Developments in Magnetic Materials

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Electromagnetic Simulations including Stress and Temperature Dependent Material Properties

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Extended Abstract

1. Introduction

The presentation will focus on the facilities provided for accurate modelling of materials in electromagnetic simulations using state-of-the-art Finite Element Analysis (FEA) programs. Enhanced ‘multi-Physics’ analysis of non-linear materials will be presented in a range of applications including quenching of superconducting magnets, induction hardening of steel automotive components and magnetisation of hard magnetic material sections & their de-magnetisation in-service. These facilities allow designers to exploit materials to their full potential, leading to the design of cost-optimised, efficient and fail-safe engineering equipment.

2. Functional, Non-linear Tensor and Vector Hysteresis properties

The design of electromagnetic equipment has evolved so that its performance is relatively insensitive to the material properties. However, in high-performance devices, economics dictate that a few percent reduction in the losses is significant, making the variation of material characteristics with parameters such as temperature or stress critical.

Functional material properties allow the user of an FEA program to describe the variation of properties such as electrical or thermal conductivity with quantities such as magnetic field or temperature. For example,

$$\sigma_{op} = \sigma_o \frac{1}{1 + 0.273E - 07 * J_{op}}$$

where J_{op} denotes the operating current density in a sample conducting material and its relationship to the instantaneous conductivity of the material, for a particular geometry.

The facility to describe materials using multi-dimensional functions based on tabulated measurements has also been developed for finite element methods. This allows a full non-linear tensor representation of any material property, for example a term in the magnetic permeability tensor could be specified as

$$\mu_{xx} = f\left(B_x, B_y, B_z, T\right)$$

3. Applications

3.1. Modelling the Quench process in Superconducting Coils

Functional material properties are paramount in the modelling of the quench process in a superconducting magnet coil, using a coupled transient electromagnetic/thermal/ circuit simulation. In the present example, a superconducting solenoid coil, operating at an initial temperature of 4.2 K, is ‘quenched’ by introducing a heat source on the inner radius for a specified period. Once initiated, the quench process propagates, as the quenched volume becomes resistive and produces ohmic heating.

The coil consists of a winding, insulation, fillers etc. The mass density and specific heat capacity of the bulk material representing the coil are an amalgamation of the properties of superconducting filaments, copper, resin and filler. The bulk thermal conductivity is nonlinear (see Fig. 1) and highly anisotropic. In the azimuthal direction, the copper conductivity is dominant. The radial and axial conductivities are different. Various nonlinear material properties are considered in the example. In particular, the critical current density of superconducting material is a function of the temperature and the magnetic field, as shown in Fig. 2.

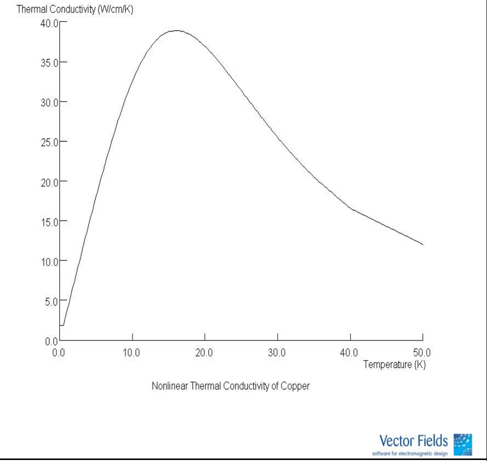

Fig.1. Thermal conductivity of copper.

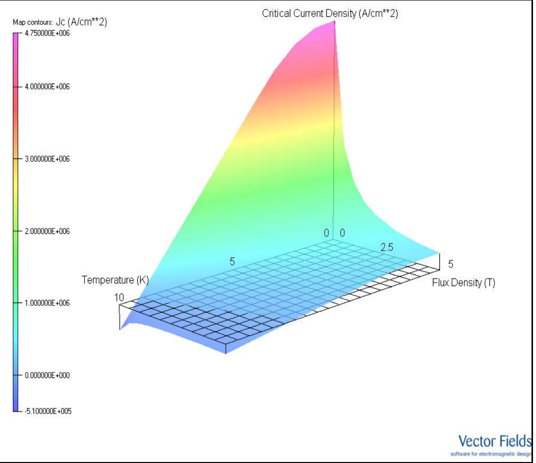

Fig. 2. Critical current density of NbTi.

