REVIEW

Electrica 2018; 18(2): 325-332

Design of Micro-Transformer in Monolithic Technology for High Frequencies Fly-back Type Converters

Abdeldjebbar Abdelkader , **Hamid Azzedine**

Department of Electrical Engineering, USTO-MB University School of Engineering, Oran, Algeria

Cite this article as: A. Abdelkader, H. Azzedine, "Design of Micro-Transformer in Monolithic Technology for High Frequencies Fly-back Type Converters", *Electrica,* vol. 18, no: 2, pp. 325-332, 2018.

ABSTRACT

This article describes the design of a micro-transformer in monolithic technology for high frequencies comprising planar type coil and a magnetic circuit made of several layers of materials. This micro-transformer is integrated into a micro-converter of fly-back type. The Mohan method was used to determine the geometric parameters and the S-parameters were used to calculate technological parameters. The study of electromagnetic effects allowed us to show the role of ferrite, which is used to confine the magnetic field lines and minimize disruption of the neighbor ship. To validate the dimensioning of the geometrical and technological parameters, with the help of the software PSIM6.0, we simulated the equivalent electrical circuit of the converter containing the electrical circuit of the dimensioned planar micro-transformer

Keywords: Fly-back converter, Planar Micro-Transformer, S-parameters, inductive elements, passive

Introduction

The passive components occupy 80% of the surface of a low-power converter. They have several roles, such as the temporary storage of electrical energy, filtering, electrical isolation, energy transfer as well as impedance matching. Today, only the integration of passive components is achievable, especially with inductive components. The barrier of integrating active components remains the most persistent obstacle that slows the rush to miniaturization [1, 2]. At the heart of isolated converters, there exists an essential element, the transformer. By reducing the dimensions, conventional coils are limited since they are wound with copper wire which prevents size reduction. The micro-transformers are formed from a thin magnetic circuit, usually made of ferrite, and on which conductive coils are inserted. The aim is to integrate the transformer in a micro-converter of flyback type for low voltages, low powers and high frequencies. The conception of a transformer goes through several phases: analysis of specifications, calculation and dimensioning of transformer parameters and validation by numerical simulation. In this work, the micro-transformer is presented under a form completely different to the geometric form of a classical transformer. This geometry is a square spiral and it adapts to the integrated technology [3, 4].

Dimensioning of the Micro Transformer

Presentation of the Micro Transformer

The micro converter fly-back presented in Figure 1, is the starting point for the design of passive components and especially, the micro transformer. This converter was chosen because it is composed of a transformer and few passive components. It operates in discontinuous conduction when the current demanded by the load is low, and in continuous conduction for higher currents. To produce such a device, we start with conventional transformer windings. To implement this function, it is necessary to have a magnetic core around

Corresponding Author:
Abdeldjebbar Abdelkader

E-mail:
abdeljebar.aek9@gmail.com

Received: 16.02.2018

Accepted: 10.05.2018

DOI: 10.26650/electrica.2018. 96182

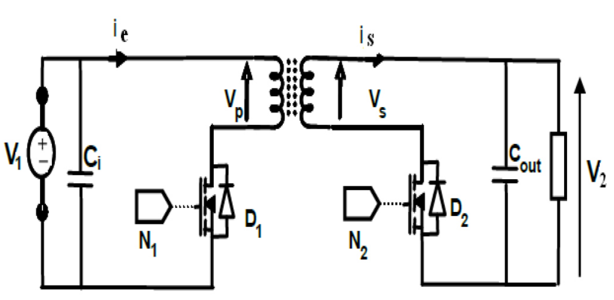

Figure 1. Schematic diagram of fly back converter [5]

Table 1. Characteristics of used materials

Materiel	Copper	NiFe	SiO_2
Conductivityσ (S/m)	$5{,}99.10^{7}$	$2{,}2.10^{4}$	0
Resistivity ρ (Ω.m)	$1{,}7.10^{-8}$	20.10^{-8}	10^{6}
Relative Permittivity ε_r	1	10	3,9
Relative permeability μ_r	1	800	1

which the primary and secondary windings are placed. This transformer, due to the magnetic coupling, naturally induces the effects of leakage mainly related to the choice of placement of windings.

The Specifications of the Micro-Converter

We selected the following set of specifications:
Input voltage V_{in} = 10v ,Output voltage V_{out} = 4v
Current output means Is = 1.5A
Average power Ps = 6W, Operating frequency
f = 40MHz

The Characteristics of the Materials Used

The Table 1 below shows the characteristics of the materials constituting the coil layers.

It shows the different geometric and electrical parameters that constitute the micro transformer Figure 2 [6]. A core with a square form for the windings has been chosen due to the limitation of surface and volume.

