

Analysis and Comparison of Electromagnetic Vibration Characteristics in Surface-Mounted and Interior Permanent Magnet Synchronous Motors

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Vibration and noise in Permanent Magnet Synchronous Motors (PMSMs) have raised concerns due to their potential impact on safety. However, no research currently fully explores the differences in vibration characteristics between the widely used Interior PMSM (IPMSM) and Surface-mounted PMSM (SPMSM) with stator slot skewing from the perspective of electromagnetic analysis. This study investigates the similarities and differences in electromagnetic vibration between IPMSMs and SPMSMs with stator slot skewing. Expressions for the magnetic flux density and electromagnetic force induced by permanent magnets and winding currents are derived for both motor types, revealing that the saliency effect in IPMSMs produces higher-amplitude electromagnetic forces, leading to larger vibrations compared to SPMSMs. However, the spatial and temporal orders of the electromagnetic force are the same for both motor types. This conclusion is further confirmed through FEA-based co-simulation.

Index Terms—Interior permanent magnet synchronous motor, surface-mounted permanent magnet synchronous motor, electromagnetic analysis, vibration.

I. INTRODUCTION

PERMANENT MAGNET synchronous motors (PMSMs) are widely used in fields such as electric vehicles and wind power generation due to their high efficiency and wide speed range[1]. And vibration and noise issues in PMSM have become a significant concern. To reduce these, stator slot skewing is commonly applied[2]. However, there is currently no research from the perspective of electromagnetic analysis comparing the vibration characteristics of the widely used IPMSM and SPMSM under stator slot skewing. This study derives the air-gap magnetic flux density and electromagnetic force equations for SPMSMs and IPMSMs with skewed slots. The results indicate that the temporal and spatial characteristics of the electromagnetic forces are the same for both motor types. However, the IPMSM exhibits higher force amplitudes, which leads to more pronounced electromagnetic vibrations. Finally, FEA-based co-simulations of both motor types validate this conclusion.

II. DERIVATION OF ELECTROMAGNETIC FORCE

The electromagnetic vibration of PMSMs is mainly caused by the radial deformation of the core due to the complex air-gap magnetic field, which is linked to the order and amplitude of the radial electromagnetic force inside the motor.[3].

Considering the effects of stator slots and saliency effect, the magnetic reluctance function can be approximated as[4]:

$$\lambda(\theta, t) = A_0 \left(1 + \sum_{j=1} A_j \cos(jZ\theta) \right) \left(1 + \sum_{k=1} A_k \cos(2k(p\theta - \omega_1 t)) \right) \quad (1)$$

where $\delta_1(\theta)$ and $\delta_2(\theta, t)$ are caused by the stator slots and the saliency effect, respectively. For SPMSMs, $A_k = 0$.

The effect of stator slot skewing on the electromagnetic force can be represented by the skewing factor[2]:

$$K_{sk} = \frac{\sin\left(np \frac{b_{sk}\pi}{t_l Z}\right)}{np \frac{b_{sk}\pi}{t_l Z}} \quad (2)$$

where b_{sk} is the skew distance, t_l is the stator tooth width.

The radial air-gap flux density for an IPMSM with stator slot skewing, accounting for both stator slotting and saliency effects, can be expressed as:

$$b_i = K_{sk} A_0 (b_{r1} + b_{r2}) \quad (3)$$

$$\begin{aligned} b_{r1} = & \sum_{\mu} F_{\mu} \cos(\mu p \theta - \mu \omega_1 t) \\ & + \sum_{\nu} F_{\nu} \cos(\nu p \theta - \omega_1 t - \theta_0) \\ & + \frac{1}{2} \sum_{\mu} \sum_j F_{\mu} A_j \cos((\mu \pm jZ)\theta - \mu \omega_1 t) \\ & + \frac{1}{2} \sum_{\nu} \sum_j F_{\nu} A_j \cos((\nu \pm jZ)\theta - \omega_1 t - \theta_0) \end{aligned} \quad (4)$$

$$\begin{aligned} b_{r2} = & b_{r1} \cdot \sum_{k=1} A_k \cos(2k(p\theta - \omega_1 t)) \\ = & \frac{1}{2} \sum_{\mu} \sum_k F_{\mu} A_k \cos((\mu \pm 2k)p\theta - (\mu \pm 2k)\omega_1 t) \\ & + \frac{1}{2} \sum_{\nu} \sum_k F_{\nu} A_k \cos\left(\frac{(\nu \pm 2k)p\theta}{-(1 \pm 2k)\omega_1 t - \theta_0}\right) \\ & + \frac{1}{4} \sum_{\mu} \sum_k \sum_j F_{\mu} A_k A_j \cos\left(\frac{(\mu p \pm 2kp \pm jZ)\theta}{-(\mu \pm 2k)\omega_1 t}\right) \\ & + \frac{1}{4} \sum_{\nu} \sum_k \sum_j F_{\nu} A_k A_j \cos\left(\frac{(\nu p \pm 2kp \pm jZ)\theta}{-(1 \pm 2k)\omega_1 t - \theta_0}\right) \end{aligned} \quad (5)$$

where b_{r2} represents the flux density function introduced by the saliency effect, Z denotes the number of stator slots, and F_μ and F_ν represent the amplitudes of the electromagnetic force induced by the permanent magnets and stator currents, respectively,

For an SPMSM with stator slot skewing, the radial air-gap flux density considering the stator slot can be expressed as:

$$b_s = K_{sk} \Lambda_0 b_{r1} \quad (6)$$

From (3)–(6), it can be observed that since $2k$ and $2kp$ are even terms, so the air-gap magnetic fields of IPMSMs and SPMSMs exhibit identical spatial harmonics and temporal frequencies. However, compared to SPMSMs, the air-gap magnetic field of IPMSMs includes an additional b_{r2} term.

