

Effect of Manufacturing Tolerances and Magnetic Anisotropy of Electrical Steel on Surface-Mounted Permanent Magnet Synchronous Motor Cogging Torque

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Cogging torque in surface-mounted permanent magnet synchronous motors (SPMSMs) is an important design criterion for applications such as reaction force actuators in steer-by-wire systems and robotics. Ideally, the cogging torque in SPMSMs can be minimized by applying a skew with an appropriate angle, considering the pole-slot combination. However, due to manufacturing tolerances (MTs), additional cogging torque harmonics may occur, which cannot be disregarded. Similarly, differences in the saturation magnetic flux density between the rolling and counter rolling directions of non-oriented electrical steel can generate additional cogging torque harmonics. **In this study, we investigated the effect of the manufacturing tolerances and anisotropic properties of non-oriented electrical steel on cogging torque.** To differentiate the additional cogging torque caused by stator and rotor MTs from that caused by the anisotropic properties of non-oriented electrical steel, the effects of stator and rotor MTs were analyzed using 2D finite element analysis (FEA). Subsequently, 2D FEA was conducted by considering the anisotropic properties of non-oriented electrical steel. This analysis results confirmed that additional cogging torque harmonics, distinct from those caused by stator and rotor MTs, were generated.

Index Terms—Cogging torque, manufacturing tolerance (MT), non-oriented electrical steel, surface-mounted permanent magnet synchronous motor (SPMSM)

I. INTRODUCTION

SURFACE-MOUNTED permanent magnet synchronous motors (SPMSMs) have the advantage of being insensitive to manufacturing tolerances (MTs) due to the large effective air-gap and having small cogging torque and torque ripple [1]. Consequently, SPMSMs are widely used in applications where motor cogging torque needs to be minimized [2]. The cogging torque could become a critical performance metric for user convenience or for precise control. In ideal SPMSMs, the cogging torque occurs at harmonics that are multiples of the least common multiple of the pole and slot numbers [3]. However, when asymmetries occur due to factors such as MTs, additional harmonic components of cogging torque are generated [4]. Specifically, due to the MTs of the stator and rotor, additional cogging torque harmonics of the pole number order and slot number order are generated, respectively [5].

Although non-oriented electrical steel shows minimal anisotropy in saturation flux density [6], its effect on cogging torque—highly sensitive to magnetic properties—has not been thoroughly studied. Therefore, this study investigates the impact of saturation magnetic flux density according to RD of non-oriented electrical steel on cogging torque. To distinguish the additional cogging torque caused by stator and rotor MTs, 2D finite element analysis (FEA) was conducted while accounting for these MTs. Subsequently, assuming that the saturation magnetic flux density of the counter RD is 2% lower than the RD, additional cogging torque was calculated using 2D FEA. It was found out that the anisotropic properties of non-oriented electrical steel can cause twice the pole number order harmonic cogging torque, which was not caused by the stator MTs. **Although the variation in magnetic properties due to**

anisotropy is relatively small (typically less than 4%), its effect on specific cogging torque harmonics can be significant in precision applications such as robotic actuators. In this study, this phenomenon is isolated and analyzed separately from the influence of manufacturing tolerances.

II. COGGING TORQUE BY MANUFACTURING TOLERANCES

In this section, the additional cogging torque harmonics resulting from MTs are analyzed. Four types of rotor MTs and two types of stator MTs, which significantly affect additional cogging torque, were investigated. For each MT, a total of 100 analysis points was determined randomly, assuming that the tolerance follows a normal distribution with three standard deviations. To calculate the additional cogging torque harmonics, 2D electromagnetic FEA was performed. The configuration of the target SPMSM used in this study are presented in Fig. 1(a). For a core material, 50PN470 was used, which is a non-oriented electrical steel. The target model is an 8-pole 12-slot SPMSM, which ideally results in a 24th harmonic cogging torque. To eliminate this 24th harmonic cogging torque, a two-step skew with a skew angle of 7.5° was applied. Fig. 1(b) shows the cogging torque calculated by 2D FEA

A. Additional Cogging Torque by Rotor Tolerances

The rotor MT types that significantly impact the cogging torque of the SPMSM were analyzed. Four types of rotor MTs were investigated: magnetization angle, bond thickness, PM thickness, and asymmetry between PM sides. To evaluate the influence of each rotor MT type on cogging torque, 100 simulation cases were conducted using 2D electromagnetic FEA for each rotor MT type. **Each MT was varied independently using**

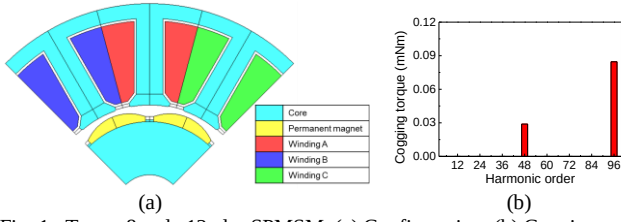


Fig. 1. Target 8-pole 12-slot SPMSM. (a) Configuration. (b) Cogging torque.