Dimensioning of the Magnetic Circuit

From the specifications, we define the characteristics of the micro-converter which is the starting point for the design of micro-transformer. It consists of two inductors placed on a magnetic material and separated by a dielectric, which also provides magnetic coupling. The values of the frequency f and the input voltage V_e allow us to calculate the value of the primary and secondary inductances L_t and L_b of our transformer [7, 8].

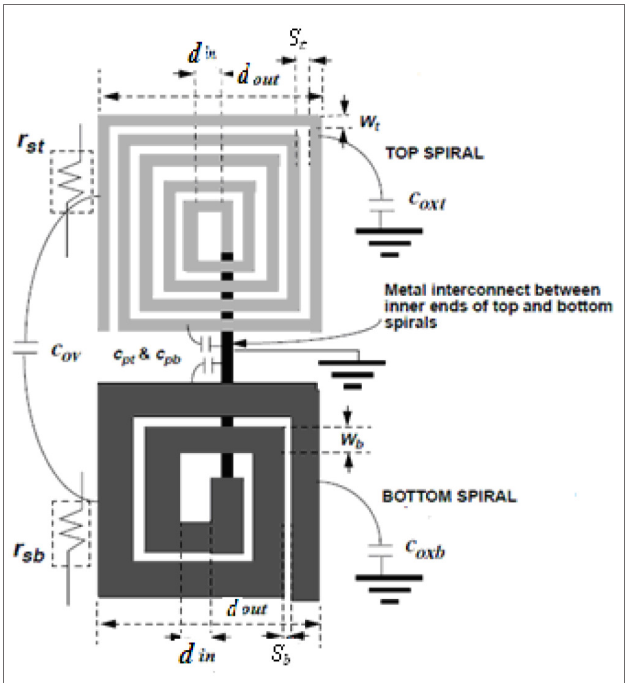

Figure 2. The different parameters characterizing the micro-transformer [7]

$$L_t = \frac{V_e^2 \alpha^2}{2 f P_s} \qquad L_b = m^2 L_t \tag{1}$$

$$m = \frac{1 - V_s \alpha}{\alpha V_e} \tag{2}$$

m: turn ratio=0.4 , L_t= 52nH and L_b= 8.3nH

Calculation of the Energy Stored In The Magnetic Core

The dimensioning of the magnetic core depends on the volume required to store energy which is calculated from the volumetric energy density given by equation (3) [9].

$$W = \frac{1}{2} L_t i_e^2 = \frac{1}{2} L_b i_s^2 = 937.10^{-9}\, j \tag{3}$$

Calculation of the Volume Density Of Energy

To determine the volume V of permalloy (NiFe) necessary for this storage, we need to know the volume density of energy of this material. This volume V is given by relationship (4) [10].

$$V = \frac{W}{W_{max}} \qquad W_{\max} = \frac{B_{\max}^2}{2\mu_0 \mu_r} \tag{4}$$

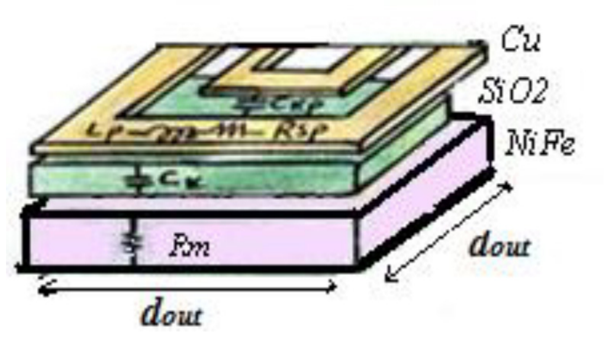

Figure 3. Geometric form of the magnetic core [11]

With a relative permeability μ_r *=800* and saturation induction B_{max}*=0.6T* of permalloy, we obtain: W_{max}*=179jm*$^{-3}$, and *V=0.052mm*^{3} of Nife is needed to store 0.937 μJ.

Core Dimensions

With the volume of the ferromagnetic core being evaluated as *V=0.052mm*^{2}, the core as a block is considered as having a thickness of e_{Nife} and a section of $A=d_{out}{}^2$, S is the section on which we will put the spiral coil. To define the dimensions of the core see Figure 3, d_{out}*=1800 μm* was opted for and we section *A* and the thickness core e_{Nife} was calculated by using equation "7" $A = 324.10^4\ \mu m$

$$e_{Nife} = \frac{V}{A} = 16.15\mu m \tag{5}$$

Calculating of Turn's Number

The primary and secondary values of inductance are given by the following formulas (method Mohan) [12, 13].

