



RESEARCH ARTICLE

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

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Abstract

This article presents the study of thermal behaviour of an air inductor 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.

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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 resistors. 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 electronics 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 inductor.

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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 inductor 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 inductor in order to optimize and realize the component.

Description Of The Technological Process

The design of the studied inductor is shown in figure 1

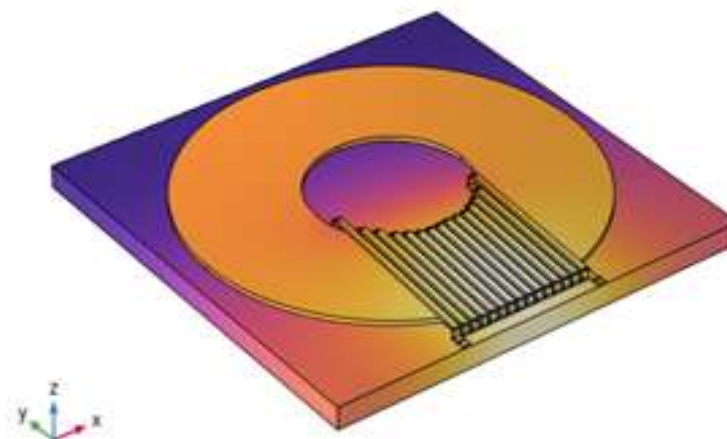


Fig.1:- Design of the inductor.

Description And Geometric Parameters Of The Inductor

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.

Geometrical parameters of the inductor

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

Table 1:- Geometric parameter of the inductor.

Parametres	Designations	Values
Wcu	Conductor width	300 μm
Dext	Outside diameter	20mm
Dint	Inside diameter	8mm
H	Vertical height of the via	$E_{pf} + 2 * E_{pc}$
D	Distance between spires	200 μm
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
E _{pf}	Thickness of the ferrite	200 μm
E _{cu}	Thickness of the conductor	140 μm
E _{sub}	Substrate thickness	200 μm

μ_r	MnZn Permeability	2300
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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	Copper	Alumina	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
Relative permeability			2300
Volume losses (KW/m ³)			450

Formulas, Models And Transfer Methods

In order to calculate to extract the values of inductor, resistor 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:

Formulas

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

For the determination of resistor:

$$R_s = \frac{\rho \cdot l}{S} \quad (1)$$

With it :

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

- For the determination of thermal resistor:

$$R_{th} = \frac{\Delta T}{P_j} = \frac{T_{cu} - T_a}{P_j} \quad (2)$$

- For the determination of thermal capacity:

$$C_{th} = \frac{\tau}{R_{th}} \quad (3)$$

- For the thermal time constant:

$$\tau = R_{th} * C_{th_{tot}} \quad (4)$$

- For temperature determination:

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

S: conductor section in [m²]; l: effective length of the magnetic core in metres [m]; δ : skin thickness; f: frequency in Hz ; ρ : resistivity of the conductor in $\Omega \cdot m$ ($1.7.10^{-8} \Omega \cdot m$ for copper). R_{th} : Thermal resistor in [$^{\circ}C/W$]; C_{th} : Thermal capacity in [J/ $^{\circ}C$]; τ : Tau in [s] and Temperature in [$^{\circ}C$].

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

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 inductor are typically as shown in the figures below, the nodal method is retained for our toroidal structures.

- **Air**

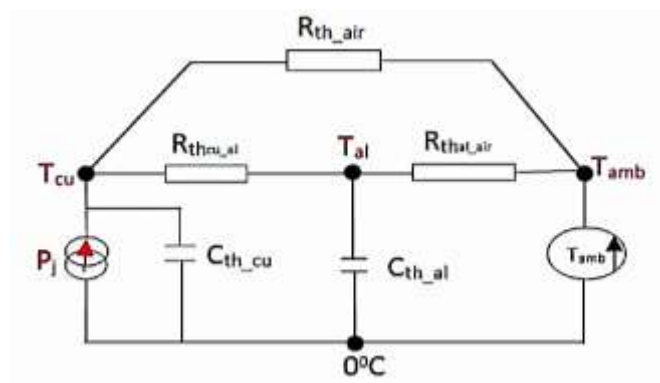


Fig.2:-Thermal model of air inductor[4].

