Novel Method for Fast Analysis of Cogging-Torque Harmonics in Permanent-Magnet Synchronous-Machines

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Abstract— **For servo drives such as Permant-Magnet Synchronous-Machines (PMSM) the reduction of cogging-torque harmonics is of major interest. Usuallly the analysis of the cogging-torque harmonics is limited to studies of symmetric machines without errors e.g. in magnetization due to manufacturing-tolerances. The novel method presented in this paper allows for fast analysis of PMSMs with asymmetric geometry and erroneous magnetization.**

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 deals with two effects of magnetization errors. Often the manufacturing process of machines and their permanent-magnet materials result in a reduction of remanance flux-density of the permanent magnet material. Furthermore, the direction of magnetization can vary. As an example, a motor with $N_S = 18$ stator slots and $2p = 8$ poles is studied by numeric Finite-Element (FE-)simulations considering a reduction of the remanence of $\Delta b = 5\%$ and an angular deviation of the magnetization direction of $\Delta\alpha = 2°$. To reduce the computational costs required for the numeric analysis, a reliable linear model is introduced for all relevant error configurations. An analytic model for the analysis of cogging-torque harmonics is presented to evaluate the various error configurations.

II. Numeric Model

The FE-simulation is performed with a static solver calculating the torque values for one 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 $2p$: $o = \text{LCM}(N_s, 2p) = 72$. 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.

III. Linear Model

In this study, the effects of erroreous 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 both considered error principles are combined. Table I collects the complete number of constellations. The number of relevant variants rises drastically in case of error combinations. The linear model superposes the cogging-torque behaviour of the reference model with the cogging-torque of the "infected" models with single basic errors. For example the linear model of a PMSM with only one magnet with reduced remanence is calculated by superposition of the results of the FE-models (reference and one error pole) and substracting the result of the reference model. For this case the error is 0. Our studies have shown that the maximum cogging-torque error is below 6 % when compared to simulation results of the same configuration. Simulation time is now almost negligeable.

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

	Δb	$\Delta\alpha$	Δb+$\Delta\alpha$
N_{con}	256	6.561	1.679.616
$N_{con,rel}$	18	265	119.952

IV. Analytic Model

An analytic model for the analysis of cogging-torque harmonics depending on the magnetization-error configuration can be set up as follows.

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

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

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.

V. Conclusion

The novel method allows for fast analysis of cogging-torque harmonics caused by manufacturing tolerances in PMSMs. An analytic model is presented to estimate the sensitivity of a machine geometry to magnetization-error configurations. The full paper will discuss the linear model and the magnetization-error configurations more detail.

References

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