$$L_t = \frac{\mu..n_t^2.D_{moy}.C_1}{2}\left(ln\left(\frac{C_2}{\rho}\right)+\rho.C_3+\rho^2C_4\right) \tag{6}$$

$$L_b = \frac{\mu..n_b^2.D_{moy}.C_1}{2}\left(ln\left(\frac{C_2}{\rho}\right)+\rho.C_3+\rho^2C_4\right) \tag{7}$$

D_{moy} is the average diameter of the inductor defined from the inner diameter and outer diameter d_{out} and d_{in} equation (8) [14].

$$D_{moy} = \frac{d_{out}+d_{in}}{2} = 1350\mu m \tag{8}$$

ρ is the form factor, defined by relationship "9"

$$\rho = \frac{d_{out}-d_{in}}{d_{out}+d_{in}} = 0.33 \tag{9}$$

C_1, C_2, C_3, C_4 are the constants of Mohan given by Table 2.

Table 2. The constants of mohan

Geometry	C_1	C_2	C_3	C_4
Square	1.27	2.07	0.18	0.13

The primary and secondary turn's numbers are calculated by using expressions 10 and 11

$$n_t = \sqrt{\frac{2L_t}{\mu.D_{moy}.C_1\left(ln\left(\frac{C_2}{\rho}\right)+\rho.C_3+\rho^2C_4\right)}} \tag{10}$$

$$n_b = \sqrt{\frac{2L_b}{\mu.D_{moy}.C_1\left(ln\left(\frac{C_2}{\rho}\right)+\rho.C_3+\rho^2C_4\right)}} \tag{11}$$

After calculation, we find: $n_t = 5$, $n_b = 2$

Calculating the width of the primary and secondary conductors

To eliminate the skin effect so that the electrical current is distributed over the entire section of the conductor, one of the following conditions must be satisfied: *W*≤2δ or t≤2δ

Where w and t the width and thickness of the conductor. For a frequency f = 40 MHz, ρ_{copper}*=1.7.10*$^{-8}$*[Ω.m]* and μ_r*=1 [H/m]* a skin thickness δ is obtained by used of equation "12", [15].

$$\delta = \sqrt{\frac{\rho}{\pi.\mu_0.f}} = 10.38\mu m \tag{12}$$

We impose one of two values *W* or t and compute the second. It is preferable to impose the value of the thickness "t" of the conductor, since the width *W* should be optimized to reduce the parasitic effects linked to the substrate and the core. By assigning to "t" a value that verifies ≤2δ , the width can be calculated by the use of equation (13).

$$S = W.t \tag{13}$$

When a current I flows in a conductor of section S its current density J_{avg} is given by expression (14).

$$I = S.J_{avg} \tag{14}$$

$$j_{avg} = \frac{1}{\delta}\int_0^\delta j(w)\ dw = \frac{1}{\delta}\int_0^\delta j_0 e^{\frac{-w}{\delta}} dw = j_0\left(1-e^{-1}\right) \approx 0.63 j_0 \tag{15}$$

In most cases, the micro-wires are in contact with a semiconductor substrate that has good heat conduction properties. This allows boundary conditions of $J_o = 10^9 A/m^2$ [14].

by considering the same surface current density in the two windings, and the same thickness value of the primary and secondary conductors t, we obtain the following results. Results are obtained by putting *t=20.76 µm*, W_t and W_b

Calculation of primary and secondary Inter-turn's spacing S_t and S_b

$$S_t = (d_{out} - d_{in} - 2W_t.n_t)/2(n_t - 1) \tag{16}$$

$$S_b = (d_{out} - d_{in} - 2W_b.n_b)/2(n_b - 1) \tag{17}$$

Calculation of primary and secondary Conductor length

$$l_t = 4.n_t(d_{out} - (n_t - 1).S_t - n_t.W_t) - S_t \tag{18}$$

$$l_b = 4.n_b(d_{out} - (n_b - 1).S_b - n_b.W_b) - S_b \tag{19}$$

All parameters that go into the design of the micro-transformer are represented in the summary Table 3 below.

The results ontained are in agreement with integration, because the values of the different geometric parameters are within the recommended dimensions for the integration in low power electronics.

Table 3. Values of the geometrical parameters

Geometrical parameters	Values
Outer diameter: d_{out}	1800 µm
Inner diameter: d_{in}	900 µm
Core thickness: *e*	16.15 µm
Skin thickness: δ	10.38 µm
Number of primary turns: n_t	5
Number of secondary turns: n_b	2
Width of the primary W_t	45 µm
Width of the secondary: W_b	196.87 µm
Thickness of the primary: t_t	20.76 µm
Thickness of the secondary: t_b	20.76 µm
Primary spacing: S_t	56.25 µm
Secondary spacing: S_b	56.25 µm
Primary total length: l_t	2.7 cm
Secondary total length: l_b	1.07 cm

Modeling of Micro Transformer

The use of S-parameters will help to determine the values of the primary and secondary inductances, the primary and secondary series resistors and the quality factor. The calculation with the S-parameters is made from the π-electric model of the micro-transformer "Figure 4".

