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2D Semi-Analytical Modeling of Eddy Currents in Multiple Non-Connected Conducting Segments

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I. Introduction

To model parasitic forces and power losses due to eddy currents in electromagnetic devices, several techniques can be used. An often used method is the finite element method (FEM). Because of the relatively high computation time of the finite elements method, alternative analytical methods, such as the harmonic (Fourier) model [1],[2], can be used. However, to include the reaction field of eddy currents in a segment which is not spanning the entire periodic width, the classical Fourier is not suited. In [3], eddy currents in a segmented structure are approximated by applying the method of images to the results of the Fourier analysis technique applied to the non-segmented structure. In [4] a technique has been developed to include the spatially dependent conductivity of a region in the solutions of the Fourier model, thereby modeling the eddy currents and their reaction field in segmented structures. However, when applied to a geometry with multiple conducting segments, the model calculates the currents as if the segments are electrically connected.

In this paper, the 2D Fourier analysis technique from [4] is extended to analytically model eddy currents in multiple non-connected conductive segments. The forces on conducting parts due to induced eddy currents and the power losses are calculated using the developed method and compared to FE results.

II. General Solution

In Figure 1 a periodic section of a coreless motor in the 2D Cartesian coordinate system is shown. The model is periodic in the x -direction and, therefore, all magnetic field solutions and quantities dependent on x are written as a Fourier series. In the two conducting segments, eddy currents are induced by the time varying magnetic field originating from a three phase coil set. The model is divided into horizontal regions and the permeability inside a region is assumed constant. The surface on which the coils are placed is assumed infinitely permeable. Maxwell equations for quasi-static fields are used and the vector potential A is introduced, which only has a z -component. In the airgap and coil region the vector potential has to satisfy the Laplace and Poisson equation respectively.

In a conducting region the induced current in a segment is written as

$$\mathbf{J}_{ind,z,i} = -\sigma_i f_i(x) \delta A_z / \delta t - f_i(x) c_i, \quad (1)$$

where σ_i is the value of the conductivity in segment i and $f_i(x)$ is the spatially dependent function belonging to the segment as shown in Figure 1. An unknown constant c_i multiplied with $f_i(x)$ is added to the time derivative of the vector potential in (1) which is necessary to correctly model the eddy currents in multiple non-connected segments. The expressions for the induced currents are used to obtain the diffusion equation

$$\delta A_z^2 / \delta x^2 + \delta A_z^2 / \delta y^2 = \mu_r \mu_0 \sum_i (\sigma_i f_i(x) \delta A_z / \delta t + f_i(x) c_i). \quad (2)$$

The solution for the vector potential is determined applying the method of separation of variables and is presented in [4]. Because of the added unknowns in (1) and (2) the particular solution of conducting regions is changed. All regions contain an unknown a and b per harmonic in the solution for the vector potential. The expressions for the magnetic field strength and magnetic flux density components can be derived from the vector potential.

Boundary conditions are applied between the regions to obtain a system of equations. By solving this system the unknown a and b per harmonic for each region can be found. However, because an extra unknown c_i is added for each conducting segment an equal amount of conditions has to be added to the system of equations. Since the current in a segment can only flow inside the segment itself, the integration of the current density in a segment should equal zero. Because the vector potential is multiplied with the Fourier series of f_i in the current density expression of (1), a non-zero 0th harmonic

is created. Hence, because of the Fourier series only the 0th harmonic can give a results not equal to zero after integration over the periodic width. The expression for the 0th harmonic of the current density is therefore used to obtain the extra required condition per segment.

After all unknowns have been obtained, the field and current density distributions are calculated. The forces are computed using Maxwell's stress tensor. By inclusion of time harmonics in the solution, the transient behavior of eddy currents is simulated in conducting parts of linear motor topologies.

III. Results

To verify the developed model it is applied to the model shown in Figure 1 and the results are compared to results obtained with the finite element software Flux 2D [5] for a range of frequencies of the currents in the coil array. In the semi-analytical model 105 spatial harmonics are used, which have a total computation time of less than 0.5 s. As depicted in Figure 2, the results of the semi-analytical model are in good agreement with the finite element analysis. A maximum error of 0.24 N is obtained between the models. For higher frequencies, where the reaction field has a relative large influence on the eddy current distribution, the forces and field distributions are correctly calculated thereby demonstrating the model works for a wide frequency range.

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Figure 1. Modeled periodic geometry containing two conducting segments and their accompanying spatial functions

Figure 2. Forces on the conducting segments, calculated by the semi-analytical (ANA) and finite element (FEM) model