Experimental and Numerical Analysis of Thermal and Thermomechanical Behavior of a Power Inductor Accompanied by a Reliability Study

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Abstract. In practice, when feeding the electrical and electronic components, they generate heat by Joule’s effect, which will cause an increase in temperature and provoking mechanical deformations related to the expansion of the materials. It is therefore this aspect that is the subject of our study on the thermal and thermomechanical characterization of a ferrite power inductor by experimental and numerical channels. For this purpose, a finite element model was developed and calibrated by comparing its results to the experimental results obtained via thermal measurements and measurements by speckle interferometry system. A reliability analysis on the power inductor was performed numerically, based on the coupling between finite element model validated and the methods of Monte Carlo, FORM and SORM.

1. Introduction
The studied power inductor belongs to a dc-dc converter system. It is composed of a copper coil glued to a ferrite core. Ferrite was chosen in the composition of the power inductor because of the effectiveness of their magnetic and electric properties. However, the ferrite has a drawback of a mechanical nature, owing to its fragility and its sensitivity to temperature variations [1]. In fact, during operation of the power inductor, it will be exposed to a high amperage supply (up to 130A). This will create a temperature rise due to heat loss and will entail a failure mode and even cause rupture of the ferrite core (figure 1).

(a) Rupture of the Power inductor  (b) The power inductor

Figure 1. The power inductor studied

This article focuses on the study of the thermal and thermomechanical behavior of a power inductor, given its high sensitivity to thermal stresses which they are exposed. To do this, we developed a finite element model of a 3D power inductor with ANSYS, to view its thermal behavior, when the variation of the electric current of 0A to 50A and also calculate the mechanical displacement generated by the thermal stresses. To confirm and validate the numerical results, experimental tests were previously-
performed using thermal measurements and mechanical measurements by an electronic speckle pattern interferometry (ESPI).

Uncertainties in the physical properties of ferrite such as thermal conductivity or coefficient of thermal expansion can significantly affect the performance of the power inductor. It is for this reason that the purely deterministic analysis has been replaced by a probabilistic analysis that takes into account the uncertainties of the ferrite material properties. Indeed, a reliability study on power inductor was undertaken, with application of three reliability analysis methods namely: the Monte Carlo method and methods Form / Sorm to calculate the probability of failure [2].

2. Experimental measurements
To supply the thermomechanical numerical model, it is measured synchronously the growth in temperature at different points of the inductor and the displacements undergone by the ferrite core surfaces. It was decided not to work on a single inductor but on a complete dc-dc converter system so as not to block the possible deformations and be as close as possible to real conditions functioning. The figure 2 shows the fixation systems of the dc-dc for measurements on the side and on top of the inductor.

![Figure 2. Fixation systems of the DC-DC](image)

(a) Measurement on the side  (b) Measurement on the top

To realize the thermal load in the structure, the inductor is fed by a current source. The coil of the inductor heats by Joule effect and communicates this heat to the ferrite core.

2.1. Thermal measurements
The temperature measurements are made by using six thermocouples affixed at several points of the inductor. Two thermocouples in top and bottom of the coil, three thermocouples in top, middle and bottom of the ferrite and the last to measure the ambient temperature. Figure 3 describe these measurement points.

![Figure 3. Position of the thermocouples](image)

Measures acquisition is made by the module TC08 of Pico Technology. A Labview routine was developed for synchronization with image acquisition.

2.2. Optical measurements
In order to obtain the displacement of the ferrite core surfaces, a field measuring is required via an interferometry system composed by: a CCD camera; a Nd-YAG laser source of 100mW; piezo actuator attached to a mirror; a computer system including a holographic processor [3-5].
The video signal from the camera is sent simultaneously to a video acquisition module Managed National Instrument by Labview which will allow to process the raw images. The video capture card is synchronized by the RTSI bus with a general acquisition module, which allows to synchronize with temperature measurements. The real image (figure 4a) is given for information. The measures consists of acquiring raw images with specklegramme (figure 4b) and calculate the cards of phases folded (figure 4c). The cards of phases folded of reference calculated from the first 4 images is subtracted to the following phase maps [6].

![Real image](image1)
![Specklegramme](image2)
![Folded Phase](image3)

**Figure 4. Overview 1**

The phases folded being modulo $2\pi$, it’s necessary to demodulate them to obtain the displacement. To achieve this, many phase demodulation algorithms can be used. The reference [7] is one such example. For this study, we will use one provided by the Fringe Analysis 4 of HOLO3 and the Matlab routines developed in the laboratory, in particular using [8]. Starting from the unfolded phase $\phi$ reduces to the surface studied and the wavelength of the laser $\lambda$ illuminating the test structure, the displacement field off plan is given by:

$$d = \lambda / 4\pi \times \phi$$  \hspace{1cm} (1)

3. Numerical Model

Solving a problem by thermomechanical finite element method is performed in two steps: the first step is the resolution of the thermal problem. In order to the temperature field independently of the mechanical conditions. The second step is evaluate deformations produced by this temperature field. The finite element model relating to the power inductor is composed of a coil (5.5 turns) glued to a ferrite core and the assembly is bonded to an aluminum plate (figure 5).