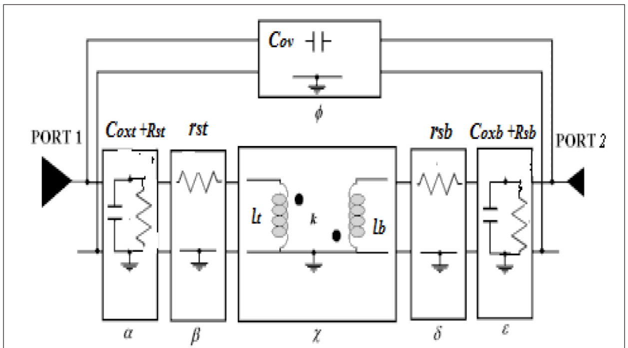

Figure 4. Network Model of integrated transformer [7]

S_{11}, S_{12}, S_{21}, S_{22} are the S parameters. Z_0 = 50 Ω is the characteristic impedance of the line.

From the low-frequency S-parameters, the Z-parameters at each frequency point are determined. This can be shown as follows:

$$Z_{11} = Z_0 \frac{(1+S_{11}).(1-S_{22}) + S_{21}.S_{12}}{(1-S_{11}).(1-S_{22}) - S_{12}.S_{21}}$$

$$Z_{21} = Z_{12} = Z_0 \frac{2.S_{12}}{(1-S_{11}).(1-S_{22}) - S_{12}.S_{21}}$$

$$Z_{22} = Z_0 \frac{(1+S_{11}).(1-S_{22}) + S_{21}.S_{12}}{(1-S_{11}).(1-S_{22}) - S_{12}.S_{21}}$$

From these equations we find the variables that make up the model Pi shown in "Figure 4" and the inductances of the primary L_t and secondary L_b. These inductances are taken from the imaginary part of the impedances, are expressed by expression (20) [16, 17].

$$L_t = \frac{Im(Z_{11})}{\omega} \quad L_b = \frac{Im(Z_{22})}{\omega} \tag{20}$$

And series resistors of the integrated inductors r_{st} primary and r_{sb} secondary are extracted from the real part of the impedances and are expressed by expression "21"

$$r_{st} = Re(Z_{11}) \quad r_{sb} = Re(Z_{22}) \tag{21}$$

The expressions of quality factors extracted from the real and imaginary part of the impedances are given by expressions "22"

$$Q_t = \frac{Im(Z_{11})}{Re(Z_{11})} \quad Q_b = \frac{Im(Z_{22})}{Re(Z_{22})} \tag{22}$$

The transformer model Figure 5 is similar to the model of a spiral inductor. Indeed, the transformer is simply a pair of spiral inductor magnetically coupled. This model includes the series inductances of the primary and secondary coils *(L_t, L_b)*, the series resistances of second primary coil *(r_{st},r_{sb})*, the coupling capacitances between the turns *($C_{ov1,2}$)*, the capacities between the secondary and primary coils and the substrate *(C_{oxt}, C_{oxb})*, the substrate capacity of primary and secondary coils (C_{st},C_{sb})

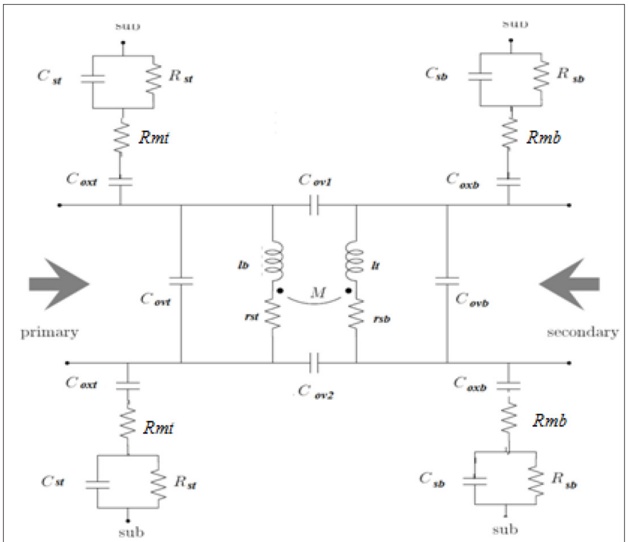

Figure 5. Model of the equivalent electrical circuit of micro-transformer [13]

Calculation of the Electrical Parameters

Presented now are the analytical expressions of the electrical circuit's different elements [7].
The series resistance: r_{st},r_{sb}

$$r_{st} = \frac{\rho.l_t}{W_t.\delta.(1-e^{\frac{t}{\delta}})} \quad r_{sb} = \frac{\rho.l_b}{W_b.\delta.(1-e^{\frac{t}{\delta}})} \tag{23}$$