The temperature rise propagates rapidly in the azimuthal direction, as the thermal conductivity in this direction is much greater than it is in other directions (see Fig.3 & 4). The axial thermal conductivity is higher than the radial because the coil is wound in helical layers with fibreglass sheets separating the layers and hence adding to the resistance of heat propagation in the radial direction (see Fig. 5 & 6).

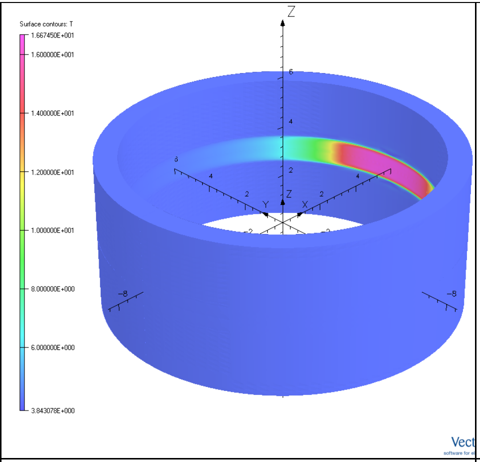

Fig.3. Quench initiation.

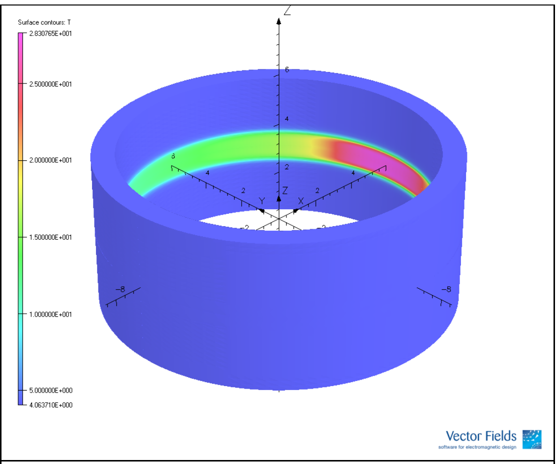

Fig. 4. Temperature wavefront propagation.

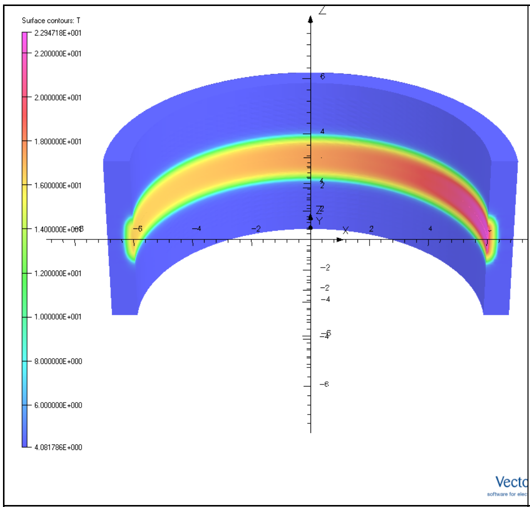

Fig. 5. Radial penetration of temperature rise.

