

Design Methodology to Reduce Electromagnetic Vibration of 10 pole 12 slot IPMSM by Mitigating Radial Force

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This paper proposes a methodology to reduce electromagnetic vibration of 10 pole 12 slot permanent magnet synchronous machine (PMSM) by mitigating 2nd and 10th order radial force, which have critical impact on generation of vibration. By deriving an equation that describes the relationship between the radial force and flux density harmonics, flux density harmonics of permanent magnet (PM) field and armature reaction field, which should be minimized to reduce 2nd and 10th order radial force are identified. Based on the equation, coupled with flux density analysis, PM angle is determined, and notches are grooved on the stator tooth. As a result, 2nd and 10th order radial force is reduced so that the electromagnetic vibration of 10 pole 12 slot PMSM is decreased.

Index Terms—Electromagnetic vibration, flux density harmonics, notch, PMSM, radial force density

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been investigated in many industries due to their superior efficiency and high-power density, making them suitable for various applications [1]-[2]. However, increased power density correlates with high air gap flux density, which induces large radial force. Accordingly, high power density leads to significant electromagnetic vibration of a motor [2]. Consequently, PMSM designs must consider not only high efficiency and power density, but also vibration characteristics.

Several methodologies have been explored to mitigate radial force to reduce electromagnetic vibrations of PMSMs. In [3], stator notching is introduced as a method to suppress 2nd order radial force, reducing electromagnetic vibration of a 10 pole 12 slot PMSM. However, tooth modulation effect can result in 10th order radial force modulating into 2nd order component, necessitating the decrease of both 2nd and 10th order radial forces for comprehensive electromagnetic vibration reduction [1]-[2]. Furthermore, a previous investigation on a 10 pole 12 slot PMSM implements a segmented permanent magnet (PM) to inject specific order permanent magnet flux harmonics, canceling 10th order radial force [4]. Nevertheless, the proposed PM segmentation, which involves two magnet grades in one pole, is not evaluated for its impact on average torque or other electromagnetic performances.

This paper proposes a design methodology for enhancing the vibration characteristics of a 10 pole 12 slot interior permanent magnet synchronous motor (IPMSM). First, a base model is selected by investigating the fundamental component of PM flux density, which has an impact on the generation of both 2nd and 10th order radial force, according to the PM angle. Subsequently, the flux density harmonic of armature reaction field, which influences the generation of 10th order radial force, is analyzed according to the notch configuration. Through this analysis results, notches are applied on the stator to reduce the armature field flux density harmonic. As a result, this design process leads to a proposed model with suppressed 2nd and 10th order radial forces, greatly reduced electromagnetic vibration, compared with the base model.

II. TOOTH MODULATION EFFECT AND RADIAL FORCE DENSITY

A. Tooth Modulation Effect

It is evident that low-spatial order radial force is critical for the electromagnetic vibration since the vibration displacement is inversely proportional to the fourth power of the radial force order [1]-[2]. Therefore, decreasing low-spatial order radial force is a reasonable approach to minimize the electromagnetic vibration of a motor.

According to the Nyquist-Shannon theorem, if the sampling frequency is lower than twice the highest frequency of the original signal, signal modulation occurs when reconstructing the digital signal [1]-[2]. This phenomenon also appears on a stator system of motor so that high-spatial order radial force can be modulated into low-spatial order component because of tooth structure. In case of 10 pole 12 slot motor, 2nd and 10th order radial forces are generated, and these components are dominant at $2f_e$. Especially, 10th order radial force can be modified and combined with 2nd order component. Hence, both 2nd and 10th order radial force must be reduced to minimize electromagnetic vibration of 10 pole 12 slot motor.

B. Radial Force Density

The n^{th} order radial force of PMSM is produced by interaction between flux density harmonics of armature reaction field and PM field. For example, 10th order radial force of 10 pole 12 slot PMSM is produced by superposition of 5th order PM field flux density, and interaction between 5th order flux density of PM field and armature reaction field [4]. Thus, 10th order radial force can be expressed as (1).

$$f_{r10} = \frac{1}{2\mu_0} [B_{r_PM5}^2 \cos(10\theta - 10\alpha_{PM5}) + B_{r_PM5} B_{r_a5} \cos(10\theta - 5\alpha_{PM5} + 5\alpha_{a5}) + \dots] \quad (1)$$

Where $B_{r_PM}(\theta, \alpha)$ and $B_{r_a}(\theta, \alpha)$ represent radial flux density of PM field and armature reaction field respectively, while α_{PM} and α_a denote phase of each flux density [4].

III. DESIGN METHODOLOGY MITIGATING ELECTROMAGNETIC VIBRATION

A. Base Model Analysis

In this section, double V-type IPMSM is investigated as a base model, and all the analysis in this paper is performed at same target operating point (1000rpm, 4.8Nm).

