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Dimensioning of a non-planar wound inductor of a Buckconverter

Abstract*. The concept of inductance in the broad sense is a subject which gave rise to publication from the end of the XIXth century until today. The applications have evolved but the problems are recurrent. Whatever the field, the problem of calculating the inductance and resistance of an electrical circuit is central. In power electronics, this type of component is used for energy storage and must have a minimum of joules losses. This compromise turns out to be difficult to achieve. The objective of this article is the description of the method of dimensioning of non-planar coils which can be adapted to magnetic circuits of the EFD type. We will determine according to its geometric parameters the type of magnetic circuit to be used to reinforce the value of its inductance and the electrical parameters of the Buck type converter, in which the coil will be integrated..*

Streszczenie. *W artykule opisano metodę wymiarowania nie-płaskiego dławika stosowanego w przekształtnikach typu Buck. Podano metodę obliczania indukcyjności oraz strat na ciepło. (**Obliczanie wymiarów dławika stosowanego do współpracy z przekształtnikiem typu B**uck)*

Keywords: Convertisseur Buck, Magnetic core, Inductance coil, Resistance coil
Słowa kluczowe: przekształtnik typu Buck, dławiok, obód magnetyczny

Introduction

The power supplies, necessary to operate the various electronic functions, are composed of active components ensuring the transfer of energy and associated passive components having various roles such as the storage of electrical energy, filtering, galvanic isolation, energy transfer as well as impedance matching.

Given the significant developments in recent years, experienced by portable and embedded electronic systems, the associated energy need has become more demanding both by the complexity of the functions to be provided and the performance required.

Several companies offer magnetic circuits of different shapes; such in E for EFD X.Y.Z of different dimensions (XYZ) from the company TDK or the firm SMC XYZ from the Wilco Company and Soft Ferrite and Accessories of Ferro cube Company.

In this article, we will describe a method of dimensioning of non-planar coils using EFD ferrites which adapts well to coils wound around cores and applications in converters. [1,2, 3, 4, 5, 6]. .

Presentation of Buck converter

The realization of a power supply requires a great experience of the conversion structures, of the phenomena which surround it (harmonics, heating, electromagnetic emissions) of the components and of the conditioning to optimize the bulk. The most used structures are the buck and buck-boost converters because they present good compromises in compactness and controllability. In addition, consisting of few components, energy losses are limited and the reduced volume.

For low current and voltage applications, the buck is recognized as the most suitable converter [6,7, 8, 9] (fig.1).

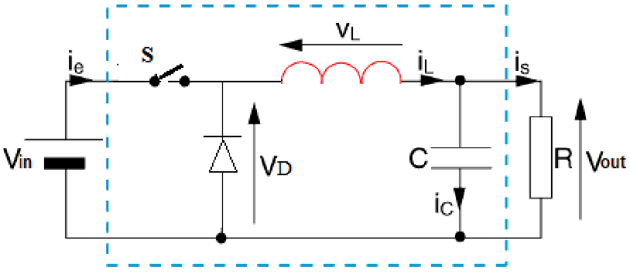

Fig.1. Schematic diagram of a DC-DC buck converter

The switch S has a duty cycle α which ranges from 0 to 1.

The figure 2 indicates relevant waveforms of the circuit when the switch S is turned ON and OFF at frequency *f,* figure. 2 gives the shape of the current I_L and output current I_S as a function of the time of a Buck converter where T is the period of the signal [7, 9]:

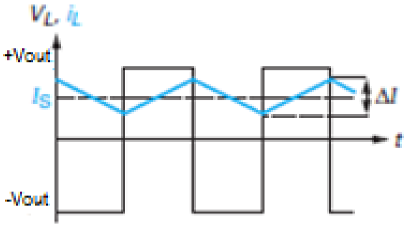

Fig 2.Waveforms of the voltages and currents with time in a Buck converter

We recall in table I, the characteristic equations, of the functioning of the Buck converter structure.

Table1. Characteristic equations of the Buck converter

Voltage Gain	Current in inductance	Ripple Current
$\frac{V_{out}}{V_{in}} = \alpha$	$0\langle t\langle \alpha T$: $I_L = \frac{V_{in} - V_{out}}{L}\alpha T$ $\alpha T\langle t\langle T$: $I_L = \frac{-V_{out}}{L}(1-\alpha)T$	$\Delta I_L = \frac{\alpha(1-\alpha)V_{in}}{Lf}$

Dimensioning of the coil

Topology of the magnetic circuit

We will use a numerical application for the dimensioning of the coil wound around the core in order to better guide the reader.

