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STUDY OF THE THERMAL BEHAVIOUR OF AN INDUCTOR ON A TORIC MAGNETIC CIRCUIT

Abstract : This article presents the study of thermal behaviour of an air inductance with closed toric magnetic circuit (3C90). The paper is based on simulation and analytical calculation. The COMSOL software allowed us to design and study the influence of different geometric parameters of the structure. The choice of the equivalent thermal model retained from our component is the nodal. We studied the temperature distribution of the conductor, core, substrate and assembly. To do this, several geometric parameters are studied: the thickness of the conductor, the number of turns and the current.

The results showed a good correlation between simulations and analytical calculations.

Keywords: magnetic circuit inductance - thermal effect - nodal method

INTRODUCTION

Discrete passive components occupy virtually no space in static converters. They are generally cumbersome, expensive and loss-making. Apart from this, we encounter the problem of heat dissipation which reduces the performance and longevity of magnetic components. These authors presented an electrothermal model of a magnetic component. The losses in the magnetic material are modelled using the model of Jules and Atherton, which they modified to take into account the effects of temperature. On the other hand, the model presented takes into account losses in windings, including eddy current losses. The model has been successfully applied to a transformer but only for low frequency excitations [1]. In their work they also presented the thermal model of a power transformer (61.6 kVA) operating at medium frequency (2kHz). In the first part, the authors specify the approaches used to determine losses in the transformer. To this end they use the Steinmetz formula for determining losses in magnetic material and the Dowell formula for losses in conductors. The transformer consists of two C Met glas POWERLITE cores. The authors have introduced a dynamic thermal model with temperature-dependent thermal resistances. They also show its limits for heat dissipation and cooling throughout the process. For the purpose of studying temperature distribution and highlighting hot spots for different insulations [2]. In order to improve the heat transfer between rooms, air and also reduce the heat that is caused by the passage of current in the conductor. [3] conducted their study on the PSEM model (mail-in metal envelope). They used a finite element tool and CFD software for simulation. After evaluation of the performance of this conductor, experimental test results show a reduction in temperature of 15 to 18% compared with the standard conductor.

Knowledge of thermal behaviour is essential for the proper functioning of electronic systems. Note that when a component is run by a current, it releases heat reducing its performance and sometimes leads to its destruction. Thus, poor heat flow management has a detrimental impact on the reliability and proper operation of electronic system. It is therefore imperative to conduct studies in order to know the evolution of temperature in toric inductance.

1. BACKGROUND

The integrated components are highly thermosensitive, beyond certain temperature limits, their reliability and performance deteriorate. To ensure their proper functioning and guarantee their longevity, the operating temperature must therefore be very well controlled. For this, the analysis of thermal behaviour becomes indispensable from the design and realization of any electronic component due to the increasing density of components. Therefore, a study of the geometric parameters is made on the structure. Our objective is to find an acceptable temperature for the proper functioning of the inductance under consideration. It is in this context that, to meet these requirements, we have made the study of influence of geometric parameters on the characteristics of toric magnetic core 3D inductance in order to optimize and realize the component.

2. DESCRIPTION OF THE TECHNOLOGICAL PROCESS

The design of the studied inductance is shown in figure 1

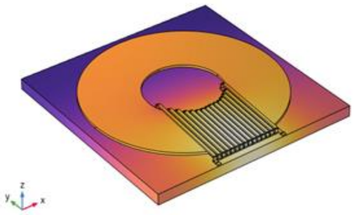

Fig.1 : Design of the inductor

3. DESCRIPTION AND GEOMETRIC PARAMETERS OF THE INDUCTANCE

3.1 3.1 Description of software

COMSOL software takes into account the geometries of multilayer structures and correctly simulates complex electromagnetic effects such as couplings and parasitic effects. It allows you to draw a 3D structure and then calculate many quantities such as propagation constants, parameters S, parameters admittance Y and impedance Z. It allows you to obtain accurate results with a minimum of steps and simulation time.

COMSOL contains several physical modules: electrochemistry, fluid flow, optics, radio frequency, heat transfer, etc. The module we are interested in is the heat transfer but more precisely the heat transfer into the solid.

3.2 Geometrical parameters of the inductance

The geometric parameters of the simulated inductance are listed in the following table:

Table 1: Geometric parameter of the inductance

Parametres	Designations	Values
Wcu	Conductor width	300µm
Dext	Outside diameter	20mm
Dint	Inside diameter	8mm
H	Vertical height of the via	Epf + 2* Epc
D	Distance entre spire	200µm
Px	Width of outer vias	0.6mm
Py	Length of outer posts	1mm
V	Gap between the plot and the ground plane	0.45mm
N	Number of turns	15
Epf	Thickness of the ferrite	200µm
Ecu	Thickness of the conductor	140µm
Esub	Substrate thickness	200µm
µr	MnZn Permeability	2300

3.3 Characteristics of the material used

For our structure, we used three (3) materials which are copper, aluminum and 3C90. Their characteristics are recorded in table 2 below.

