Permanent Magnet Eddy Current Losses in 2D FEM Simulations of Electrical Machines

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***Abstract*—The prediction and calculation of eddy current losses occurring in permanent magnets of electrical machines is of particular interest. Most accurate results are achieved using transient 3D finite element simulations, which require long computation times and elaborate models. Due to this, 3D models are only applied during the final stage of the machine design process and 2D models are used instead. However, difficulties arise when using 2D FEM simulations, since the calculation of eddy currents is typically a 3D problem. This paper presents an approach to calculate permanent magnet losses of electrical machines by 2D finite element simulations. The approach discussed is applicable to surface mounted as well as interior permanent magnets.**

***Index Terms*—Permanent magnet modeling, eddy-currents, losses, numerical simulation, PM machines.**

I. Introduction

Permanent magnet synchronous topologies (PMSM) are widely applied in electrical machines. Main reasons are: high power density and high efficiency.

Current applications, for instance in electrical and hybrid vehicles, require operation in a wide range of speed. Due to this, next to the mechanical losses, iron and permanent magnet (PM) losses become increasingly important.

PM materials have excellent magnetic properties, but these are strongly dependent on the temperature. NdFeB based PMs have relative large values for the reversible temperature coefficient. This thermal constraint requires that the PM losses are small enough not to heat up the material above an allowed temperature.

Most accurate results are obtained with 3D computations [1] requiring long computation times and exhaustive model building. Analytical methods are mainly limited to surface mounted PM machines [2], [3] and are derived for particular machine designs.

In this paper eddy current losses are calculated starting from a 2D FE solution. For this purpose a modified 2D vector potential solver, 2D-A-ϕ-Solver, is used. In this approach the voltage drop across each single permanent magnet is set to zero in order to fulfill Gauss' law [6]. Furthermore the eddy current reaction is taken into account [4], [5].

These radial 2D FEM simulations neglect axial effects and assume simplified eddy current paths in the PM as if these were ideally shorted at the edges (See Fig.1(a)). Due to this, deviations between simulated eddy currents in 2D radial FEM and 3D FEM solutions occur.

In order to include axial effects and the skin effect, the 2D-A-ϕ-Solver is coupled to a modified 2D-T-Ω-Solver and the PM is divided into virtual slices (See Fig.1(b)). The thickness of the virtual slice is chosen along with the penetration depth. Here, the modified 2D-T-Ω-Solver is used to calculate axial eddy currents. Hence, the proposed method allows the calculation of eddy current losses inside PMs of different geometric dimensions, i.e., axially long as well as short magnets.

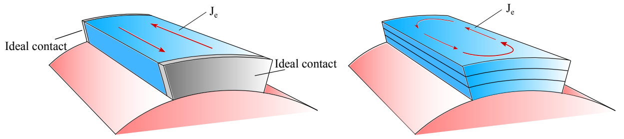

Figure 1: (a) Simplified eddy current path assumed for radial 2D FEM. (b) Division of the PM in virtual slices to include the skin-effect.

II. Permanent Magnet Modeling and Application

The $A-\phi$ approach [1], [7], based on the magnetic vector potential is:

$$\mathrm{curl}\,(\nu \mathrm{curl}\,\mathbf{A}) = \mathbf{J}_s - \sigma\partial_t\mathbf{A} - \sigma \mathrm{grad}\,\phi + \mathrm{curl}\,\nu\mathbf{B}_r. \quad (1)$$

In combination with the boundary conditions and Gauss' law (2), a system with two partial differential equations is obtained, which may be solved by a variational approach.

$$\sigma \mathrm{div}\,(\partial_t\mathbf{A} + \mathrm{grad}\,\phi) = \mathrm{div}\,\mathbf{J}_s = 0 \quad (2)$$

Finally, the eddy current losses could be calculated by Joule's law. Therewith it is possible to calculate the eddy current distribution and losses in 2D simulations of axially long machines, i.e., axially long permanent magnets. Once the width b of the permanent magnets becomes comparable to the length l, or even shorter, the aforementioned approach needs to be modified. On that account, a modified 2D $T-\Omega$ solver is used to calculate the eddy current distribution in the axial direction. Coupling both 2D solver leads to quite accurate results, featured by a speed-up of 600% when compared to 3D FE simulations. Details on the implementation and results will be given in the full paper.

The developed model is applied to the simulation of a permanent magnet synchronous machine with surface mounted magnets. Obtained results will be compared to 3D finite element simulations.

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