The combined choices of the operating frequency, the magnetic material, the maximum induction and the current density determine the losses in the inductance and therefore it's heating; these choices are linked together and are made from curves *B (H)* and curves giving the losses as a function of the frequency for a given induction Bmax, for different magnetic materials. We will use the N87 ferrite from EPCOS from TDK Company, its resistivity allows to limit the eddy currents. EPCOS N87 ferrite material has been designed for energy conversion applications; it has been optimized for operating conditions [10]:

- Working frequency between 25 to 500 KHz
- Maximum Induction between 0,3T to 0,35T
- Minimum loss at 100°C for 0,3T

We can find different shapes in E-I and E-E to better channel the magnetic field lines and different applications.

Consider the case of a buck converter whose characteristics are:

- Input voltage V_{in} =5V
- Output voltage $Vout$ = 2.5V
- Switching frequency f = 300KHz
- Magnetic induction B_{max} = 0.3T
- Converter output power P = 1W
- A ripple of the inductance current of 10% on either side of the average current.

The coil has n turns, of total length l_T, wound around an E-shaped core (figure 3) without air gap with a flattened central leg, of effective section Ae.

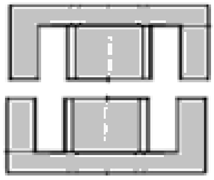

Fig.3. Diagram of two E-shaped core

The winding must be able to enter the window of the magnetic circuit where it will occupy part of the surface, the total section of the copper A_{co} must therefore be less than or equal to the winding surface A_w (fig.4):

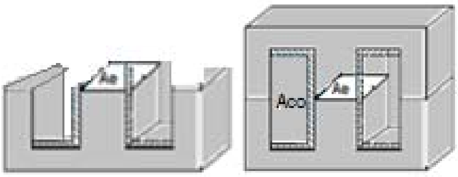

Fig.4: Effective area of the core Ae of an E-shaped core and 2E

It will be necessary to take into account the place of the insulation covering the conductors of the turns and the inter-turn space lost during the winding.

Calculation of geometric parameters of the coil

From the data of the converter, we deduce the output current and the value of the necessary inductance:

(1) $$I_S = \frac{P}{V_{out}} = \frac{1}{2,5} = 0,4A$$

The maximum current in the coil:

(2) $$I_{\max} = I_n + \Delta I/2 = 0,4 + (10\%.0,4)$$
$$I_{\max} = 0,44A$$

The value of the inductance for $\alpha = V_s / V_e = 1/2$:

(3) $$L = \frac{1}{4}\frac{V_{in}}{\Delta I.f}$$
$$L = \frac{5}{4.(2.0,04).300.10^3} = 52,08\mu F$$

The maximum energy density stored in a volume of magnetic circuit is expressed by:

(4) $$W_{V\max} = \frac{W_{L\max}}{V_e} = \frac{B_{\max}^2}{2\mu_0\mu_r}$$

With μ_0 et μ_r, respectively, the magnetic vacuum and relative permeabilities of the medium, Ve, the effective magnetic volume, and W_{Lmax} being the maximum energy stored in the coil:

(5) $$W_{\max} = \frac{LI_{\max}^2}{2}$$

This makes it possible to deduce a relationship between the characteristics of the magnetic circuit (V_e, μ_r) and the maximum energy stored in the coil:

(6) $$\frac{V_e}{\mu_r} = \frac{LI_{\max}^2\mu_0}{B_{\max}^2}$$

Where also, depending on the effective section of the magnetic circuit A_e and the effective length of the magnetic field lines l_e given by the manufacturer:

(7) $$\frac{A_e l_e}{\mu_r} = \frac{LI_{\max}^2\mu_0}{B_{\max}^2}$$
$$\frac{V_e}{\mu_r} = \frac{52,08.10^{-6}.0,44^2.4.\pi.10^{-7}}{0,3^2}$$
$$\frac{V_e}{\mu_r} = 0,14078.10^{-9}\,mm^3$$

We refer to table 2, summarizing the essential characteristics of E-cores (EFD) without air gap, from the EPCOS ferrite catalog [10] and the calculation of the ratio for three dimensions of EFD core:

Tableau 2. Characteristics of EPCOS E-core ferrites

EFD	μ_r	A_L nH	A_e mm^2	l_e m	V_e mm^3	V_e/μ_r mm^3
10.5.3	1150	450	7.2	23.1	166	0.144
15.8.5	1400	780	15	34	510	0.364
20.10.7	1440	1200	31	47	1460	1.013
25.13.9	1560	2000	58	57	3310	2.122

The EFD 10.5.3 core is large enough to contain the calculated inductor. For our coil, the other cores would be oversized.