The oxide capacities: C_{oxt}, C_{oxb}

$$c_{oxt} = \frac{.\varepsilon_{ox}}{2.t_{ox,t}}.W_t.l_t \quad c_{oxb} = \frac{.\varepsilon_{ox}}{2.t_{ox,b}}.W_b.l_b \tag{24}$$

The coupling capacitance between the turns C_{ovt}, C_{ovb} $C_{ov1,2}$:

$$c_{ovt} = \frac{\varepsilon_{ox}}{2.S_t}(t_t.l_t) \; c_{ovb} = \frac{\varepsilon_{ox}}{2.S_b}(t_b.l_b) \tag{25}$$

$$c_{ov1} = \frac{\varepsilon_{ox}.W_t.l_t}{t_{ox}} \quad c_{ov2} = \frac{\varepsilon_{ox}.W_b.l_b}{t_{ox}} \tag{26}$$

The substrate capacity of primary and secondary coils: C_{st},C_{sb}:

$$c_{st} = \frac{\varepsilon_{si}.l_t.W_t}{2.e_{si}} \; c_{sb} = \frac{\varepsilon_{si}.l_b.W_b}{2.e_{si}} \tag{27}$$

The substrate resistance of the primary and secondary coils: R_{st}, R_{sb}

$$R_{st} = \frac{2.\rho_{si}.e_{si}}{l_t.W_t} \quad R_{sb} = \frac{2.\rho_{si}.e_{si}}{l_b.W_b} \tag{28}$$

$$R_{mt} = \rho_{Nife}\frac{e_{Nife}}{l_t.W_t} \quad R_{mb} = \rho_{Nife}\frac{e_{Nife}}{l_b.W_b} \tag{29}$$

3.2. Results of Electrical Parameter's Calculation

The Table 4 summarizes the different calculated electrical parameters.

Table 4. Values of micro-transformer's electrical parameters

Electrical parameters	Values
primary inductance L_t	52 nH
secondary inductance L_b	8.3 nH
Primary serial resistance r_{st}	1.11Ω
Secondary serial resistance r_{sb}	0.10 Ω
Primary oxide capacitance C_{oxt}	2.96 pF
Secondary oxide capacitance C_{oxb}	5.08 pF
Primary résistance of substrate R_{st}	2.99 KΩ
Secondary résistance of substrate R_{sb}	1.74 KΩ
Primary capacitance of du substrat C_{st}	0.64 pF
Secondary capacitance of substrate C_{sb}	1.10 pF
Capacitance inter-spacing of primary C_{ovt}	0.16 pF
Capacitance inter-spacing of secondary C_{ovb}	0.064 pF
Coupling capacitance between the primary and secondary coils C_{ov1}	5.45 pF
Coupling capacitance between the secondary and primary coils C_{ov2}	10.05 pF
Primary magnetic resistance Rmt	5.22 µΩ
Secondary magnetic resistance Rmb	3.04 µΩ

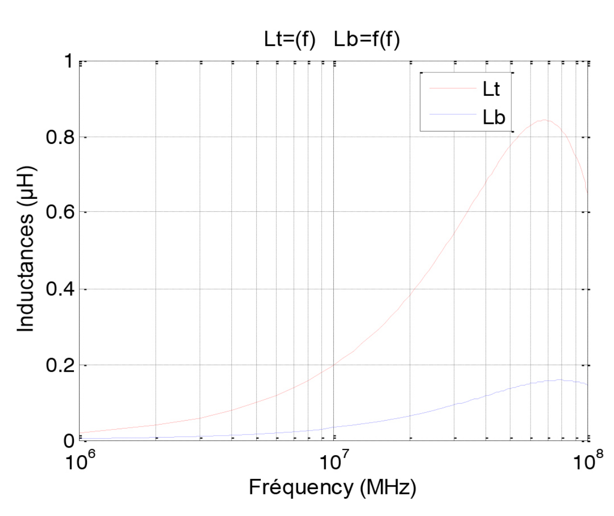

Figure 6. Influence of the operating frequency on the value of L_t and L_b inductors

