

Flux Linkage Decomposition-based Analysis and Harmonic Reduction Design of Induced Voltage in High-Speed Multilayer IPMSM

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A multi-layer interior permanent magnet synchronous motor (IPMSM) offers high power density, with increased saliency ratio and reluctance torque achieved by adjusting the number of permanent magnet (PM) layers. However, this also raises induced voltage harmonics, which can exceed the DC-link voltage, leading to unstable control. To ensure stable operation, the induced voltage must remain within the DC-link voltage. This paper proposes a design method to analyze and mitigate the significant harmonic components by decomposing the induced voltage. Using 2D finite element analysis (FEA) with a fixed permeability method, the induced voltage is separated, and its main harmonic components are identified. A design strategy is then introduced to reduce harmonic magnitude by optimizing the number of slots and applying rotor skew and eccentricity. The proposed method is validated through both simulations and experiments conducted on a prototype.

Index Terms— Harmonic reduction, Induced voltage decomposition, multi-layer interior permanent magnet synchronous motor.

I. INTRODUCTION

THE DEMAND for high-quality electric motors has grown across industries due to stricter environmental regulations. Thus, permanent magnet synchronous motors (PMSMs) are widely used for their high-power density and efficiency. Among them, multi-layer interior PMSMs (IPMSMs) are particularly suited for high-speed operation, offering increased reluctance torque by enhancing the difference between d - and q -axis inductance with additional PM layers. However, this also raises induced voltage, especially at higher speeds, requiring greater d -axis current for flux weakening control. This increases core saturation, leading to voltage harmonics that may exceed the DC-link voltage, causing unstable motor control, current distortion, and a failure to meet torque and power targets. Thus, designing multi-layer IPMSMs for high-speed applications requires ensuring the induced voltage remains within the DC-link voltage limits.

While many studies have focused on loss, noise, vibration, and torque ripple in IPMSMs [1], [2], few have addressed the analysis and reduction of induced voltage harmonics particularly for multi-layer IPMSMs [3].

This paper analyzes the induced voltage components of a multi-layer IPMSM at high speed, separating and identifying the main harmonic components. Based on this analysis, a design method is proposed to reduce the induced voltage harmonics, resulting in an improved design that meets DC-link voltage requirements. The proposed method is validated through experiments, confirming the effectiveness.

II. INDUCED VOLTAGE OF MULTI-LAYER IPMSM

A multi-layer IPMSM can yield a high reluctance torque by adjusting the number of PM layers. As the number of PM layers increases, the difference in d - and q -axis inductance increases [4], and thus the magnitude of the reluctance torque can be increased. However, this also increases the magnitude of the inductance, which causes the induced voltage to increase.

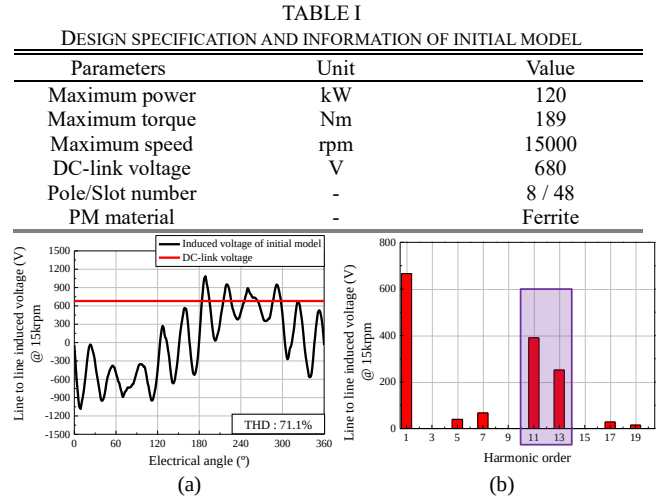


Fig. 1. DC-link voltage and line to line induced voltage of initial model (a) waveform and (b) harmonic analysis.