We can therefore deduce the number of turns of the coil knowing its specific inductance A_L :

(8) $$n = \sqrt{\frac{L}{A_L}}$$

So: $$n = \sqrt{\frac{52,08.10^{-6}}{450.10^{-9}}} = 10,75$$

Or again, the magnetic flux through the n turns of the coil is:

(9) $$\phi_{\max} = LI_{\max} = nB_{\max}A_e$$

Which allows to deduce the number of turns:

(10) $$n = \frac{LI_{\max}}{B_{\max}A_e}$$

So either:

$$n = \frac{52,08.10^{-6}.0,44}{0,3.7,2.10^{-6}} = 10,609$$

We will opt for n = 10 turns around the central core.

The current density depends on the frequency and the number of winding layers which induces a temperature rise, it should not be underestimated as this leads to higher sections of wire and the skin effect is likely to appear, especially if the section of the wires is circular-. For frequencies of hundreds of KHz a value of J = 5A / mm2 is allowed.

The conductor cross section can be deduced from the selected current density:

(11) $$s = \frac{I}{J} = \frac{0,4}{5} = 0,08mm^2$$

At this frequency, we must make sure that the current flows over the entire cross-section of the conductor, so that the current density is not greater than that which we set, so the skin thickness must be greater than the radius of the conductor

Le radius of the wire is therefore:

(12) $$s = \pi R^2 \Rightarrow R = \sqrt{\frac{s}{\pi}} = 0,16mm$$

where μ_r, is the wire's relative magnetic permeability, for copper conductor case μ_{co} =1 and copper electric resistivity ρ_{co}=1.7 $10^{-8}\Omega$m at 20°C.

We must also ensure that the 10 turns wound around the central core of effective area A_e can fully enter the winding surface window A_w whose dimensions in mm are shown in figure 5, so:

(13) $A_{co} = n\, s < A_w$

The area occupied by the 10 turns in the window of the surface magnetic circuit A_w is 10 times greater than the section of the turns, therefore a total surface of copper: A_{co} = 0.8mm2, which is clearly sufficient even if we add the thickness insulating layers of the wires and the nature of the tight or flaccid winding since for an E 10/5/3 core: A_w = 5.8mm2 (fig. 5).

This surface can be higher when using a 2E magnetic circuit (fig. 4) and will increase the number of turns.

For the calculation of the length of the turn, we assume that the turn completely surrounds the core of surface *Ae*, therefore the perimeter of the core can be compared to the length of the coil. Knowing the dimensions of the core; given by the manufacturer (fig. 5), we deduce the average length of a turn winding the central leg of the core at E [10]:

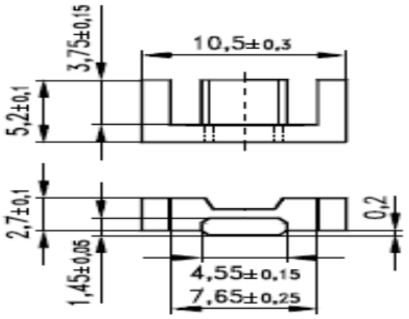

Fig.5 : Magnetic circuit of the EFD 10.5.3 core

For a winding around the central core, so:

$$l_w = 17,8mm \simeq 18mm$$

The total average winding length:

(14) $$l_T = nl_s = 10.18 = 180mm$$

Calculation of resistance coil

Knowing the dimensions of the coil, we will use the classic formula of static resistance for a copper wire of circular section:

(15) $$R_S = \frac{\rho_{cu} l_T}{s} = \frac{1,7.10^{-8}.180.10^{-3}}{0,08.10^{-6}} = 38,25m\Omega$$

Calculation of losses

- Calculation of copper losses

(16) $$P_{co} = R_S I^2 = 6,12mW$$

- Calculation of losses in ferrite

Figure 6 illustrates the magnetic losses per unit of volume for a sinusoidal flux, as a function of the frequency and the magnetic induction for a ferrite material type N87 of EPCOS:

