Analysis of Cogging-Torque Harmonics due to Manufacturing Tolerances in Permanent-Magnet Synchronous-Machines

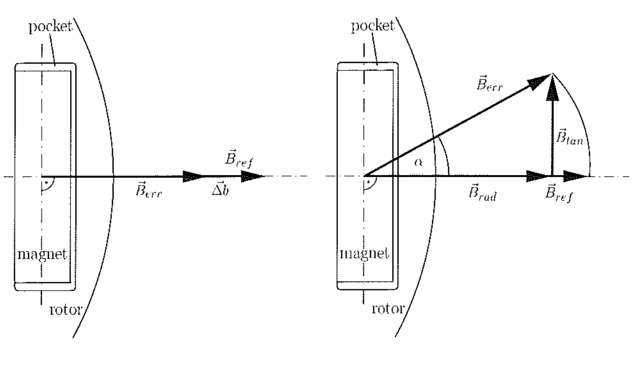
C. Schlensok, K. Hameyer

RWTH Aachen University, Institute of Electrical Machines, D-52056 Aachen, Germany
E-mail: Christoph.Schlensok@iem.rwth-aachen.de

***Abstract*— For servo drives such as Permanent-Magnet Synchronous-Machines (PMSM) the reduction of cogging-torque harmonics is of major interest. Usually the analysis of the cogging-torque harmonics is limited to studies of symmetric machines without errors e.g. in magnetization due to manufacturing-tolerances. In these cases only the geometrical parameter such as slotting, the pole-arc shapes, the teeth shapes, etc. are considered. Here, next to these the impact of manufacturing-tolerances is studied. Three different mechanisms are studied and a combined models method is introduced.**

I. INTRODUCTION

The reduction of cogging torque has been subject to studies since some years [1, 2]. It can be stated that just a few have considered problems with errors in magnetization or placement of the magnets having severe effects to the performance of the motor in respect to its cogging torque. This paper studies the impact on three manufacturing-tolerances such as the deviation of: the magnitude of the remanence Δb, the magnetization angle $\Delta\alpha$, and the positioning of magnets Δx. Here, a motor with $N_S = 18$ stator slots and $2p = 8$ poles is studied by numeric Finite-Element (FE-)simulations. The magnets are magnetized parallel and buried in the pockets of the rotor lamination. A reduction of the remanence of $\Delta b = -0.05\,\mathrm{T}$ at a nominal remanence of $B_R = 1.05\,\mathrm{T}$ is considered as well as an angular deviation of the magnetization direction of $\Delta\alpha = \pm 2°$ and a tangential shift of the magnets in the pockets of $\Delta x = \pm 0.2\,\mathrm{mm}$. Fig. 1(a) describes the model modification of error mode Δb. The magnitude of the remanence vector $B_R = B_{ref} = 1.05\,\mathrm{T}$ which is equal to the reference value is reduced to the erroneous magnitude $B_{err} = 1.00\,\mathrm{T}$ resulting in $\Delta b = -0.05\,\mathrm{T}$. In the case of an angular deviation the remanence vector is rotated $\Delta\alpha = \pm 2°$. In Fig. 1(b) the deviation is overemphasized. The angular deviation results in a reduced radial component B_{rad} of B_{err} and an additional tangential component B_{tan}.



(a) Effect Δb. (b) Effect $\Delta\alpha$.

Fig. 1. Description of the Model Modifications for the Effects Δb and $\Delta\alpha$.

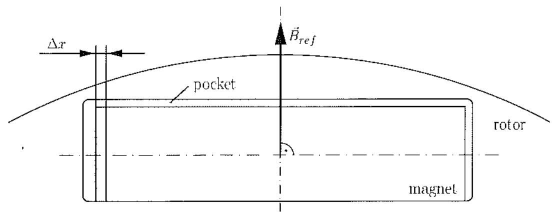


Fig. 2. Description of the Model Modifications for the Effect Δx.

The third error mechanism is depicted in Fig. 4. Each of the magnets can be shifted from the centre position in the pocket by $\Delta x = \pm 0.2\,\mathrm{mm}$.

The error mode Δb results in $2^8 = 256$ error configurations, since each of the eight magnets can be erroneous independent from the others. For the two other effects there are $3^8 = 6561$ error configurations. To reduce the computational costs required for the numeric analysis, a reliable linear model is introduced. Applying the method Design Of Experiment (DOE) [3, 4] the number of relevant configurations is reduced to minimum. All remaining relevant error configurations are analysed by the linear model. An analytic model for the analysis of cogging-torque harmonics is presented to evaluate the various error configurations.

II. MODELLING

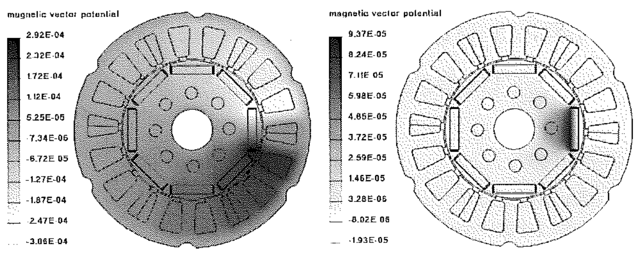
For the analysis of the cogging three different models are applied and combined.