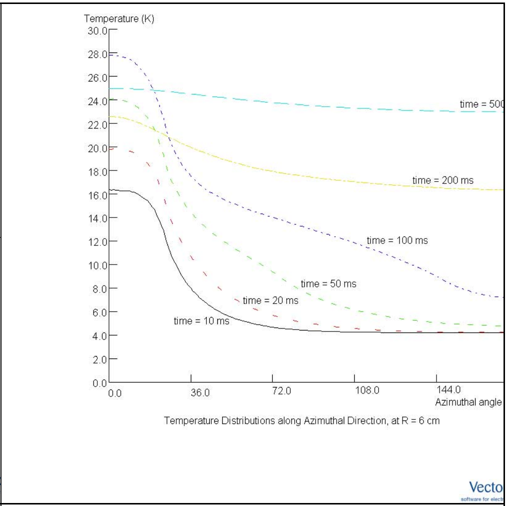

Fig. 6. Temperature distribution along the azimuth.

3.2. Induction hardening of Automotive Components

In this application, a constant velocity joint casing is heated by means of alternating magnetic field of suitable frequency to a temperature above the Curie point, followed by immediate quenching. The core of the component remains unaffected by the treatment and its physical properties are those of the bar from which it was machined, whilst the hardness of the surface is significantly improved. Three water-cooled solenoids shown in Fig. 7 are fed with a 10 kHz alternating current, inducing a magnetic field which is concentrated on the surface of the steel, owing to skin effect. A flux concentrator inside the coil bore increases the system efficiency

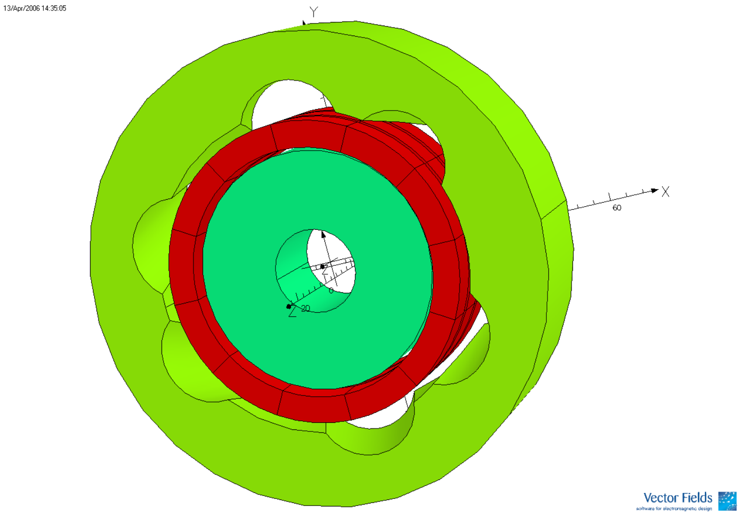

Figure 7. Layout of the device for Induction Hardening of a CV Joint

Accurate modeling of the skin effect is paramount in this application, and this is dependent on the material permeability and conductivity, both of which vary with temperature as follows:

$$\mu_{op} = 1 + \sqrt{\frac{(800 - \min(T_{op};800))}{800}}\,\frac{200}{1 + H_{mean}/1100}$$

$$\sigma_{op} = \sigma_o \frac{1}{T_{op}^{1.1861}}$$

Note well the requirement for the modeling of the transition of the magnetic properties of steel beyond the Curie Temperature of 800 deg C. The transient electromagnetic and thermal solvers are employed in parallel, with the thermal solver requesting a new electromagnetic solution at appropriate time steps. The electromagnetic solver computes the correct heat input to the thermal problem, based on the instantaneous values of the steel permeability and conductivity, for accurate re-evaluation of temperature rise. Figures 8 & 9 aim to demonstrate the ‘heat penetration process’ by depicting the temperature in the device at 0.09 and 0.23 sec.