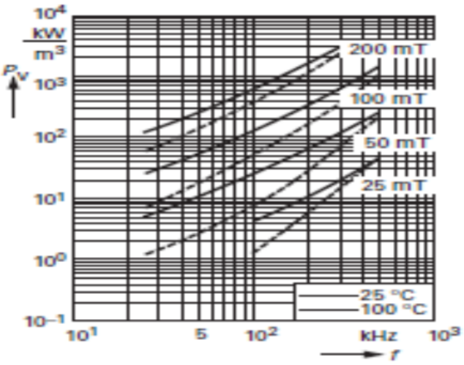

Fig 6 Magnetic losses per unit volume of N87 ferrite

As the current ripple in the coil is 10% on either side of the average value of the current, the corresponding magnetic induction variations B are also 10% of the maximum induction, ie 0.03T.

Magnetic losses per unit volume at 300KHZ for an induction of B = 0.03T are estimated at around 25mW / cm^3 in sinusoidal regime. For a triangular shape of the magnetic flux; which constitutes 75% of the sinusoidal form; we can estimate these losses at:

(17) $$P_{me} = (P_V\, 75\%)V_{me} = 3,112mW$$

Calculation of the elements of the converter

Calculation of the converter capacity C

In figure 1, the filtering capacitor stores or restores its charge Q leading to a variation of the voltage across its terminals [12, 13]:

(18) $$\Delta V_c = \frac{\Delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\Delta I_L}{2}\frac{T}{2}$$

If the capacitor is perfect we can assimilate: $\Delta V_c = \Delta V_S$.

By replacing the variation of the ripple by its expression from equation 3, we deduce the value of the filtering capcity::

(19) $$C = \frac{V_{out}\left(1 - \frac{V_{out}}{V_{in}}\right)}{8Lf^2 \Delta V_{out}}$$

So : $C = 0,13\mu F$

Calcul de la résistance de charge du convertisseur

The load resistance connected to the converter output is of the order of:

(20) $$R_C = \frac{V_{out}}{I_s} = \frac{2,5}{0,4} = 6,25\Omega$$

Buck converter simulation

The figure 7 show the Buck converter where the coil is represesented by a serial circuit (L, R_L). For the simulation we used PSIM software using the calculated electrical parameters.

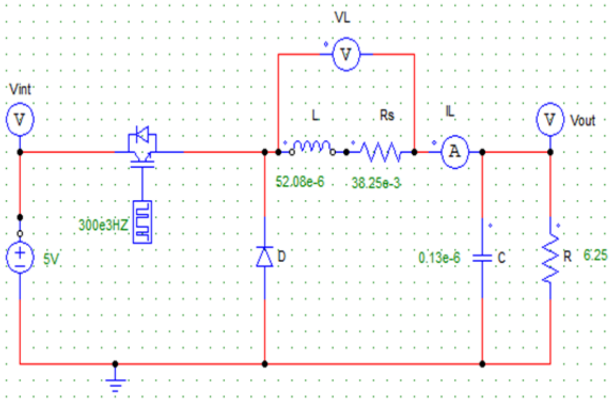

Fig 7. Schematic diagram of the Buck converter

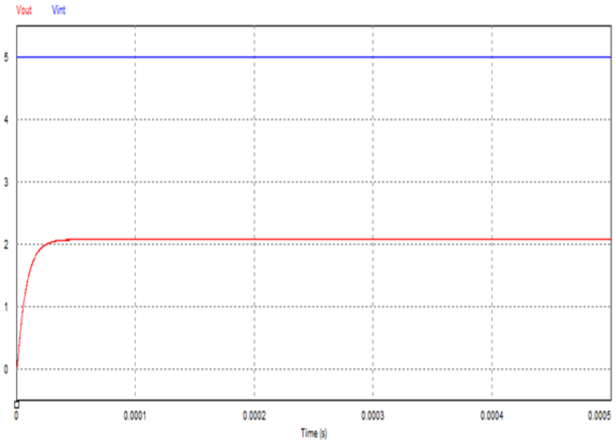

Fig 8. Output voltage (V_{out}), and inut voltage versus time.