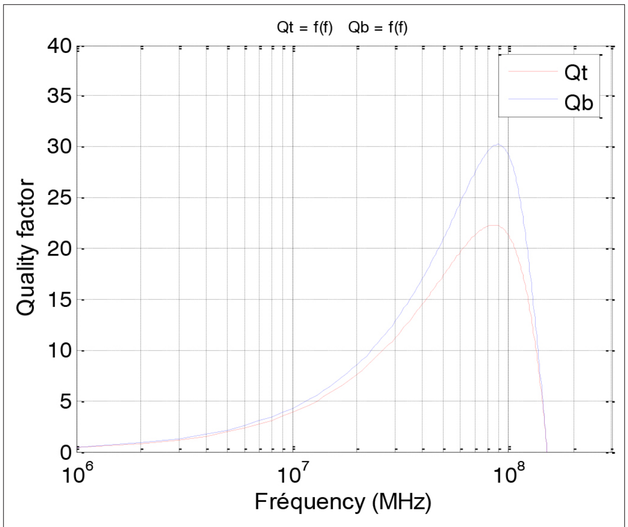

Figure 7. Influence of primary and secondary series resistance versus frequency

The Influence of Frequency on the Inductances of the Primary and Secondary

"Figure 6" shows the influence of the frequency on the inductances of the primary L_t and secondary L_b. These inductances are extracted from the imaginary part of the impedances and are given by the expressions (20).

The figure above shows two distinct zones specific to the operation of the integrated inductors (primary and secondary). At the operating frequency (40MHz), the inductive behavior is recognized. Beyond the resonance frequency (80MHz), it is the capacitive behavior.

Influence of Frequency on the Series Resistances of the Primary and Secondary

"Figure 7" shows the influence of the frequency on the series resistors r_{st} of primary and r_{sb} of secondary. These resistances are extracted from the real part of the impedances and are expressed as (21).

The resistances r_{st} and r_{sb} have very low values at the operating frequency (40 MHz), so the losses by Joule effects are very low. At resonance, the primary and secondary series resistances result in a peak.

Influence of Frequency on the quality Factor of Primary and Secondary Inductances

"Figure 8" shows the influence of the frequency on the quality factors of inductors primary and secondary. The expressions of quality factors extracted from the real and imaginary impedances are given by the expression "22".

Simulation of the Equivalent Electrical Circuit

Simulations were conducted to determine the influence of losses on the micro converter. The PSIM 6.0 software has been selected to simulate the operation of the converter. The following three electrical parameters of the micro converter had to be calculated [10].
Load resistance of the Fly-back converter

$$R_s = \frac{V_s}{i_s} = 2.66\Omega \tag{30}$$

Capacity of the fly-back converter, for a voltage undulation equal to 0.01V, the capacitor C is equal to:

$$C_s = \frac{\alpha^2 m V_e}{(1-\alpha)\Delta V_s R_s f} = 1.87\text{x}10^{-6}\,\text{F} \tag{31}$$

Magnetizing inductance

$$L_m = n_t^2 \frac{\mu_{Nife} d_{out}^{\;2}}{2e} \approx 2.5\text{mH} \tag{32}$$

The integrated Transformer

The transformer that we will be placed in the converter is lossless (integrated). Now the equivalent circuit of the converter containing the micro transformer is simulated.

The electrical circuit of the assembly is given in Figure 9.The simulation of voltages and currents are calculated by using the PCIM6.0 software.

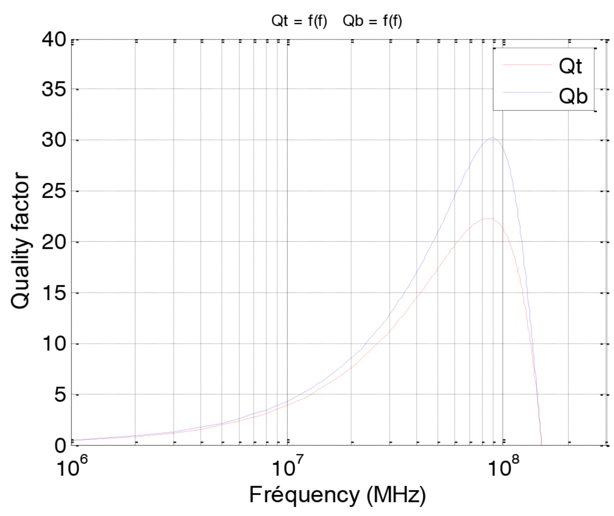

Figure 8. Quality factor of primary and secondary versus frequency

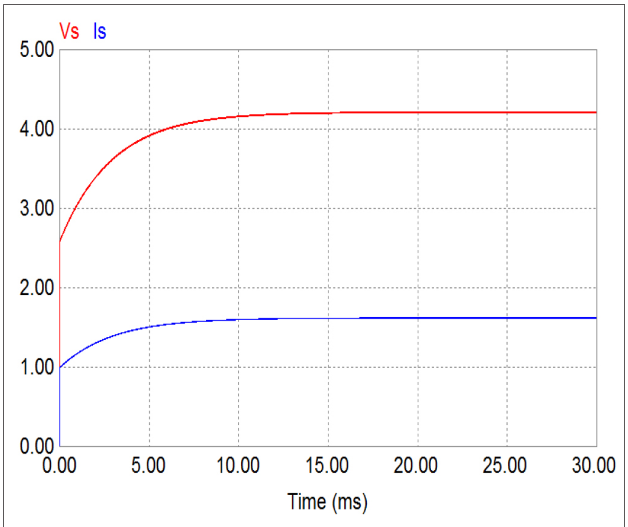

Figure 10. Output voltage of the micro converter containing the integrated transformer