Table 2: Material Characteristics

Characteristics	Cuivre	Alumine	3C90
Thermal conductivity (W/m*K)	400	35	5
Electrical conductivity [S/m]	$5.998.10^{-7}$	0	$2{,}088\ .10^{-3}$
Density (kg/m^3)	8700	3965	4800
Thermal capacity (J/kg*K)	385	730	440
Perméabilité relative			2300
Volume losses (KW/m3)			450

4. FORMULAS, MODELS AND TRANSFER METHODS

In order to calculate to extract the values of inductance, resistance and quality factor of our structure, we used an electrical model which is the RL model usable in low frequency. It does not take into account capacitive couplings and is as follows:

4.1 Formulas

Analytically, the values of resistance and temperature are calculated from the following formulas:

- For the determination of resistance:

$$R_s = \frac{\rho.l}{s} \tag{1}$$

With it :

$$\delta = \sqrt{\frac{\rho}{\mu_0.\mu_r.\pi.f}} = \frac{6.6}{\sqrt{f}}$$

- For the determination of thermal resistance:

$$R_{th} = \frac{\Delta T}{P_J} = \frac{T_{cu} - T_a}{P_J} \tag{2}$$

- For the determination of thermal capacity:

$$C_{th} = \frac{\tau}{R_{th}} \tag{3}$$

- For the thermal time constant:

$$\tau = R_{th} * C_{th_{tot}} \tag{4}$$

- For temperature determination:

$$T = T_{amb} + P_t * R_{th} * \left(1 - e^{\frac{-t}{\tau}}\right) \tag{5}$$

S: conductor section in [m2]; l: effective length of the magnetic core in metres [m]; δ: skin thickness; f: frequency in Hz : resistivity of the conductor in Ω.m (1.7.10-8Ω.m for copper). Rth: Thermal resistance in [°C/W]; Cth: Thermal capacity in [J/°C]; τ: Tau in [s] and Temperature in [°C].

Before presenting the results of simulations and theoretical calculations, we will present the modelling and transfer mode.

4.2 Toroidal inductor models

The definition of the model is very important for a study. In order to preserve the proper functioning of the structure, the modeling has the role of making a study for the performance of components in clairvoyance to protect the working state. It is most important during design, implementation and ultimately use. The elements of the studied inductance are typically as shown in the figures below, the nodal method is retained for our toroidal structures.

- **Air**

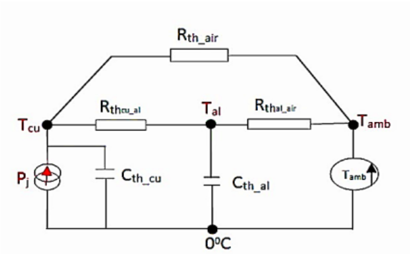

Fig.2 : Modèle thermique de l'inductance à air [4]

- **With magnetic core**

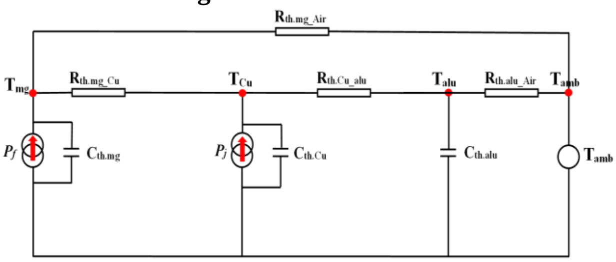

Fig.2: Thermal model of the inductance with magnetic material [5]

4.3 Transfer mode

There are several modes of transfer such as conduction, convection... We are interested in the conduction mode of transfer, because conduction takes place in an opaque medium without material displacement, under the influence of a temperature difference. It is also a mode of spontaneous heat transfer from a region of high temperature to a region of lower temperature, and described by the so-called Fourier law [6][7][8].

$$\varphi_{\text{conduction}} = \frac{-\lambda dT}{d_x} \qquad (6)$$

$\varphi_{\text{conduction}}$: the density of the flux of the heat $[W.m^{-2}]$

λ: thermal conductivity , of , material $[W.m^{-1}K^{-1}]$

T: Temperature [°K]

5. RESULTS OF CALCULATIONS AND SIMULATIONS

We calculated the losses in Table 3 by varying the conductor thickness for a fixed current of 0.5A.

Table 3: Calculation of losses for different conductor thicknesses

Pour I=0.5A	
Ecu (µm)	**P (mW)**
70	76,7
140	26,75
200	19
300	12,7

a. Air and MnZn inductors

We have maintained the geometrical parameters of the air inductance and added the material 3C90 with a thickness of 200µm, the results are in figure 3.

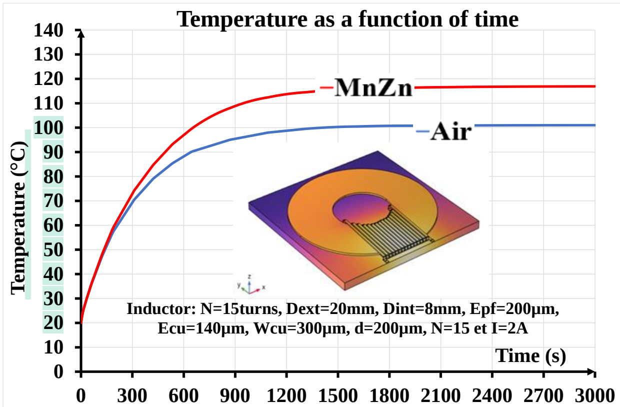

Fig.3: Temperature as a function of time (inductors with air and MnZn material).