- With magnetic core

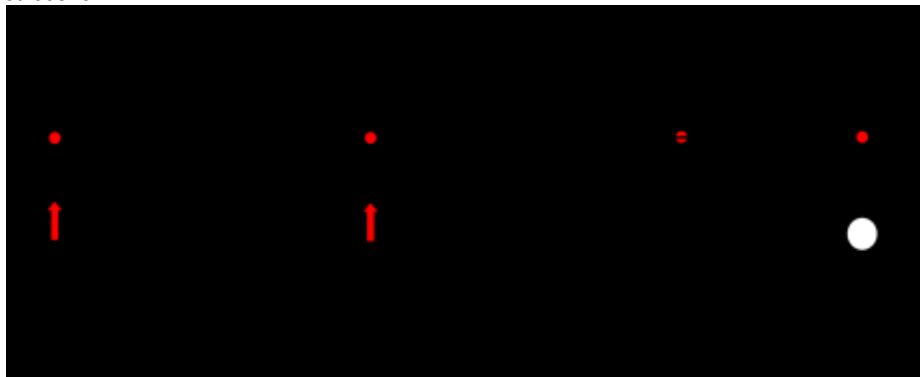


Fig.2:- Thermal model of the inductor with magnetic material [5].

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].

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

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

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

T: Temperature [$^{\circ}\text{K}$]

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.

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

Air and MnZn inductors

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

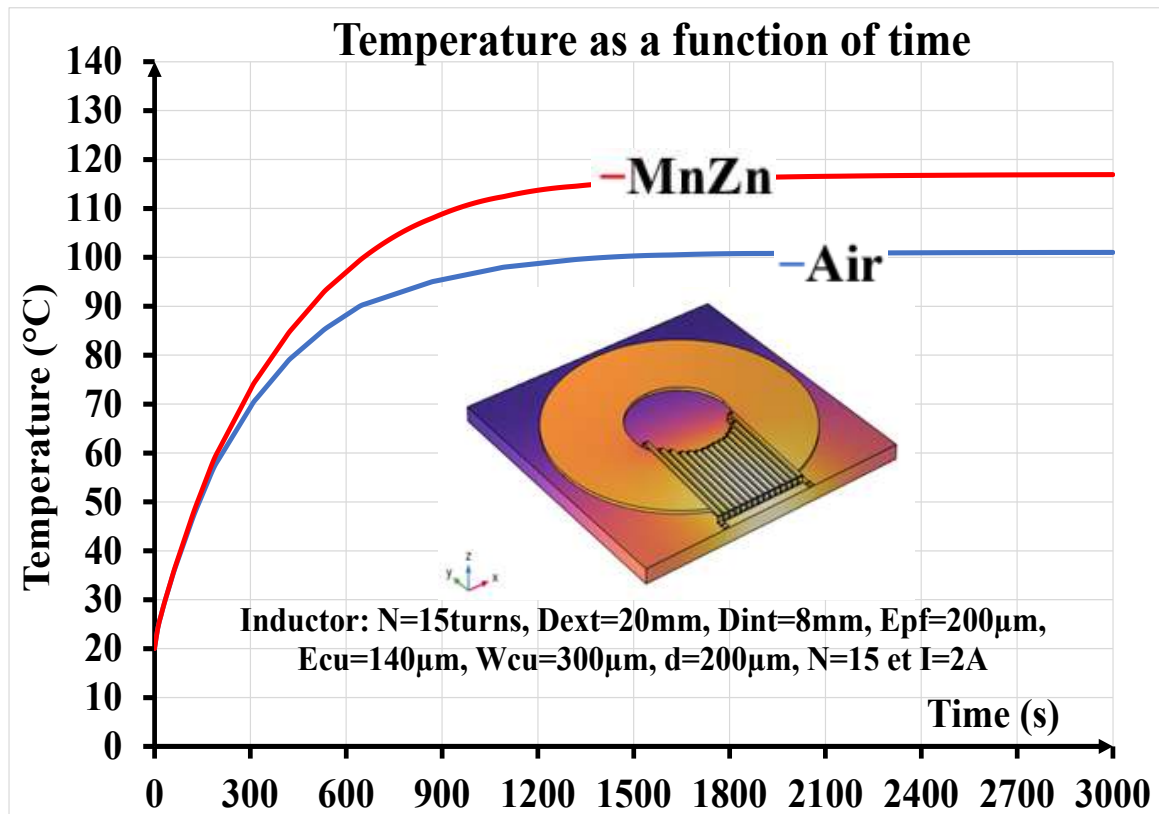


Fig.3:-Temperature as a function of time (inductors with air and MnZn material).

The temperature for air structure is slow 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.