A. Numeric Model

The numeric, 2D-FE-model of the PMSM for cogging-torque simulation consists of 60.000 triangular elements. The simulation is performed with a static solver [5] calculating the torque of a complete rotor revolution. The main harmonic o of the cogging torque of the "healthy" machine (no errors, reference model of PMSM) is the Least Common Mean of N_S and $2p$ [6]: $o = \mathrm{LCM}(N_s, 2p) = 72$. All other harmonics are very small in magnitude. In the case of a magnetization error and depending on its magnitude, further harmonics occur. Studies have shown, that certain error configurations result in corresponding harmonics, which again refer to a significant superposed pole-pair number in the air-gap field. Table I resumes o and p for the studied machine.

TABLE I. Orders o and corresponding number of pole pairs p.

o	18	36	54	72
p	2	8	6	4



(a) Error Mode Δb. (b) Error Mode $\Delta\alpha$.

Fig. 3. Deviation of the Magnetic Vector Potential of Two Single Erroneous Models.

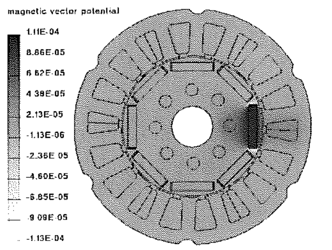


Fig. 4. Deviation of the Magnetic Vector Potential for Error Mode Δx.

The effect of superposed pole-pairs can only be stated in the case of the error modes Δb and $\Delta\alpha$. This is due to the fact that in both cases the radial component of the magnetisation magnitude is reduced. In the case of $\Delta\alpha$ also a tangential component is added as the comparison of the magnetic vector potential of two single-magnet error-configurations for both modes in Fig. 3 depicts. The figures show the deviation of the potential field of the two error models towards the reference model, resulting in the superposed field due to the errors. In both cases the resulting deviating field shows extra pole pairs. For error mode $\Delta\alpha$ the tangential component also generates a radial pole distribution.

Error mode Δx does not show any significant impact on the pole-pair numbers of the air-gap flux-density. Fig. 4 depicts the deviation of the potential field of a single erroneous model. The deviation appears only around the affected magnet showing black and white shades. All the other regions remain medium grey which refers to no deviation.

B. Linear Model

In this study, the effects of erroneous magnetization (Δb) and an angular error of the magnetization ($\Delta\alpha$) of the permanent-magnet material are regarded. The complete FE-simulation of all relevant constellations $N_{con,rel}$ is not reasonable if the considered error modes are combined. Table II collects the complete number of constellations. In order to reduce computation time significantly a linear model is applied. The linear model superposes the cogging-torque behaviour of the reference model with the cogging-torque of the "infected" models with single basic errors as in Fig. 3 and 4. It allows for the analysis of the combination of two error modes when applying DOE.

TABLE II. Error-Principles and Number of All and Relevant Constellations.

	Δb	$\Delta\alpha$	Δx
N_{con}	256	6561	6561
$N_{con,rel}$	18	265	265

C. Analytic Model

An analytic model for the analysis of cogging-torque harmonics depending on the magnetization-error configuration resulting in a significant superposition of pole pairs can be set up as follows.

$$p_x \geq p_{ref}:$$

$$o(p_x) = \mathrm{LCM}(N_s, 2p) - \frac{p_x - p_{ref}}{p_{sym}} \cdot \frac{\mathrm{LCM}(N_s, 2p)}{p_{ref}} \quad (1)$$

$$p_x < p_{ref}:$$

$$o(p_x) = -\frac{p_x - p_{ref}}{p_{sym}} \cdot \frac{\mathrm{LCM}(N_s, 2p)}{p_{ref}}. \quad (2)$$

p_{ref} is the pole-pair number of the PMSM (here: $p = 4$) and p_x the analyzed one. With $p_{sym} = 2$ a $180°$-symmetry of the machine model is considered. Else $p_{sym} = 1$ is set.

III. RESULTS

With the combined models method the three pure error modes and their combination are studied and analysed. All three error modes are based on reasonable manufacturing tolerances. Considering the maximal tolerance for each error mode Δx is stated to have the strongest impact on the cogging torque behaviour of the regarded PMSM. The impact of error mode $\Delta\alpha$ is negligible small in comparison to the others. The combination of two or three modes results in a low effect compared to the impact of the modes Δx and Δb.

IV. CONCLUSION

The paper introduces a fast method combining three models: numeric, linear, and analytic. It allows for fast analysis of cogging-torque harmonics caused by manufacturing tolerances in PMSMs. An analytic model is presented to estimate the sensitivity of the machine's geometry to magnetization-error configurations. The full paper will discuss the impact of the various magnetization-error configurations more detailed.

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