The temperature for air structure is low than with magnetic core. It evolves rapidly this is due to the thermal capacity of the air by contrast that with magnetic material is slow. The one with magnetic material can be related to thermal capacity and losses in the magnetic material.

b. Inductor results with MnZn

b.1 Temperature as a function of the thickness of the conductor

The purpose of this paragraph is to study the influence of conductor thickness on the temperature of the conductor. For this, we have kept the following parameters fixed such as I=2A, N=15, d=200µm and variable Ecu of 70, 140, 200 and 300µm. The results are shown in Figure 4 below:

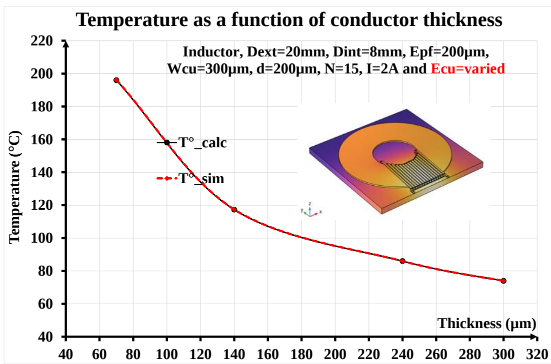

Fig.4: Temperature as a function of conductor thickness

2 Fig.4 shows the influence of conductor thickness on temperature. The more the conductor is thick, the lower the temperature. This is explained by the fact that the thickness of the conductor has a direct impact on the resistance even (formula 1). When the thickness of the conductor is increased, the resistance decreases and therefore the losses by joule effect also decrease. As losses decrease with increasing conductor thickness, temperature also decreases.

To have an acceptable operating temperature, the
2 thickness of the conductor must be increased.

b.2 Temperature as a function of current

In order to observe the influence of current on the temperature of the 3D inductance, we have varied the current from 0.5 to 2A with a step of 0.5A. The geometric parameters are: Ecu=140µm, Wcu=300µm, d=200µm. For these different current values, we have plotted the temperature as a function of time in the figure below.

1

5

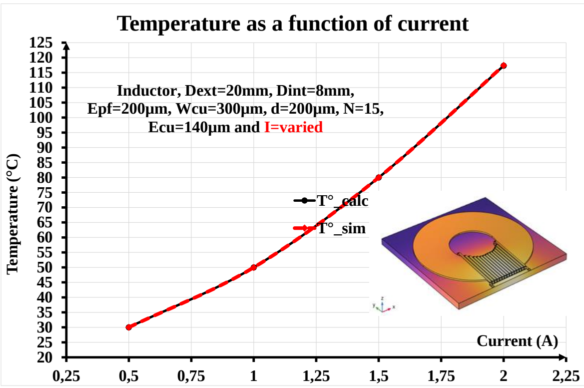

Fig.5: Temperature as a function of current

8 The parabolic evolution of the curves in figure 5 can be explained by the fact that the temperature is a function of the joule losses and these joule losses
5 ($P=RI^2$) are proportional to the square of the current intensity.

b.3 Temperature according to number of turns

1 To study the influence of the number of turns on the temperature value, we performed simulations by varying the number of turns by 3, 5, 7, 9 and 15. The simulated temperature values are shown in Figure 6 below.

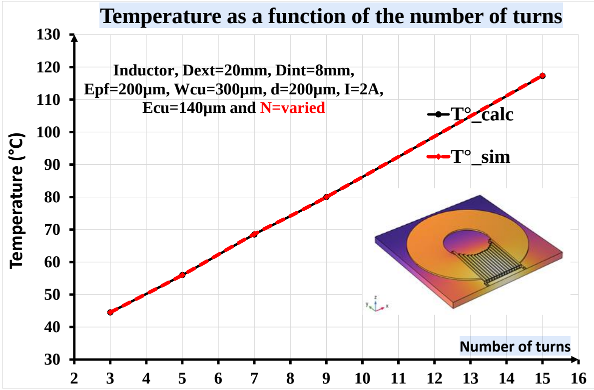

Fig.6: Temperature as a function of the number of turns

Fig.6 shows that when the number of turns is increased, the temperature increases sharply. As the length of the conductor increases, the resistance increases and the joule losses become more and more important.

The number of turns strongly influences temperature.

CONCLUSION

In this article, we studied the influence of geometric parameters on thermal behavior of the inductance over closed toric magnetic circuit. The concept of heat transfer and mode of heat transfer were studied. The equivalent thermal model of our chosen structure is nodal. The simulations allowed us to verify that the joule losses are proportional to the square of the injected current. By applying a current of 2A, the thickness of the conductor is greater than or equal to 140µm and N=15. At this thickness, the operating temperature is stable at 117°C for the structure with core. The magnetic material used in our study is 3C90 and its curie temperature is 220°C.

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