From (3)–(6), the electromagnetic force of SPMSMs and IPMSMs can be calculated as:

$$p_s = \frac{(K_{sk} \Lambda_0)^2}{2\mu_0} b_{r1}^2 \quad (7)$$

$$p_i = \frac{(K_{sk} \Lambda_0)^2}{2\mu_0} (b_{r1} + b_{r2})^2 \quad (8)$$

$$= \frac{(K_{sk} \Lambda_0)^2}{2\mu_0} b_{r1}^2 \left(1 + \sum_{k=1} A_k \cos 2k(p\theta - \omega_1 t) \right)^2$$

$$r = \frac{p_i - p_s}{p_i} \quad (9)$$

$$= \frac{(K_{sk} \Lambda_0)^2}{2\mu_0} b_{r1}^2 \cdot \left(\sum_{k=1} \frac{A_{k1} A_{k2}}{2} \cos 2(k_1 + k_2)(p\theta - \omega_1 t) \right. \\ \left. + 2 \sum_{k=1} A_k \cos 2k(p\theta - \omega_1 t) \right)$$

Since the spatial harmonics and temporal frequencies of the air-gap flux density in IPMSMs are identical to those in SPMSMs, the electromagnetic force in both motor types share the same spatial harmonics and temporal frequencies. However, the introduction of the saliency effect amplifies primary electromagnetic force causing vibration in the IPMSM by a factor of r , making the vibration amplitude of the IPMSM greater than that of the SPMSM.

III. THE VERIFICATION OF USING FEA-BASED CO-SIMULATION

To validate the theoretical derivations, this paper establishes a multiphysics coupled finite element model for the 8-pole 48-slot IPMSM and SPMSM to analyze and compare their electromagnetic vibration responses. Fig. 1 shows that the temporal and spatial order of the primary electromagnetic force causing vibration are identical for both motor types. Furthermore, Fig. 2 indicates that while the vibration frequency distributions of the IPMSM and SPMSM are largely similar, the maximum vibration acceleration amplitude of the IPMSM is higher than that of the SPMSM. The simulation results are in complete agreement with the theoretical derivations presented earlier.

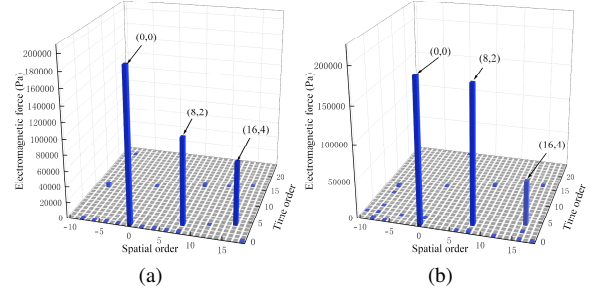


Fig. 1: Electromagnetic force. (a) IPMSM. (b) SPMSM.

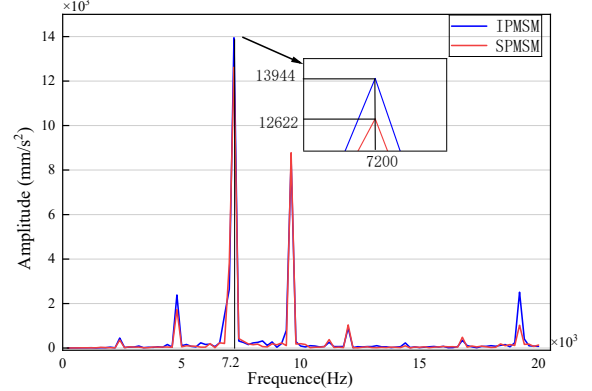


Fig. 2: Vibration amplitude in IPMSM and SPMSM.

IV. CONCLUSION

This paper compares the vibration characteristics of IPMSM and SPMSM with stator slot skewing from the perspective of electromagnetic analysis. By deriving the magnetic flux density and electromagnetic force for both types of motors, it can be found that the spatial order and temporal frequency of the primary electromagnetic force causing vibration in both IPMSM and SPMSM are the same. However, due to the saliency effect, the amplitude of the primary electromagnetic force causing vibration in IPMSM is larger than that of SPMSM, leading to higher vibration acceleration amplitudes for IPMSM compared to SPMSM, although the exact magnitude depends on design parameters such as magnet material and geometry. Additionally, the vibration frequency distributions of both IPMSM and SPMSM are roughly identical. Finally, this conclusion is validated through FEA-based co-simulations.

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