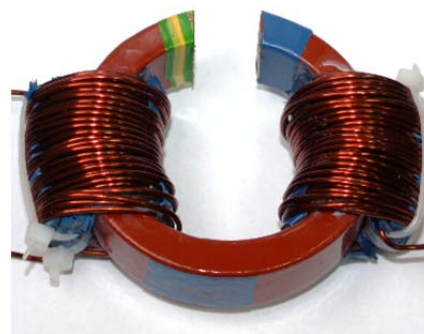Fig.14. Constructed prototype of inductors for the LCLC filter

Voltage and currents waveforms computed in simulation have been compared with the measured waveforms. Fig. 15a shows the converter output voltage E_1 and Fig. 15b, c presents the current flowing through the filter capacitor C_1 and the filter coil L_1.
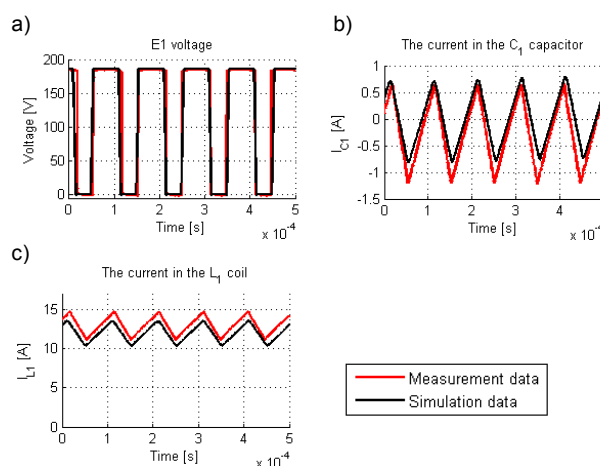
a)

b)

c)

Fig.15. The output waveforms of the converter E_1 (a); capacitor C_1 current (b) and the coil L_1 current (c): the measured (red) and computed waveform (black)

The advanced FE-circuit simulation is an accurate tool in predicting the operation of the filter as it is clearly evident from Fig. 15.

Fig. 16 presents the comparison of measurements of the state of the art LC filter and the LCLC filter arranged on the same core. In the plots: blue – E_1 voltage; purple – capacitor (C or C_1) current; green – capacitor C_2 current; black – inductor L nominal current; red – inductor (L or L_1)

current. As it is shown in Fig. 16a and Fig. 16c both filters behave identically. The saturation of the inductor of the LC filter is observed in Fig. 16b while in Fig. 16d the LCLC filter still does not saturate even with bigger current.
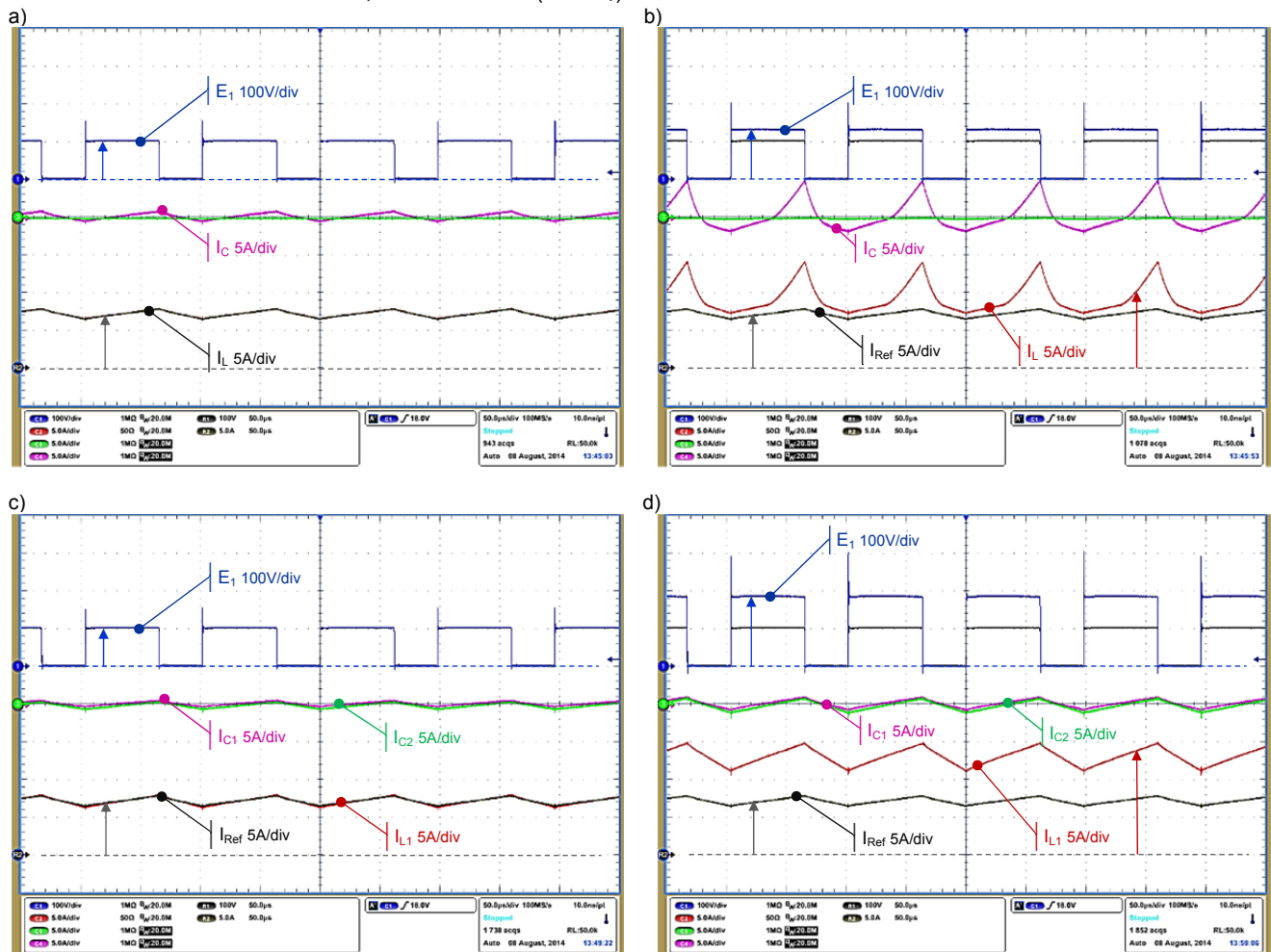
a)

b)

c)

d)

Fig.16. The output waveforms of the classic LC filter with the nominal 7,5 A current (a) and the above saturation current 10 A (b) and the proposed LCLC filter with the nominal current 7, 5A (c) and 12,5 A still below saturation (d)

Conclusions

A two-dimensional finite element model has been used for the analysis of the working principle of the LCLC converter output filter. The magnetic flux density in the core of operating inductors has been calculated. The presented analyses prove that the newly proposed LCLC filter topology with the reduced DC-bias flux not only operates properly but may also result in the reduction of the core size or increased current rating. It has been confirmed that the simulation results are in accordance with the experimentally measured values and therefore the Comsol Multiphysics software is a suitable tool to design and test both the inductive device itself and as a component of the complex topology. This applies also to inductive devices of even a non-standard shape.

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