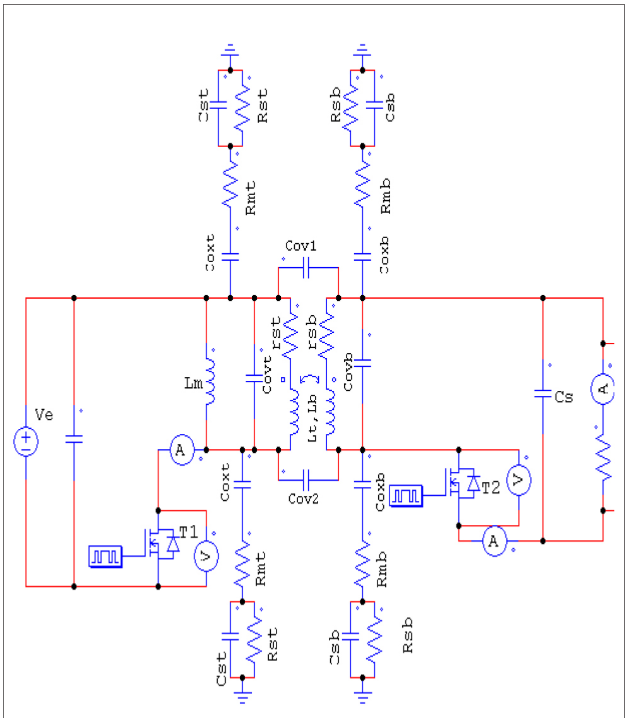

Figure 9. Equivalent electrical circuit of the micro converter containing the integrated transformer

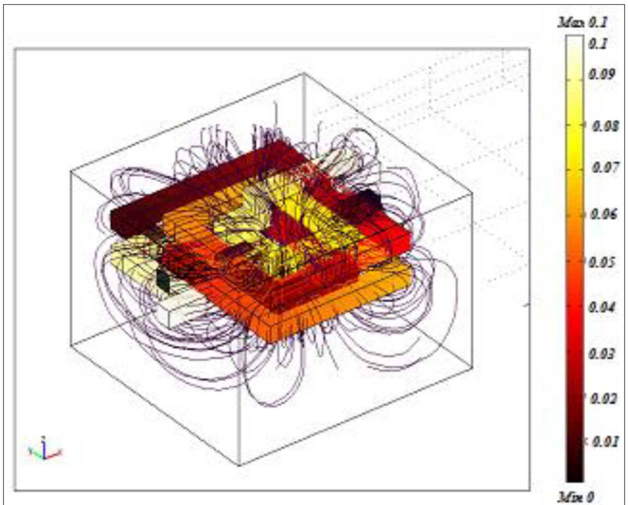

Figure 11. Magnetic field distribution in the micro-transformer without magnetic core

For the integrated transformer, the results Figure 10 are encouraging because a continuous output voltage and a continuous output current are obtained and their values are very close to those of the specifications (Vs= 4.2V and Is = 1.6A).

Therefore, it can be concluded that the geometrical dimensioning of the transformer gave good results.

Simulation of Different Effects on the Micro Transformer

In this section, we the distribution of magnetic field lines in the micro-coils of the micro transformer will be presented.

Using the FEMLAB 3.1 software, an overflow of the magnetic field lines in all directions can be observed in Figure 11. These lines occupy all the space and are stopped only by the simulation boundaries of a coil in the air. This distribution can induce disturbances of the components located in the immediate vicinity of the micro transformer.

In Figure 12, the coils are deposited on a magnetic core, the majority of these field lines being confined in this core. This is explained by the high permeability of ferrite. The insertion of

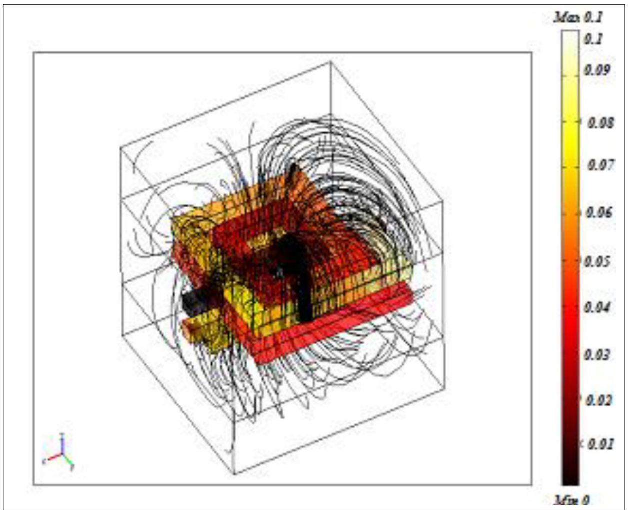

Figure 12. Magnetic field distribution in the micro-transformer with a magnetic core

the ferrite layers thus makes it possible to increase the number of magnetic field lines and to limit their overflow.