Inductor results with MnZn

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 $I=2\text{A}$, $N=15$, $d=200\mu\text{m}$ and variable E_{cu} of 70, 140, 200 and $300\mu\text{m}$. The results are shown in Figure 4 below:

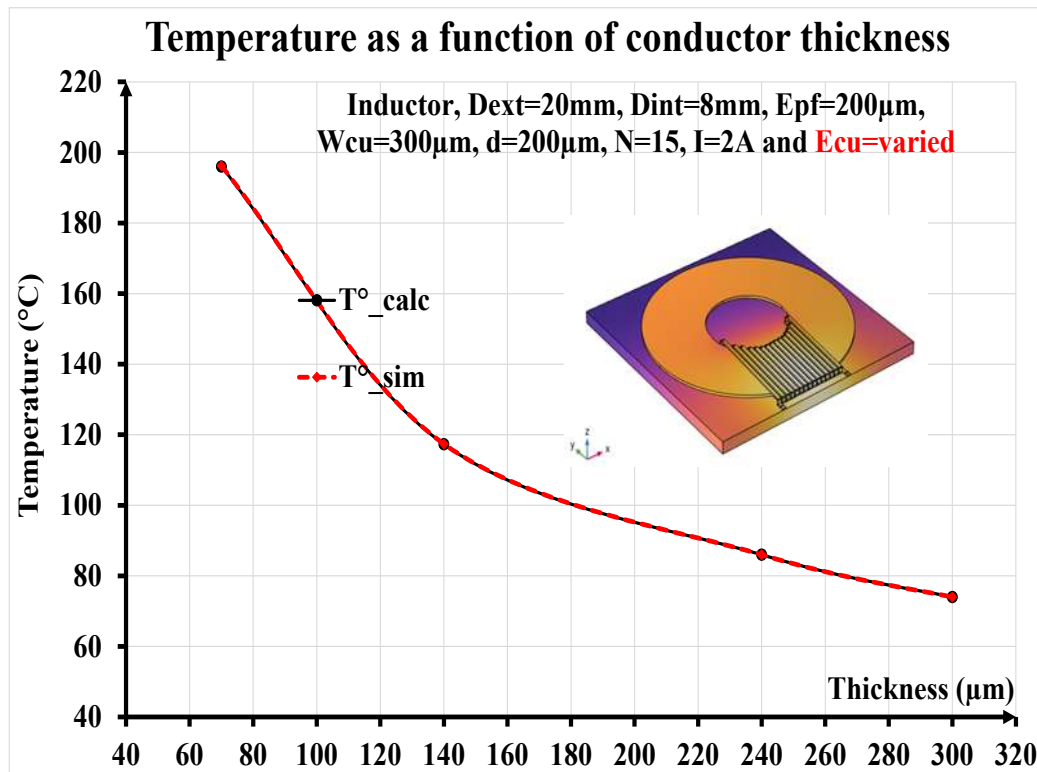


Fig.4:-Temperature as a function of conductorthickness

Fig.4 shows the influence of conductorthickness on temperature. The more the conductoristhick, the lower the temperature. This isexplained by the factthat the thickness of the conductor has a direct impact on the resistoreven (formula 1). When the thickness of the conductorisincreased, the resistordecreases and therefore the losses by joule effectalsodecrease. As lossesdecreasewithincreasingconductorthickness, temperaturealsodecreases.

To have an acceptable operating temperature, the thickness of the conductor must beincreased.

Temperature as a function of current

In order to observe the influence of current on the temperature of the 3D inductor, we have varied the currentfrom 0.5 to 2A with a step of 0.5A. The geometricparameters are: $E_{cu}=140\mu m$, $W_{cu}=300\mu m$, $d=200\mu m$. For thesedifferentcurrent values, we have plotted the temperature as a function of time in the figure below.

The parabolicevolution of the curves in figure 5 can beexplained by the factthat the temperatureis a function of the joule losses and these joule losses ($P=RI^2$) are proportional to the square of the currentintensity.

