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# DEVELOPMENT OF A 3D NONLINEAR RELUCTANCE NETWORK FOR MODELING A SUPERCONDUCTING SYNCHRONOUS MACHINE

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**Abstract** – This paper presents a 3D nonlinear reluctance network for modeling a superconducting synchronous machine. The model can handle the strong saturation of the ferromagnetic materials due to the high magnetic field produced by the superconducting coils. The model is validated through 3D FEM computations and measurements.

## I. INTRODUCTION

Superconducting (SC) coils can produce strong magnetic fields used in different applications like MRI and electrical machines. Superconductors in a bulk form can also be used as screens that can expel strong magnetic fields. These two properties of SC materials gave rise to some original topologies of electrical machines like the one studied in this paper [1]-[2].

The complex geometry of the studied machine requires a 3D electromagnetic model. In addition, the high saturation level of the ferromagnetic materials makes the model non-linear. In this paper, a meshed nonlinear reluctance network is developed to compute the electromagnetic field distribution in the studied device. The results of field and emf (electromotive force) computations obtained with the proposed nonlinear magnetostatic model are compared with those issued from 3D finite element simulations and experiments.

## II. DESCRIPTION OF THE MACHINE

The studied SC machine (Figure 1) can be seen as a claw pole type synchronous machine. It consists of a superconducting inductor and a conventional 3-phase copper armature [1].

The inductor is composed of two coaxial SC coils supplied by a dc current and separated by an inclined elliptical shape SC bulk. The axial magnetic field created by the two solenoids is diverted by the SC bulk which results in two magnetic poles mainly oriented in the radial direction. To increase the magnetic field created by this inductor and reduce the leakage flux, ferromagnetic parts are inserted between the coils and the screen. By adding an external 3-phase armature, we obtain a 2-pole synchronous machine (Figure 1).

The inductor is cooled in liquid helium at 4.2 K. The armature of the machine consists of 48 semi-closed slots where the 2-pole, 3-phase winding is placed. A single-layer, full-pitch configuration has been adopted with 840 turns in series per phase. The current in the SC coils is set to  $I_e = 97$  A which results in a current density of 250 A/mm<sup>2</sup> in the NbTi conductor. The main geometrical parameters of the studied inductor are shown in Figure 2 and their values given in Table I.

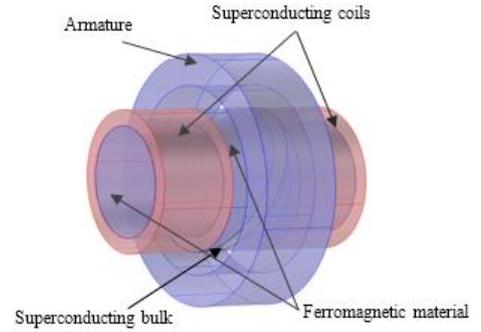


Fig. 1. 3D view of the studied machine.

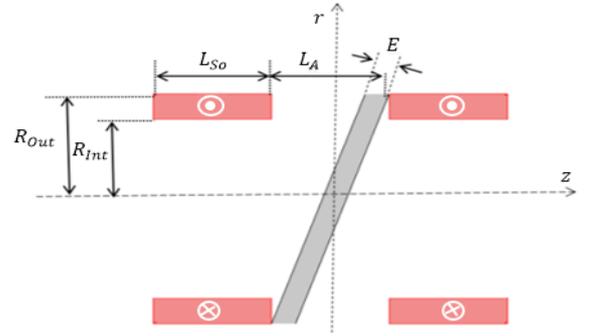


Fig. 2. 2D axial view of the inductor with its geometrical parameters.

TABLE I  
MAIN PARAMETERS OF THE STUDIED MACHINE

Symbol	Designation	Value	Units
NbTi	Solenoid wire material	-	-
$d_w$	NbTi round wire diameter	0.7	mm
$R_{Out}$	Solenoids outer radius	68	mm
$R_{Int}$	Solenoids inner radius	53	mm
$L_A$	Distance between solenoids	45	mm
$L_{So}$	Length of the solenoid	45	mm
YBCO	SC bulk material	-	-
$E$	Thickness of the SC bulk	10	mm
$e_g$	Magnetic air-gap	15	mm

## III. 3D NONLINEAR RELUCTANCE NETWORK.

Figure 3.a shows a 3D reluctance network (RN) of a cylindrical element for which ( $R_r, R_\theta, R_z$ ) are the reluctances in the radial, ortho-radial and axial directions respectively. The studied machine is decomposed into a number of cylindrical elements to form a global reluctance network. The details of the reluctance's expressions and the mesh are given in [2] where a linear model with a low permeability value ( $\mu_r = 4$ ) is used to consider the high saturation level of the iron parts. In this paper, the iron saturation is taken into account in an iterative way.

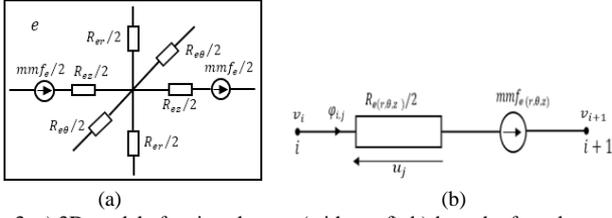


Fig. 3. a) 3D model of active element (with mmf), b) branch of an element.

