Eddy Current Computation in 2D-FEM for Permanent Magnet Loss Determination

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2D Finite Element Modeling (FEM) of electromagnetic devices, including massive parts with eddy currents, often requires that the total net current through these parts is zero. One commonly studied device incorporating these aspects is the permanent magnet synchronous machine (PMSM) for which the calculation of eddy current losses in the permanent magnets (PM) is of importance when operating at high frequency. The presented work deals with a technique allowing the imposition to zero of the total net current through each of the permanent magnets in a PMSM. Results of the proposed technique in 2D-FEM approach are compared with the ones of 3D FEM in terms of eddy current spatial distribution and losses.

***Index Terms*—Eddy currents, permanent magnets, 2D Finite Element Analysis.**

I. INTRODUCTION

QUANTIFYING eddy currents in rare earth permanent magnets is a task of great importance in the design of permanent magnets synchronous machines (PMSM). Indeed, eddy current losses can lead to a temperature increase so that partial or even total demagnetization occurs [1]. The most accurate way to deal with the calculation of these currents is obviously the use of 3D Finite Element Method but at the expense of the computation time that is a key point for fast design or optimization requirements. Thus, several works have then been conducted to determine eddy currents, with less computation time, using analytical approaches or 2D-FEM [2-5]. To achieve this goal, two main aspects have to be taken into account. The first one is related to the 3D closing paths of the current that are accounted for by a correction factor. The second aspect is the imposition to zero, at each instant, of the global current through the conductive part (PM). In the approaches [2-5], results are obtained with varying accuracies and computation times. In this work, an approach based on the imposition of global quantities [6] is applied in 2D-FEM to insure that the total net current through a permanent magnet being zero. The second section describes the mathematical model while the third highlights the accuracy of the proposed approach by comparison with the 3D-FEM results.

II. MATHEMATICAL MODEL

Let us consider a magnetodynamic problem composed of a domain D of boundary Γ ($\Gamma=\Gamma_B\cup\Gamma_H$ and $\Gamma_B\cap\Gamma_H=0$). In D, a conducting domain D_c of boundary Γ_c ($\Gamma_c=\Gamma_{Jind}\cup\Gamma_E$ and $\Gamma_{Jind}\cap\Gamma_E=0$) is introduced (Fig. 1). To solve the problem, the electric formulation can be used. The magnetic flux density **B** and the electric field **E** can be expressed such that:

$$\mathbf{B}=\mathbf{curl\,A} \text{ with } \mathbf{A}\times\mathbf{n}=\mathbf{0} \text{ on } \Gamma_B \quad (1)$$

$$\mathbf{E}=-\partial_t\mathbf{A} - \mathbf{grad}\varphi - v_1\mathbf{grad}\alpha \text{ with } \varphi=0 \text{ on } \Gamma_{E1} \text{ and } \Gamma_{E2} \quad (2)$$

where **A** is the magnetic vector potential, φ is the electric scalar potential, v_1 is the value of φ on Γ_{E1} and α a scalar function equal to 1 on Γ_{E1} and 0 elsewhere.

Then, the equations to be solved are:

$$\mathbf{curl\,H} - \mathbf{J}_{ind} = \mathbf{Js} \text{ and } \operatorname{div}\mathbf{J}_{ind} = 0 \quad (3)$$

$$\text{with } \mathbf{J}_{ind}=\sigma\mathbf{E} \text{ and } \mathbf{H}=\mu^{-1}\mathbf{B} \quad (4)$$

where $\mathbf{J}_{ind}$ is the eddy current density in D_c and $\mathbf{J}_s$ the current densities in the stranded inductors. To impose the current flowing thought D_c, an additional equation must be added [6]:

$$I = \int_{D_c}\mathbf{J}_{ind}\cdot\mathbf{grad}\alpha dD_c \quad (5)$$

Then, the potential v_1 is a new unknown of the problem.

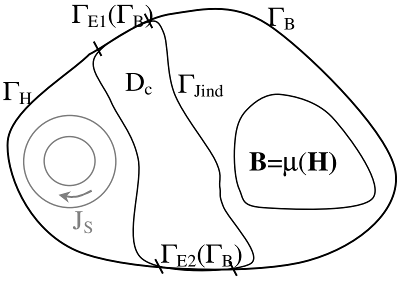

Fig. 1. Illustration of the magnetodynamic problem in the domain D.