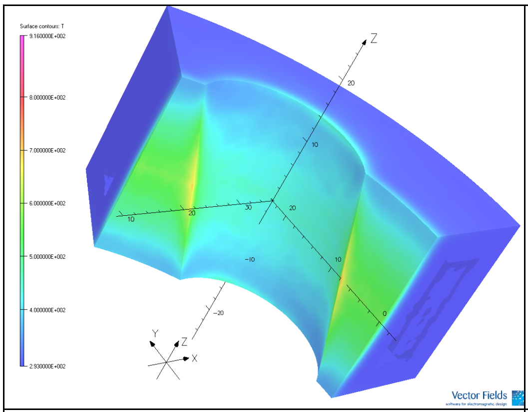

Fig. 8. Temperature distribution @ 0.09 s

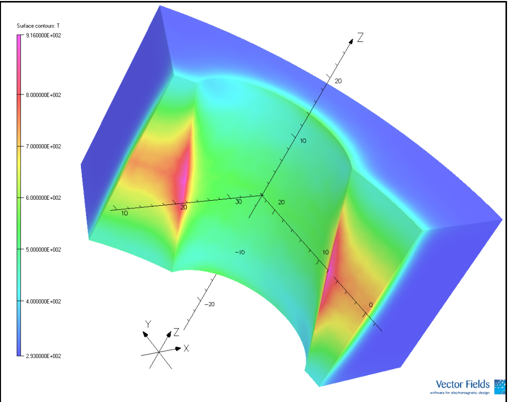

Fig. 9. Temperature distribution @ 0.23 s

3.3. Modelling the Magnetisation Process in Hard Magnetic Materials

A transient, non-linear, eddy-current simulation of a PM magnetisation fixture can be performed in three-dimensions. The model of the permanent magnet material may be based on measured characteristics. During the transient analysis the materials follow virgin BH curves while the field is increasing, and then secondary, temperature dependent ‘de-magnetisation’ BH curves as the field decreases.

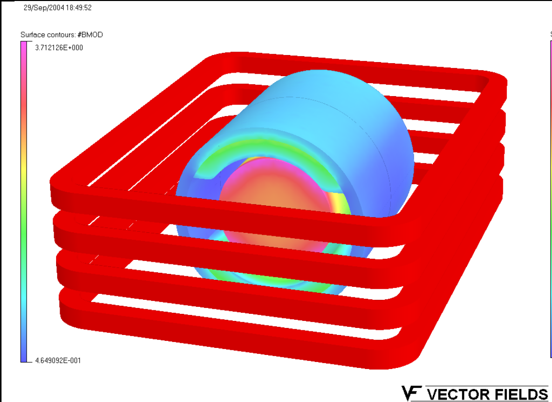

Fig.9. 3D FEA magnetiser model

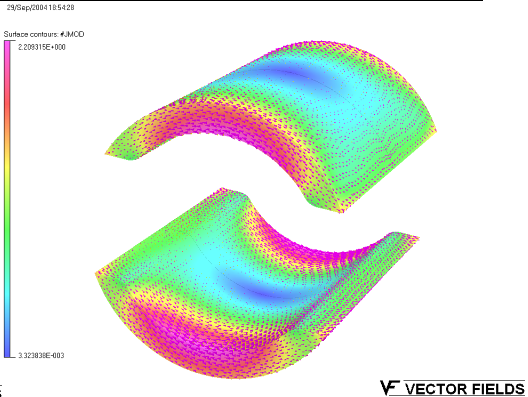

Fig. 10. Flux in the magnetised rings.

The push for increased efficiency, smaller size, reliable performance and low cost solutions has forced the need for extending the demagnetisation model to account for demagnetisation of the magnetised segments ‘in service’. Additional data defining the recoil behaviour of the material is provided and the necessary field history of the material is stored so that de-magnetisation in the application device, such as an electrical machine, can be modelled. Further work is currently concentrating on the extension of facilities for modelling the degradation of permanent magnets ‘in service’. Vector hysteresis models are also being evaluated to further enhance the accuracy of materials modelling, leading to the design of even more efficient electrical machines.

4. Conclusions

Novel modelling methods for accurate modelling of materials in electromagnetic simulations using state-of-the-art Finite Element Analysis (FEA) programs have been presented. Enhanced ‘multi-Physics’ analysis of non-linear materials was presented in a range of applications including a quench in superconducting magnets, induction hardening of steel automotive components and magnetisation of hard magnetic material sections & their de-magnetisation in-service.