Temperatureaccording to number of turns

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

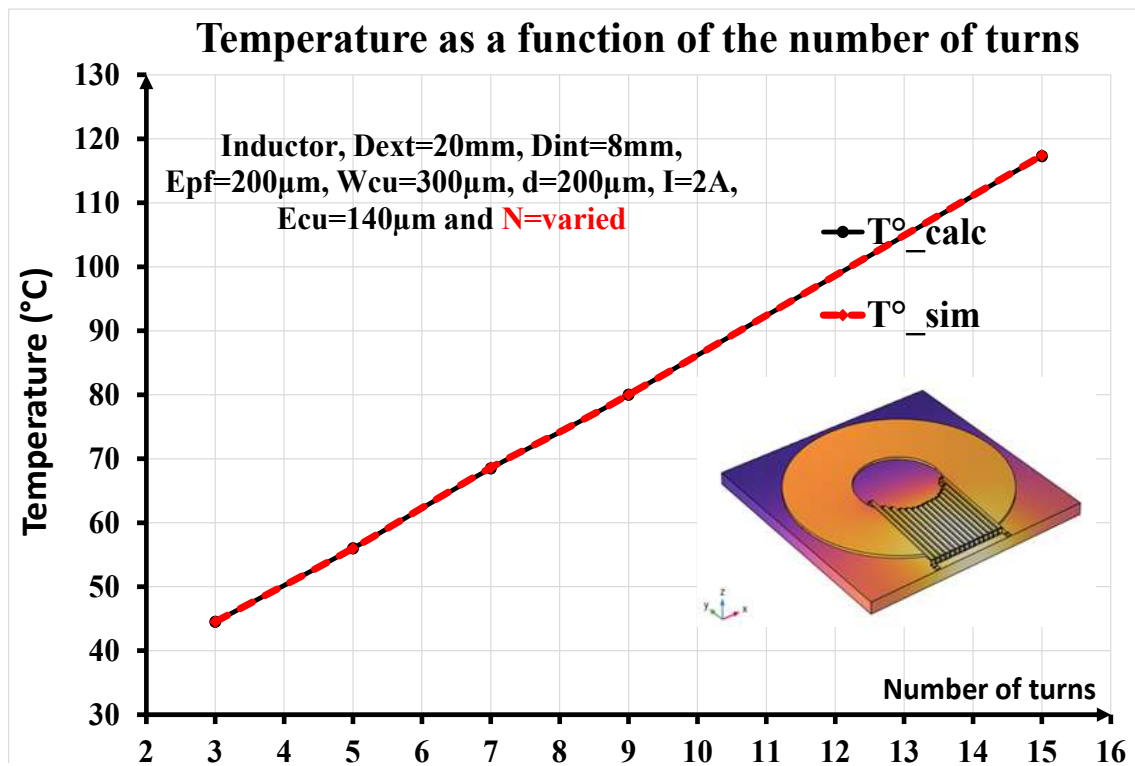
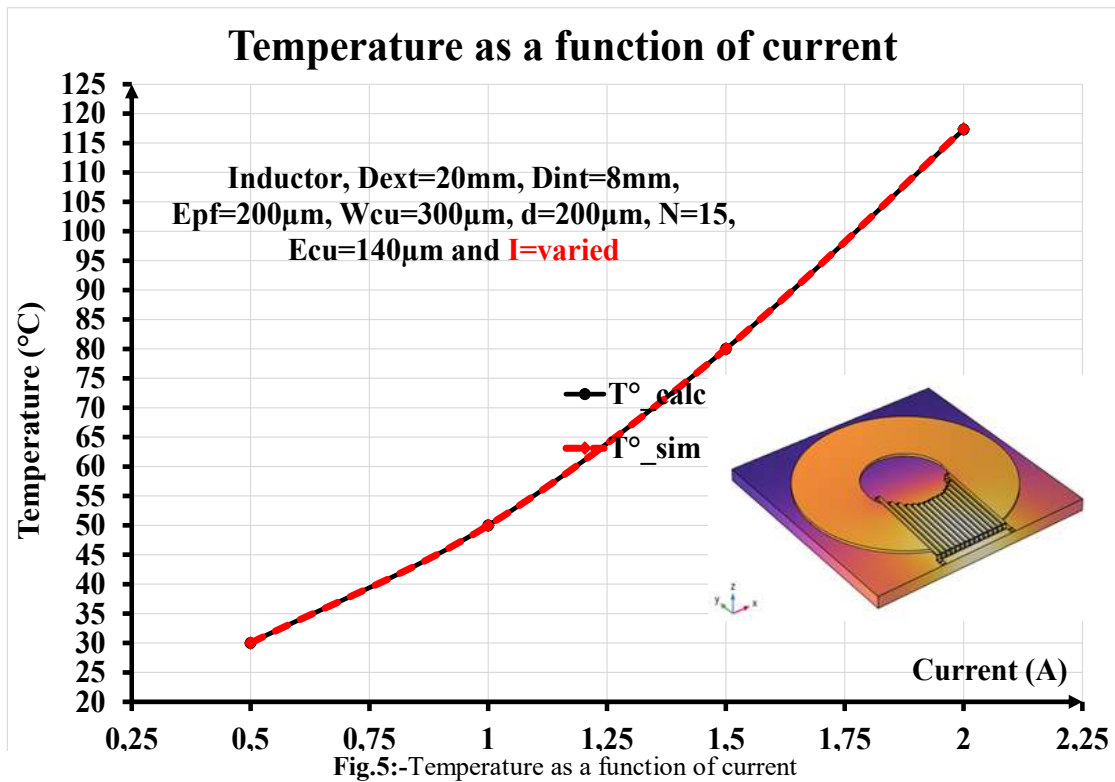


Fig.6 shows that when the number of turns is increased, the temperature increases sharply. As the length of the conductor increases, the resistor increases and the joule losses become more and more important.

The number of turns strongly influences temperature.

Conclusion:-

In this article, we studied the influence of geometric parameters on thermal behavior of the inductor 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 $140\mu\text{m}$ 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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