Eddy Current Losses in Permanent Magnets of Permanent Magnet Synchronous Machines — Comparison between Finite Element and Analytical Calculation Methods

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Abstract – **The paper presents electromagnetic finite element analysis and analytical evaluation of eddy current losses of permanent magnets used in permanent magnet excited synchronous machines. The calculation methods as well as measurement results are compared against their results for linear and rotational arrangements. The finite element analyses utilise different formulations with various orders of the shape functions by utilizing an identical mesh discretisation. Therefore, the representation of the skin depth can be discussed in detail.**

Index Terms – **Permanent magnets, Eddy currents, Permanent magnet machines, Finite element methods.**

I. Introduction

The rated apparent power of permanent magnet excited electrical machines increases more and more. Nowadays, the range up to 50 MVA is considered as a realisable trend of development. Due to sub- and superharmonics of the air-gap field, the eddy current losses generated in the permanent magnets of such machines may always lead to an excessive heating [1]–[5]. In particular with surface mounted permanent magnets, this can cause the magnets to get partially or even fully demagnetised [6]–[9]. Therefore, the precalculation of these eddy current losses caused by the harmonics of the air-gap field is a matter of interest with the design process of such electrical machines, on one hand by using very fast evaluation methods for the standard design procedures, on the other hand by using highly accurate calculation methods for reference purposes [10]–[12].

As depicted in Fig. 1 and Fig. 2, linear as well as rotational arrangements are considered. Both arrangements are described with few parameters, such as air-gap δ, ratio of pole pitch and air-gap τ_p/δ, ratio of magnet height and air-gap h_M/δ as well as the pole coverage as ratio of magnet width and pole pitch b_M/τ_p. With the same parameters and an increasing ordinal number of the harmonics in circumferential direction, it is expected that the difference between both arrangements will disappear.

The analytical calculation based on Laplace and Helmholtz equations of the magnetic vector potential within the respective regions utilises a pole coverage of $b_M/\tau_p = 1$. The finite element analyses deal with this coverage for a direct comparison of the results as well as the practical range of $b_M/\tau_p \approx 2/3 \ldots 3/4$. Both calculation methods use an excitation with a surface current sheet along the circumferential direction at the inner stator boundary which can cover for any harmonic order generated from either PWM modulated stator currents, the slotting and the saturation.

Additionally, the finite element analyses are carried out with different orders of the finite element shape functions by using an identical mesh discretisation. Thus, the representation of the varying skin depth can be discussed in detail. With respect to the comparison with measurement data, the total eddy current losses and the magnitude of the magnetic flux density within the air-gap along the pole pitch represent the most significant analysis results.

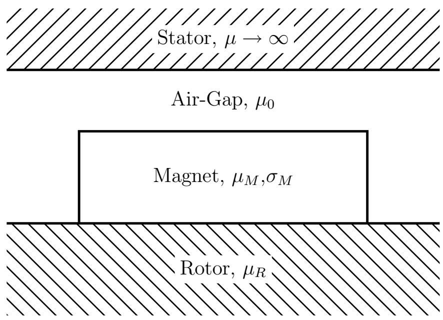

Fig. 1: Simplified geometry of a pole pitch with a linear arrangement

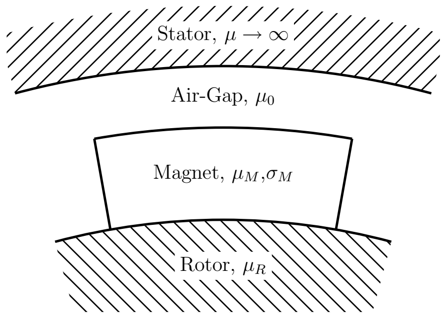

Fig. 2: Simplified geometry of a pole pitch with a rotational arrangement

II. Sample Analysis Results

Fig. 3 and Fig. 4 depict the power losses of one NdFeB magnet in dependence of the excitating frequency and the ordinal number of the harmonics for a constant current sheet excitation of $\hat{K}_z = 10^4\,\mathrm{A/m}$ obtained from second order finite elements. Fig. 5 depicts the respective relative error between finite element analyses and analytical results. Both arrangements show the data of air-gap $\delta = 2\,\mathrm{mm}$, ratio of pole pitch and air-gap $\tau_p/\delta = 60$, ratio of magnet height and air-gap $h_M/\delta = 3$ as well as pole coverage of $b_M/\tau_p = 2/3$ and $b_M/\tau_p = 1$.

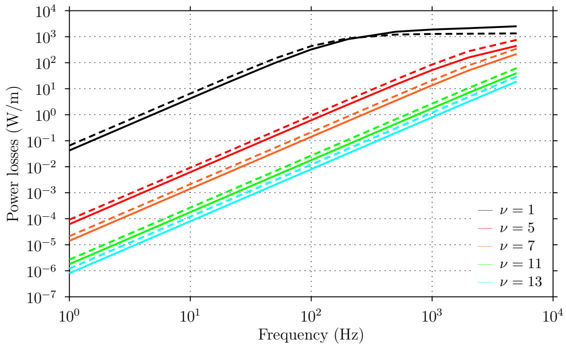

Fig. 3: Power losses of various harmonics versus frequency with the linear arrangement, finite element analyses, pole coverage 2/3 (solid lines) and 1 (dashed lines)

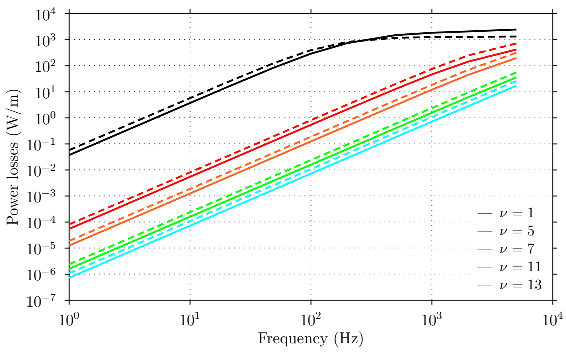

Fig. 4: Power losses of various harmonics versus frequency with the rotational arrangement, finite element analyses, pole coverage 2/3 (solid lines) and 1 (dashed lines)

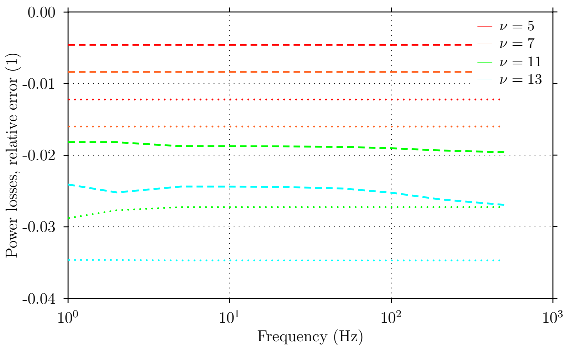

Fig. 5: Relative error of the power losses of higher harmonics versus frequency with the linear (dotted lines) and rotational (dashed lines) arrangement, pole coverage 1

Obviously, the total eddy current losses are quite similar between both arrangements. The relative error between numerical and analytical results is very small with the general tendency that the finite element results get smaller with higher ordinal numbers.

III. Concluding Remarks

The full paper will present the analytical calculation and the various finite element analyses in more detail. Additionally, the comparison with measurement data obtained from high performance permanent magnet excited synchronous machines will be presented.

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