![Power inductor modeled in ANSYS](image4)
![Power inductor mesh](image5)

**Figure 5. Power inductor modeled in ANSYS**  \hspace{1cm} **Figure 6. Power inductor mesh**

The geometrical properties of the ferrite core are shown in figure 7 and material properties in table 1.

![Geometrical properties of the ferrite](image6)

**Figure 7. Geometrical properties of the ferrite**
Table 1. Material properties of power inductor.

|                    | Ferrite | Copper | Aluminum | Glue 1 | Glue 2 |
|--------------------|---------|--------|----------|--------|--------|
| Thermal conductivity (W/mK) | 5       | 400    | 235      | 0.4    | 1.8    |
| Coefficient of thermal expansion | 12e-6   | 1.66e-5| 2.3e-5   | 4.5e-5 | 4.5e-5 |
| Young’s modulus (Pa)          | 150     | 1.14e11| 7.3e10   | 3.55e9 | 3e9    |
| Poisson’s ratio              | 0.28    | 0.355  | 0.33     | 0.3    | 0.3    |

The temperature field and the displacement out of plane were calculated on the side of the ferrite and on top for amperage of 50A. The DC resistance of the coil measured by an ohmmeter is of the order of 0.82 mΩ. When applying a direct current, the heat losses are type $RI^2$. The applied loads: Heat losses for 50A on the ferrite and the coil; Room Temperature 20°C.

4. Presentation of the results

4.1. Thermal measurements

Following the electrical excitation sequence, is measured the evolution of the temperature (figure 8) at different locations of the inductor.

![Figure 8. Evolution of the temperature in the inductor.](image)

4.2. Optical measurements

4.2.1. Measurements on the side

The following figures 9 show the displacement of the surface, side view of the ferrite of the inductor. On this surface, the vertical profile half-base and the horizontal profile at mid-height are plotted and represented in parallel.

![Figure 9. Surfaces and profiles measured on the side.](image)
4.2.2. Measurement on top
The following figure 10 shows how the displacement of the surface, top view of the ferrite of the inductor. On this surface, the vertical profile half-base and the horizontal profile at mid-height are plotted and represented in parallel.

![Figure 10. Surfaces and profiles measured on the top.](image)

4.3. Numerical results compared with speckle interferometry measurements
We proceeded to a confrontation between the experimental and numerical results on the power inductor. We compared the thermal and thermomechanical results numerically and experimentally, while giving the relative error between these results.

- **Thermal results**

![Figure 11. Temperature fields on the coil and on the side of ferrite](image)

**Table 2. Comparison of thermal results for 50A.**

|                | Experimental results | FEM result |
|----------------|----------------------|------------|
| Ferrite        | 27°C                 | 27°C       |
| Coil           | 53°C                 | 55°C       |

- **Thermomechanical results**

![Figure 12. Displacement out of plane on side and top of the ferrite](image)

**Table 3. Comparison of thermomechanical results for 50A.**

|                                      | Experimental results | FEM result | relative error |
|--------------------------------------|----------------------|------------|----------------|
| displacement amplitude out of plane on the side | 2.693 | 2.796 | 3.8%           |
| displacement amplitude out of plane on the top     | 1.417 | 0.135 | 11%            |
5. Results of the reliability study

A sensitivity study is required to select the most significant variables influencing on the system status. The other variables that play a minor role are supposed deterministic. The sensitivity study relating to power inductor, which concerned the material properties, allowed us to predict that the variation of CTE ferrite largely affects on the displacement of the side of the ferrite. We estimated that the CTE of the ferrite follows a normal distribution with mean $1.2 \times 10^{-5}$ and standard deviation of $1.73 \times 10^{-7}$. The failure is based on the fact that at 50A the displacement on the side of the ferrite should not exceed 2.9945 $\mu$m, while specifying that this value is taken in an arbitrary manner.

The objective function can be written as follows:

$$ G = \varepsilon_{\text{max}} - \varepsilon $$

With $\varepsilon_{\text{max}} = 2.99 \mu\text{m}$

The results of calculations for estimating the reliability indices and failure probabilities are shown in table 4.

| Table 4. Reliability results | Form       | Sorm   |
|------------------------------|------------|--------|
| CTE Ferrite                  | 1.2232e-5  | 1.2232e-5 |
| $\beta$                      | 1.21       | 1.21   |
| $P_f$                        | 0.1131     | 0.1131 |
| Time                         | 23h        | 16min  | 23min |

6. Conclusion

In this article we analyzed the thermal and thermomechanical behavior of a power inductor for amperage of 50A. Firstly heat generation is computed in the coil and then it is completely simulated in ANSYS. Next, experimental tests were carried out using thermal measurements via thermocouples and mechanical measurements by an electronic speckle pattern interferometry, to measure deformation on the top and the side of the ferrite core.

On the basis of numerical and experimental results, we conclude that finite element model developed in ANSYS correctly describes the thermal and thermomechanical behavior of the power inductor. The approach adopted allowed to establish a good base to perform a reliability study, a view to calculating the probability of failure with the methods of Monte Carlo and Form / Sorm.

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