Multi-layer V-type IPMSM, which exhibits high-torque density, is advantageous for reducing radial force since PM flux density can be effectively mitigated through manipulating rotor shape [5]. To be specific, 2nd order radial force is strongly affected by the inte

raction between B_{r_PM5} and B_{r_a7} , while 10th order radial force is mainly generated by $B_{r_PM5}^2$ [4]. In addition, PM flux density harmonics are affected by pole-arc ratio a lot [6]. Therefore, it is reasonable to investigate B_{r_PM5} , according to the PM angles, shown in Fig. 1(a).

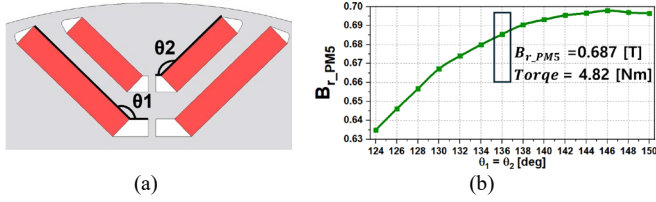


Fig. 1 (a) PM variables and (b) Analysis result of B_{r_PM5} .

Through the analysis result in Fig. 1(b), a base model with PM angle 136° is designed, exhibiting low B_{r_PM5} . Even though models with smaller angle present lower B_{r_PM5} , they do not satisfy the target torque.

B. Analysis on Stator Tooth Notch

According to (1), not only $B_{r_PM5}^2$ component, but also B_{r_a5} produces 10th order radial force by interacting with B_{r_PM5} . Thus, in this section, a design strategy to decrease B_{r_a5} is proposed, and B_{r_a} can be modified by grooving notch on stator tooth [4]. Therefore, to find a reasonable configuration that exhibits low B_{r_a5} , sensitivity analysis is performed according to the number and position of notch. Especially, 2-notch model has two notches, symmetrically grooved with respect to the center of a stator teeth, and the configuration with variables are presented in Fig. 2.

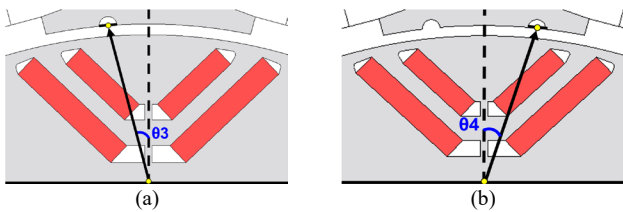


Fig. 2 Notch variables (a) 1-notch model (b) 2-notch model.

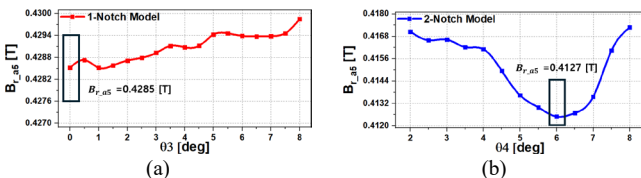


Fig. 3 B_{r_a5} analysis results of (a) 1-notch model and (b) 2-notch model.

Based on the analysis results in Fig. 3, 2-notch model with PM angle 6° is selected as the proposed model due to its low B_{r_a5} , which would lead to low 10th order radial force.

C. Comparison of Base model and Proposed model

In this section, the radial force and electromagnetic vibration are compared between the base model and proposed model, and the results are shown in Fig. 4.

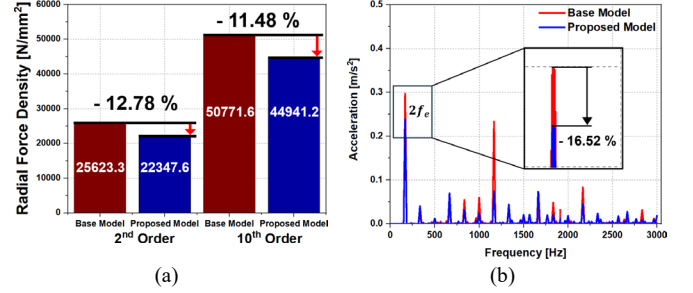


Fig. 4 Comparison of two models (a) Radial force and (b) Vibration.

As a result of notch design, 2nd and 10th order radial forces are reduced about 12.78% and 11.48% respectively. Accordingly, vibration acceleration decreased about 16.52% at $2f_e$, where both order radial force have crucial impact.

IV. CONCLUSION

The design process considering both PM angle and stator notch, proposed in this paper proves its effectiveness in reducing 2nd and 10th order radial force by comparing electromagnetic vibration of base model and proposed model.

In fact, by adjusting the front PM angle and the back PM angle respectively, flux density can be modulated further, and average torque can be increased. Hence, in the extended version, we will analytically find the optimized magnet and notch configuration which will greatly reduce the electromagnetic vibration without deteriorating other performances.

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