III. STUDIED DEVICE

The approach is applied to a 3-phase, 8-pole PMSM whose rated values are 30kW - 380V - 400Hz - 6000rpm.. The stator has 48 slots and the rotor has 8 surface-mounted NdFeB magnets of 40mm width (Fig. 2) whose electrical conductivity is 0.55 MS/m. Furthermore, the stator internal diameter and the active length of the machine are equal to 150 and 190mm respectively. Considering the symmetry of the system along the z axis, only half of the machine is modeled in 3D-FEM. The characteristics of the 2D and 3D numerical models are summarized in Table I. The boundary condition $\mathbf{E}\times\mathbf{n}=\mathbf{0}$ is imposed on the symmetry plane of the studied system. On other boundaries, the boundary condition $\mathbf{J}_{ind}.\mathbf{n}=0$ is implicitly verified in the electric **A**-φ formulation that is used. In addition, for the 2D FE model, the permanent magnets are defined as massive conductors where the net current through each magnet is imposed to zero.

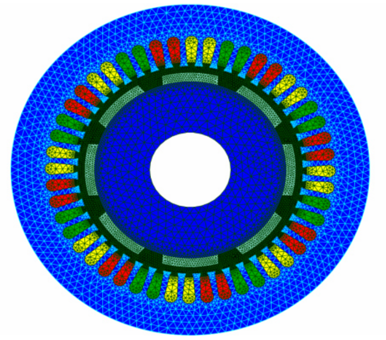

Fig. 2. Geometry and mesh of the studied PMSM.

To limit the calculation time, the magnetic behavior of the ferromagnetic material is assumed to be linear with a relative magnetic permeability μ_r=5000. Therefore, in the following results, the studied machine is supplied by a three phase current supply of 30 A-RMS that does not saturate the iron core. Simulations were achieved for two electrical periods using 50 points per period.

TABLE I
MESH DATA

Item	2D Model	3D Model
Number of elements	13375	290422
Number of nodes	13560	153939
Number of unknowns	6603	578953

IV. RESULTS

As a first comparison criterion between 2D and 3D approaches, the eddy current losses are reported in fig. 3 for the instantaneous losses at 400Hz and in fig. 4 for the average losses over a wide frequency range, up to 4800Hz.

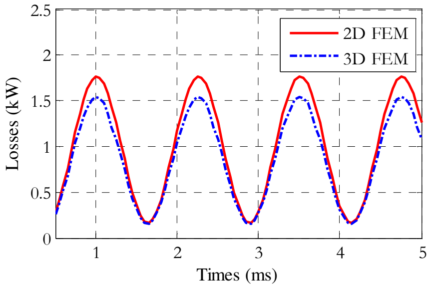

Fig. 3. Instantaneous eddy current losses for 400Hz .

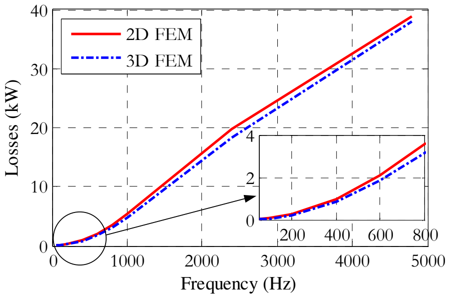

Fig. 4. Average eddy current losses as function of frequency.

Globally, the 2D FEM approach over-estimates the eddy current losses, the relative difference having a decreasing tendency with increasing frequency (12% at low frequency and only 3% at 4800Hz). The difference is emphasized on the instantaneous loss evolution for 400Hz where it can be seen a gap for the instantaneous loss peaks. Nevertheless, regarding the PM demagnetization issue, the most important losses are linked to high frequency excitation fields.

For the comparison of the local behavior of both numerical models, the distribution of the eddy current density in the cross section of a permanent magnet, taken on the symmetry plane, is considered. The eddy current density distributions are reported, for both 2D and 3D approaches on fig. 5 for, respectively, two different time instants at 400Hz and in function of the angular position in the PM. The agreement between the approaches is clearly emphasized on both figures.

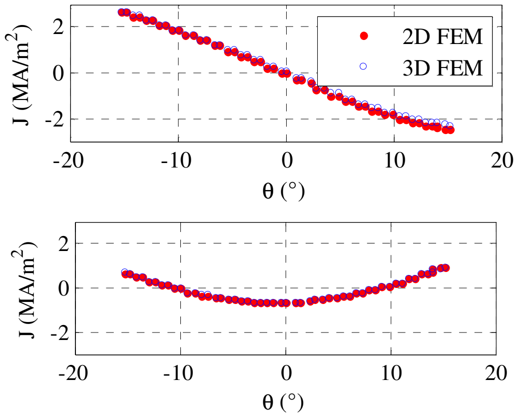

Fig. 5. Eddy current density in the PM cross-section for 400Hz at, respectively, t=2.25 ms and t=2.9 ms.

In addition, the eddy current computation, and permanent magnet loss calculation, in the 2D FE model requires less computation time than the 3D FE model (about 2 minutes versus about 1 hour). The proposed 2D FE approach is then well adapted for fast design or optimization requirements..

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