As shown in Figure 3 (b) and for a ferromagnetic material, the flux flowing in a branch is related to the potential difference between two nodes through a nonlinear reluctance. Each element being connected to its neighboring ones, the Kirchhoff's laws at each node leads to write:

$$f(u_j) = \sum_j \varphi_{i,j}(u_j) = 0 \quad (1)$$

where  $\varphi$  is the flux,  $u$  is the difference of magnetic potentials,  $i$  is the actual node number and  $j$  is the number of branches connected to node  $i$ .

The relation  $\varphi_{i,j}(u_j)$  in a reluctance of ferromagnetic branch  $j$  is defined as a polynomial function of  $u_j$  [3], deduced from the  $B(H)$  curve of the used iron material. Thus, at each node a nonlinear relation arises leading to a nonlinear system of equations describing the overall reluctance network. These equations are written in terms of the node's potentials  $v_m$  ( $m = 1, 2, 3, \dots, N-1$ ):

$$\begin{cases} f_1(v_1, v_2, \dots, v_{N-1}) = 0 \\ f_2(v_1, v_2, \dots, v_{N-1}) = 0 \\ \vdots \\ f_{N-1}(v_1, v_2, \dots, v_{N-1}) = 0 \end{cases} \quad (2)$$

where  $N$  is the total number of nodes from which we need to select a reference node whose potential is set to zero.

The nonlinear system of equations is solved by a Newton-Raphson method. Between two successive iterations  $k$  and  $k+1$ , the Newton-Raphson iterative scheme leads to (3). The iterations are stopped according to the criterion given by (4).

$$V^{k+1} = V^k - \lambda [J(V^k)] f(V^k) \quad (3)$$

$$\max \{f(V^{k+1})\} \leq \varepsilon \quad (4)$$

In (3) and (4),  $V$  represents a vector of the unknown potentials  $v_m$ ,  $J$  is the jacobian,  $\lambda$  a relaxation coefficient and  $\varepsilon$  is the wished maximum error ( $\varepsilon = 10^{-4}$  in this paper).

It has to be noted that a diamagnetic like model is used for the SC bulk to mimics its shielding properties. Hence, the relative permeability of the SC bulk is set to  $5 \cdot 10^{-2}$ . In addition, a smooth armature is considered so the slotting effect is neglected.

#### IV. RESULTS

Figure 4 presents a comparison between the radial flux densities computed by the RN and the 3D FE models. The curves are plotted on a circle of the armature bore ( $r = 87$  mm) for  $z = 0$  and  $z = L_A/4$  (see Figure 2 for the

location details). The agreement is good as the relative difference doesn't exceed 5%.

Figure 5 compares the emf waveforms obtained by the RN and FE models and by test carried out on a laboratory prototype [1]. The different waveforms are close which shows the good accuracy of the RN model.

The CPU time for a single computation is about 22 min in the FE model (magnetic vector potential formulation and a mesh of 467 348 tetrahedral elements). For the RN model, the CPU time is about 6 min (20 160 nodes). The computations are performed on Intel® Xeon® E52630 v4 @ 2.2 GHz (Turbo 3.1 GHz), 64 GB RAM, Windows 10 64 bits.

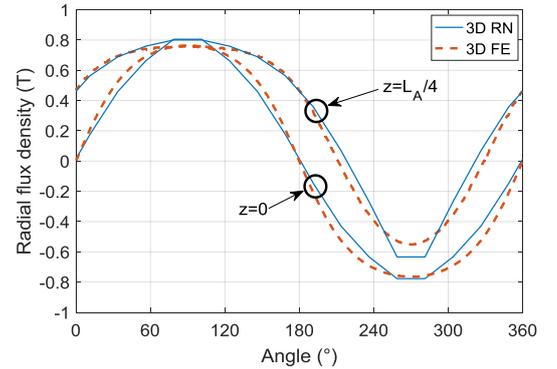


Fig. 4. Radial flux density distribution at  $z = 0$  and  $z = L_A/4$ .

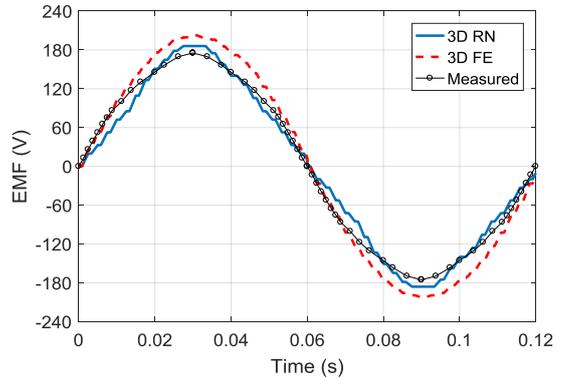


Fig. 5. No-load emf at 500 rpm and  $I_e = 97$  A.

#### V. CONCLUSION

A 3D nonlinear modelling of a superconducting machine by a meshed reluctance network has been presented. This model has been validated by FEM computations and emf measurements. The model is fast enough so it can be used for a quick sizing and optimization of the studied machine.

#### VI. REFERENCES

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