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Mustapha Toudji, Vadim Iosif, Stéphane Duchesne, Guillaume Parent, Daniel Roger. Coupled magneto-thermal formulation to characterize a coil composed of conductors with an inorganic insulation. XXIV Symposium Electromagnetic Phenomena in Nonlinear Circuits (EPNC), Jun 2016, Helsinki, Finland. pp.113–114. <hal-04114209>

HAL Id: hal-04114209

<https://hal.science/hal-04114209v1>

Submitted on 2 Nov 2023

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COUPLED MAGNETO-THERMAL FORMULATION TO CHARACTERISE A COIL COMPOSED OF CONDUCTORS WITH AN INORGANIC INSULATION

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Abstract – This paper presents a numerical model of a coil composed of conductors constituted of copper and plated nickel coating with an inorganic insulation. This model, which is based on a coupled magneto-thermal finite element formulation, takes into account the variation of the electrical conductivity and the magnetic permeability of materials due to the temperature increase and allows an overview of some phenomena as the skin and the proximity effects in conductors of the coil.

I. INTRODUCTION

Many solutions are possible in order to develop embedded systems and applications such as aircrafts and electric vehicles. One of them is the obvious increase in the size of these systems which will lead to an augmentation of the mass, and therefore of the consumed energy. The two alternatives of this solution, which are the most feasible, are the increase of the admissible winding temperature of machines or the augmentation of their rotation speed. The latter is not studied in this paper; we focused on the first alternative, which consists in the increase of the admissible winding temperature with the aim of optimizing the size and the mass of the embedded systems. In fact, since the induction in the machine is limited by the magnetic sheet performances, this optimization involves the increase of the current density in the conductors. Consequently, the thermal gradient increases.

Among essential components of rotating machines, the only one that resists the least to high temperatures is the electrical insulation system, since it is mainly made of organic polymers which retain their optimal characteristics until 200°C, or 240°C for the most efficient [1]. The copper used for the current circulation is not limited up to 900°C, and as for aluminum, it starts losing its mechanical properties from 500°C. However, their resistance increases substantially with increasing temperature and, in the case of copper, it is necessary to solve an oxidation problem occurring beyond 200°C [2]. The most common solution is to use a layer of nickel placed in contact with copper to prevent oxidation [3]. Nevertheless, the electrical conductivity and the magnetic permeability of nickel strongly depend on the temperature [4]. The magnetic material around the copper canalizes the magnetic flux and impacts the value of the inductance of the coil. The temperature variations will change the distribution of the current density in the copper and the nickel. Taking into account the skin and proximity effects the determination of the coil characteristics at the expected operating point is slightly difficult. In this paper, behaviour variations of a coil which is able to work up to 500°C are presented by means of a coupled magneto-thermal finite element formulation including conductivity and permeability variations of copper and nickel according to the temperature and taking into account the skin and the proximity effects.

II. DESCRIPTION OF THE COIL

This study was carried out on a coil made of wire, which has a ceramic insulation: the Cerafil 500. This wire has been designed to manufacture high reliability coils so as to remain in service even during severe thermal overload. Coils manufactured with this wire are able to operate under extreme conditions, with an optimal operating temperature in a range from -90 to 500°C in a steady state. The studied coil is composed of 3 layers of conductors separated by a mica film to improve the insulation capability, and each conductor's layer has 18 turns. All turns are impregnated with cement. The conductive core of the wire is composed of copper and plated nickel coating, as shown in Figure 1. Where (1) represents the mica, (2) is the ceramic, (3) is the plated nickel coating, (4) is copper and (5) represents cement.

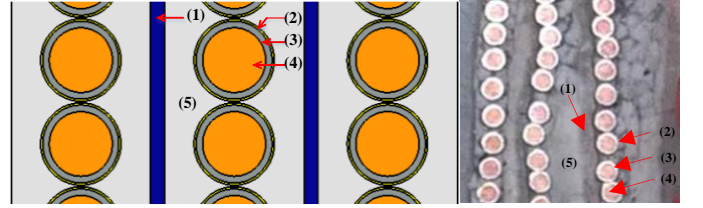


Fig.1. Coil made with the Cerafil 500.

III. NUMERICAL PROBLEM

A. Magnetic and thermal fields computation

To compute the magnetic field distribution including eddy currents, \mathbf{a} - \mathbf{v} magnetodynamic finite element formulation was used to solve Maxwell's equations associated with boundary conditions (BCs). The temperature field distribution in 2-D space is obtained by using the Fourier's law, though BCs also have to be taken into account.

