Eddy current analysis of a PWM controlled induction machine

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Summary We investigate the high frequency eddy currents and compute the Common Mode Impedance of a PWM controlled induction motor by Finite Element simulations. It is shown that in order to determine machine parameters accurately, three-dimensional analysis taking into account explicitly the eddy currents induced in the iron core laminations is necessary.

1 Introduction

Modern induction machines are most often powered by Pulse Width Modulation (PWM) voltage source inverters. Although PWM switching clearly improves the overall performance and efficiency of the drive system, it also promotes the formation of common mode voltages which may evoke harmful high frequency bearing currents [1]. While the PWM switching frequency is usually in the order of 20 kHz, the short rise time of the pulses may induce higher frequency currents of several MHz in the housing, laminated core as well as in the shaft bearings of the machine. Therefore, when analysing PWM controlled induction machines, a broad frequency range has to be considered.

An essential parameter in the equivalent circuit representation of electric drives is the Common Mode Impedance (Z_{com}). This quantity allows to compute among others the bearing currents for different machine operation conditions. In the following, Z_{com} will be determined exclusively from Finite Element (FE) simulations. Using this approach substantial information can be obtained already in the design stage without necessitating on-machine measurement data.

In the FE analysis of induction machines, several symmetries can be exploited. Usually, for the middle part a two-dimensional (2D) projection of the motor cross section is considered [2]. In this paper, however, a fully three-dimensional (3D) analysis is proposed which allows to take into account explicitly the eddy currents induced in the core laminations. The end-windings, which in general do additionally contribute to Z_{com}, are not considered in the present analysis. The Common Mode calculation is completed by assembling the parameter matrices extracted from the middle and eventually the end parts of the machine using transmission line theory [3].

2 Lamination Modelling

Eddy currents in core laminations have been found to have a large impact on the transmission line parameters and, thus, on the Common Mode Impedance of PWM driven induction machines [3,4]. Magnetic machine cores are specifically designed to supress eddy currents at supply frequency. However, higher frequency voltage harmonics arising from PWM switching may lead to pronounced eddy currents loops in the core. This is because the skin depth in the iron at PWM frequencies becomes comparable or even smaller than the thickness of lamination sheets.

When employing laminated materials in FE analysis it is often not possible to model every single iron sheet because this would lead to enormous computational costs. Instead, the lamination is treated as a homogeneous material adopting equivalent electromagnetic properties. A well-known homogenisation model utilizes a frequency dependent equivalent permeability for the iron core given by,

$$\mu_{eq} = \frac{\mu_0 \mu_r}{\alpha b} \frac{\sinh(\alpha b)}{\cosh(\alpha b)}, \qquad \alpha = \frac{(1+j)}{\delta}, \qquad (1)$$

where $\mu_0 \mu_r$ is the permeability of iron, 2b the thickness of the plate and δ the skin depth at a given frequency [5]. The magnetic field problem for the homogenised core in the middle part of the motor reduces to a planar 2D problem. While this approach allows for very efficient 2D-FE analysis, certain inaccuracies can be expected. First, the equivalent model (1) assumes a uniform primary magnetic field with no variation in the cross-sectional plane of the motor (cf. [5]). Second, possible edge effects in the eddy current distribution arising at the winding yoke transitions are not considered. Finally, in the equivalent permeability model the iron core is considered to be non-conductive. Hence, the field reaction to the eddy current loops is neglected. The conductivity of iron is only introduced in post-processing for calculating electric losses. Thus, in particular in the high frequency range, it may be necessary to perform a more detailed eddy current analysis which takes into account all of these effects in core laminations.

3 Fully 3D-FE Approach

For testing purposes, a circular conductor model is considered (see Fig. 1). The copper conductor is surrounded by a laminated iron core. The lamination layers consist of oxide insulation sheets with a thickness of 0.65 mm. The width of the air gap between conductor and core is 0.1 mm.

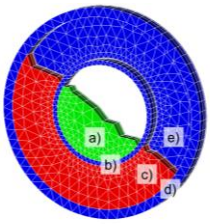

Fig. 1: Single conductor model with 5 material blocks: a) copper, b) air gap, c) iron, d) air and e) oxide layer.

In the homogenized equivalent permeability model (1), the eddy current problem can be solved analytically. For comparison, the geometry is discretized with a 3D mesh and analysed by means of FE simulations. In the first set of simulations the equivalent permeability is employed while in the second fully 3D-FE analysis including the iron and oxide layers is applied. Resulting electric losses and stored magnetic energy in the conducting parts of the arrangement are shown in Fig. 2. While the homogenized model gives quite accurate results in the copper conductor at lower frequencies (< 1 kHz), electric losses in the iron are subject to major errors (46% in this model), independent of frequency. However, at low frequencies, copper losses are much greater than iron losses. At higher frequencies, the field solution in the copper conductor is increasingly influences by the lamination and large deviations occur for both electric losses and magnetic energy. Considering the present analysis, the homogenization approach (1) might not be valid for high frequency simulations of induction motors. Therefore, the fully 3D approach will be applied to calculate the Common Mode Impedance of an existing 240 kW motor and will be presented in the full paper.

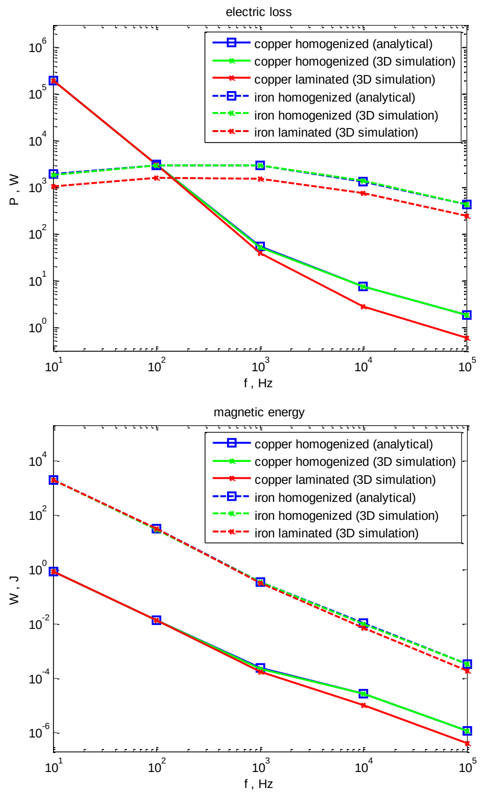

Fig. 2: Electric loss (top) and stored magnetic energy (bottom) for the single conductor model.

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