Conclusion

The aim of this study is to integrate the geometrical dimensioning of a micro-transformer and its electromagnetic modeling, into a micro-converter. This micro-transformer is intended for the field of mobile and embedded electronics requiring a conversion of energy of low power and a very high frequency range. The integrated micro-transformer is composed of several stacked layers, namely: two copper square planar coil windings, insulating layers, layers of ferrite magnetic material and a semiconductor layers.

As a starting point for this study, the specifications of the flyback type micro-converter was chosen. In the second part, according to the operating conditions of the system based on the method of Mohan, the geometrical dimensioning of the planar transformer was carried out.

In the third part, the geometric parameters to extract the various electrical parameters were used. In the last step, we integrated the dimensioned micro-transformer into a micro-converter. This step facilitated the testing of the operation of the micro-transformer. In order to validate our results, a simulation with PSIM6.0 was pwerformed using FEMLAB 3.1 simulation software to visualize the dispersion of the magnetic field lines for two different transformer models, a model with a core, and the second without a core.

Peer-review: Externally peer-reviewed

Conflict of Interest: The authors declared that this study has received no financial support.

Financial Disclosure: The authors declared that this study has received no financial support.

References

1. K. Youssouf, "Modélisation des transformateurs planaires intègres. Optics Photonic", Université Jean Monnet-Saint- Etienne, France, 2014.
2. D. D. Yaya, "Conception, réalisation et caractérisation d'inductances planaires à couches magnétiques", Université Jean Monnet-Saint-Etienne, France, 2013.
3. B. Vallet, «Étude et conception d'une nouvelle alimentation à découpage à transfert d'énergie mixte basée sur un composant passif LCT intégré" Université Joseph Fourier, 2008.
4. A. Besri, "Modélisation analytique et outils pour l'optimisation des transformateurs de puissance haute fréquence planars", Université de Grenoble, 2011.
5. T. H. Trinh, "Réseaux de micro convertisseurs, les premiers pas vers le circuit de puissance programmable", Energie électrique, Université de Grenoble, 2013.
6. R. Melati, A. Hamid, F. Baghdad, F. Taibi, "Simulation d'une micro bobine", 4ème Conférence Internationale sur l'Electrotechnique, Oran, Algeria, 2009.
7. S. Verma, J. M. Cruz, "On-chip Inductors and Transformers", Bibliometrics, 1999.
8. F. K. Wong, B. Eng, M. Phil, "High Frequency Transformer for Switching Mode Power Supplies", School of Microelectronic Engineering, Faculty of Engineering and Information Technology, Griffith University, Brisbane, Australia, 2004.
9. V. Boyer, N. Godefroy, "Alimentation à découpage Flyback", M1-IUP GEII, Université Joseph Fourier IEEE.
10. M. Derkaoui, A. Hamid,T. Lebey, R. Melati, "Design and Modeling of an Integrated Micro-Transformer in a Flyback Converter", *TELKOMNIKA*, vol. 11, no. 4, pp. 669-682 , 2013.
11. D. M. Pozar "Microwave Engineering", ^{2nd} Edition, Johnwiley and Sons Inc., 1998, pp.19-20, pp. 182-250.
12. S. Mohan, C.P. Yue, M. Del Mar Hershenson, S. Wong, T.H. Lee, "Modeling and characterization of on-chip transformers", International Electron Devices Meeting 1998, 1998, pp. 531-534.
13. S. S. Mohan, "The design modeling and optimization of on-chip inductor and transformer circuits", 1999.
14. C Alonso, "Contribution à l'optimisation, la gestion et le traitement de l'énergie", Université Paul Sabatier Toulouse III, 2003.
15. X. Margueron "Elaboration sans prototypage du circuit équivalent des transformateurs de type planar", Université Joseph Fourier, 2006.
16. R. Thüringer "Characterization of Integrated Lumped Inductors and Transformers", Wien, 2002.
17. A. Weisshaar. "Analysis and Modeling of Monolithic On- Chip Transformers on Silicon", Oregon State University, 2005.

Abdeldjebbar Abdelkader, Diploma in Electrical Engineer 1997, Diploma of magister in plasma 2009, Student in the doctorate from 2010 to date