B. Coupled magneto-thermal formulation.

The variation of the temperature in the studied system influences significantly the electrical conductivity and the magnetic permeability of copper and nickel. Figure 2 shows how the conductivity of nickel varies according to the temperature. This variation must be taken into account in the resolution of the coupled magneto-thermal formulation by using this expression:

$$\sigma(T) = \frac{\sigma_{ref}}{1 + \alpha_{\sigma_{ref}}(T - T_{ref})} \quad (1)$$

Where σ_{ref} is the conductivity at the reference temperature T_{ref} ($\Omega^{-1}\text{m}^{-1}$) and $\alpha_{\sigma_{ref}}$ is a parameter which depends on T_{ref}

$$(\alpha_{\sigma_{ref_copper}} = 3,9 \times 10^{-3} \text{ } ^\circ\text{C}^{-1} \text{ and } \alpha_{\sigma_{ref_nickel}} = 6,4 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}).$$

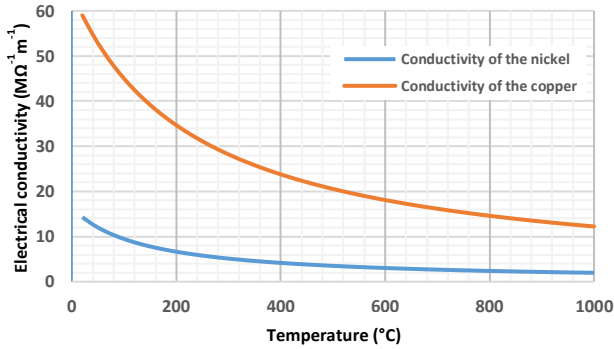


Fig.2. Variation according to the temperature of the electrical conductivity of copper and nickel.

There are two different coupling strategies: strong coupling and weak coupling. In the strong coupling strategy, only one system contains Maxwell's equation and thermal equations. Therefore, the resolution is made at only one time and allows taking into account the interaction between magnetic and thermal fields. Nevertheless, this coupling strategy is computationally very expensive. Because of that, the coupling used in this work is the weak one. For the latter, the solution resolution of the magnetic issue and the thermal problem is done separately. Firstly, it is the magnetic issue which is solved. The magnetodynamic calculation provides the current density in the conductors, which allows evaluating the Joule losses in the studied system. These Joule losses are used as source of the thermal problem in order to obtain first temperature field distribution. The electrical conductivity is then updated to proceed again to the resolution of the magnetic problem, and so on, until the convergence of the solution. Figure 3 illustrates the process of a computation in a magneto-thermal coupling.

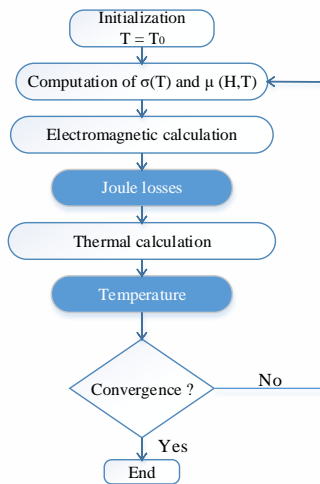


Fig.3. Process of a computation in a magneto-thermal coupling.

III. SIMULATION RESULTS

Figure 4 presents the variations of the inductance for a usual coil made with copper and for a coil made with the nickel clad

wire with the temperature at 50 Hz. These curves bring to the fore the influence of the nickel layer on the electrical behaviour of the coil. For the same number of turns and the same geometry, the inductance is 10 times higher for the coil with nickel than a coil made with copper only. When the temperature grows the magnetic characteristics of the external layer change and after the Curie point of the nickel the magnetic properties become similar to the copper one.

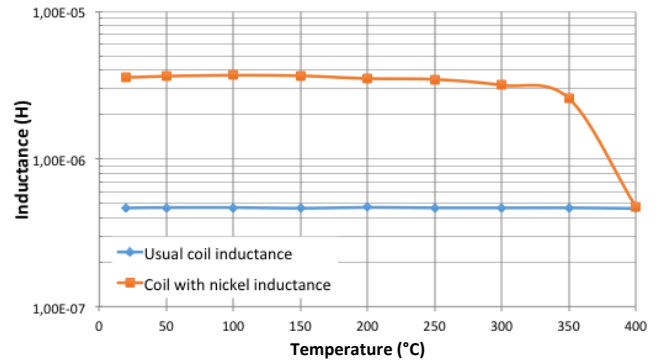


Fig.4. Simulation results.

When the frequency is higher some complex phenomena appears. The skin effect is deeply changed by the presence of a nickel layer with poor conductivity. In the same way, the proximity effect seems to be less pronounced due to a shielding effect of the nickel layer. The extended paper will show some results obtained with higher frequencies.

The nickel properties with the temperature are key parameters to have accurate results. Some works on the characterisation of the nickel layer, which is around the wire, are on progress.

IV. CONCLUSION

This study highlights the particular behaviour of a coil using wires plated with nickel, with the aim of being used in high temperature applications. The finite elements method using a coupled magneto-dynamic formulation reveals that the use of a metal with magnetic features, and a relatively low Curie temperature, creates changeable operating conditions, which must be taken into account in order to find the best configuration for the expected operating point.

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