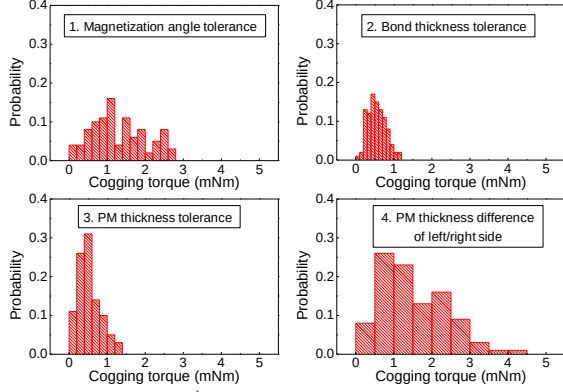


Fig. 2. Histogram of the 12th harmonic cogging torque for each rotor MT type.

normally distributed random variables with 3σ limits. When MT occur in the rotor, additional cogging torque harmonics are generated in multiples of the slot number [7]. Accordingly, the 12th harmonic cogging torque was analyzed, and the histogram for each rotor MT type is shown in Fig. 2. It can be seen that the rotor MTs can cause additional 12th harmonic cogging torque up to 4 mNm, but no cogging torque was generated for other harmonic orders such as the 8th, 16th, ... harmonics.

B. Additional Cogging Torque by Stator Tolerances

The stator MT types that significantly affect the cogging torque of the SPMSM were analyzed. Two types of stator MT were investigated: slot opening width, and stator inner radius. To evaluate the influence of each stator MT types on cogging torque, 100 cases were simulated using 2D electromagnetic FEA for each stator MT type. Each stator MTs was assumed to follow a normal distribution, with maximum and minimum tolerances set to represent three standard deviations. When MTs occur in the stator, additional cogging torque harmonics are generated in multiples of the pole number. Therefore, the 8th and 16th harmonic cogging torques were analyzed, and the histogram for each stator MT type is shown in Fig. 3. It can be seen that the stator MTs can cause additional 8th harmonic cogging torque up to 8 mNm. Among the stator MT types, the stator inner radius tolerance was found to have a significant impact on the 8th harmonic additional cogging torque. However, even after accounting for stator MTs, cogging torque for other harmonic orders, such as the 16th harmonic, did not occur.

III. EFFECT OF MAGNETIC ANISOTROPY PROPERTY

Even in non-oriented electrical steel, there is a slight difference in saturation magnetic flux density according to the RD and counter RD [5] up to 4%. The magnetic anisotropy was implemented by assigning different nonlinear B-H curves to the

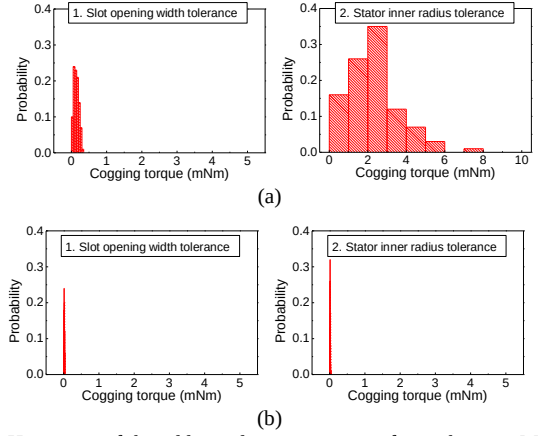


Fig. 3. Histogram of the additional cogging torque for each stator MT type. (a) 8th harmonic. (b) 16th harmonic.

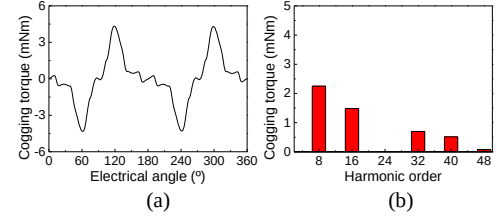


Fig. 4. Calculated cogging torque considering anisotropy characteristics of non-oriented electrical steel. (a) Waveform in one electrical period. (b) Harmonic analysis result in one mechanical period.

rolling direction (RD) and counter RD. **Specifically, the magnetic permeability was reduced by 2% in the counter RD, based on material characterization data. This modeling was applied in the FEM simulation using direction-dependent magnetic properties.** The waveform and harmonic analysis result of the calculated cogging torque are shown in Fig. 4. As can be seen, harmonic components at multiples of the pole number cogging torque occurred. Even when stator MTs were included in the analysis, the 16th harmonic cogging torque did not occur; however, after accounting for the anisotropic properties of the non-oriented electrical steel, the 16th harmonic cogging torque was generated. Other detailed analysis results (test result, 3D FEA results, ...) were included in the full paper.

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