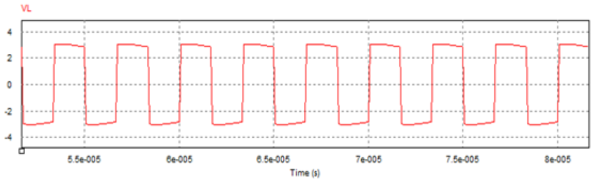

Fig 9.Votltage the inductor (V_L)versus time

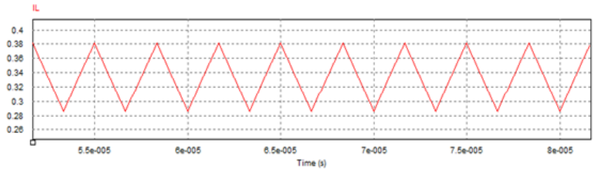

Fig 10. Current of the inductor (I_L) versus time

The figures 8 shows input voltage Vin and output voltage Vout versus time, the figure 9 shows the inductor voltage VL and the figure 10 shows the current throught the inductor versus time of the Buck converter with the non-planar coil.

From an input voltage of 5V at frequency 300 kHz, the Buck circuit deleivred a lower output voltage of 2,26V.The alternative inductor voltage from +2,5V to -2,5V charge the inductor with a maximun current of 0,38A.

The curves approximate the data of the specifications of the Buck converter and the calculations carried out, where the output voltage specified was 2,5V,the slight fluctuations are due to the additional resistors *Rs* which decrease the current in the coil, and consequently the output voltage V_{out} .

Thus, the choice of such small EFD accessories allows obtaining high inductance coils even for low voltages which allows to increase the performances of the Buck converter.

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Conclusion

We can thus conclude that the dimensioning method used of a non-planar coil, based on the data of the characteristics of the magnetic circuits and the specifications of the converter is efficient and accurate.

The inductance of the non-planar coil wound around a core, can be improved by the choice of a higher permeability material such as N97 or other ferrites while keeping a low resistance.

By increasing the frequency, we can decrease the geometric dimensions of the coil, so this study can also be used for dimensioning of micro coil. Given the compact structure, the equivalent circuit must take into account proximity effects and the electrical resistance of the magnetic circuit.

The closed structure of the magnetic circuit around the coil allows a good channeling of the field lines with a minimum of dispersion, so the same study could be used for transformer dimensioning, where the primary and secondary windings will be wound around the same core.

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REFERENCES

1. Matsumoto S., Integration of a power supply for system-on-chi, *IEICE Trans. Fund*, (1997),E80-A.
2. Lotfi A. W., Issues and advances in High Frequency Magnetics for Switching Power Supplies, Proc. Of the IEEE,89, No 6 (2001), PP. 833-845
3. Lei C., Fabrication of solenoid- type inductor with Fe-based soft magnetic core, J. Magn. Magn. Mater, (2007), Vol. 308, No 2 P: 284-288.
4. Lu H-C, Chen CC-P, Liu C-M, Hsing H-J, Huang P-S., LTCC spiral inductor synthesis and optimization with measurement verification. IEEE Trans Adv Packag. (2010), Vol 33, No 1, pp: 160-168.
5. B. Estibal, & al., MEMS Design, Realisation and Charactisation in an Educational Context, *IEE Engeneering Science and Education Journa*l, 10, No 5 (2001), pp. 197-205.
6. Wibben J. and Harjani R., A High-Efficiency DC-DC Converter Using nH Integrated Inductors, IEEE Jounal of Solid State Circuit, Vol 43, (2008), 844-854
7. C de filtrage: J. P. Ferrieux, F. Forest, Alimentations à découpage – Convertisseurs à résonance, (1999), Ed Dunod, $3^{ème}$ edition,
8. Ludwig M., Duffy M., O'donnell T?, McCloskey ., and Mathuna S.C.O., PCB integrated inductors for low power DC/DC converter, IEEE Transactions on Power Electronicx, Vol. 18, (2003), 937-945.
9. Mohan N., Undeland T. M., Robbins W. P., Power Electronics: Converters, Applications and Design, (2003), 3rd Edition, Wiley.
10. EPCOS AG Technical documentation (2015).
11. Sullivan and Sandres, Measyred Performance of a High power-Density Micro –Fabricated Transformer in a DC-DC converter" IEEE Power Electronics Specialists Conference (1996).
12. Salles A., Conception d'éléments passifs magnétiques pour convertisseurs de faible puissance. Micro électronique(2008), Université Paul et Sabatier III
13. [13] Brunet M., Composants passifs intégrés dédiés à la conversion et au stockage de l'énergie, Micro et nanotechnologies, Micro électronique, Université Paul Sabatier III, (2013).