The induced voltage is generated by the change of the flux linkage when the motor is operated under a load. The induced voltage of the multi-layer IPMSM can be expressed as the sum of the three components as follows:

$$\left[\frac{\partial \lambda_{abc}}{\partial t} \right] = L_{abc} \frac{\partial i_{abc}}{\partial t} + \omega i_{abc} \frac{\partial L_{abc}}{\partial \theta} + \omega \frac{\partial \lambda_m}{\partial \theta} \quad (1)$$

where $[L_{abc}]$ is a matrix of self- and mutual- inductance; $[i_{abc}]$ is the matrix of the phase current; ω is the rotation speed; $[\lambda_m]$ the matrix of flux linkage caused by the PM flux. The first term is the component of the time-differential current, the second term is the component of the spatial-differential inductance, and the last term is the component of the spatial-differential flux linkage from the PM.

III. DECOMPOSITION METHOD OF INDUCED VOLTAGE

The design specifications of the initial model are summarized in Table I. Fig. 1 shows the waveform and harmonic analysis of the induced voltage at maximum speed. As depicted in Fig. 1(a), the line-to-line induced voltage exceeds the DC-link voltage, with a total harmonic distortion (THD) of 71.1%, indicating sig-

nificant harmonic content. This instability leads to insufficient voltage for target torque generation at high speeds, preventing the initial model from achieving its performance goals. The induced voltage harmonics arise from iron core saturation caused by increased d -axis current during flux-weakening control. Fig. 1(b) highlights the 11th and 13th harmonics as the dominant components. To analyze these harmonics, the induced voltage components were separated, as outlined in Fig. 2. In step 1, total induced voltage is calculated through load analysis using FEA under specific conditions, determining the permeability of the iron core for each element. Step 2 involves FEA with fixed permeability and no PM flux density, applying unit current to obtain self- and mutual-inductance values. These inductances are used to calculate the induced voltage from time-differential current and spatial-differential inductance. In step 3, FEA is repeated with the same permeability, restoring PM flux density while removing the applied current. The separated components of the initial model's induced voltage are shown in Fig. 3, identifying the 11th and 13th orders as the primary harmonics, mainly caused by differential current and inductance.

IV. HARMONIC REDUCTION DESIGN

The main components of induced voltage harmonics are caused by differential current and differential inductance. When analyzed with sinusoidal current, these harmonics are primarily influenced by inductance. To reduce induced voltage harmonics, the inductance magnitude must be decreased. Three methods are employed. First, increasing the number of slots from 48 to 96 reduces the air gap cross-section area, which in turn increases air-gap reluctance. This change significantly lowers the winding factors for the 11th and 13th harmonics, reducing them from 0.966 to 0.126. Second, applying rotor skew further decreases harmonic components. In this study, a 30° electrical skew angle is applied using a 3-step skew method, which reduces the skew factors for the 11th and 13th harmonics to 0.105 and 0.095, respectively. Additionally, a 2.5° mechanical step skew is used to further suppress harmonics. Lastly, introducing rotor eccentricity increases the effective air-gap length, enhancing reluctance and reducing both inductance and harmonic components. An eccentric length of 5 mm is selected to balance power output and design specifications effectively.

V. ANALYSIS OF IMPROVED MODEL

Fig. 4(a) shows the line-to-line induced voltage waveform at maximum speed, where THD was reduced from 71.7% to 6.5%. Fig. 4(b) presents the harmonic analysis of each component, with the 11th and 13th harmonics from differential current and inductance significantly reduced. Compared to the initial model, differential current components decreased by 94.9% and 95.8%, differential inductance components by 93.4% and 93.9%, and rotating PM components by 84.1% and 89.0%.

VI. CONCLUSION AND FUTURE WORK

This paper proposes a design method to reduce induced voltage harmonics in high-speed multi-layer IPMSMs. The initial model's induced voltage was analyzed using the proposed

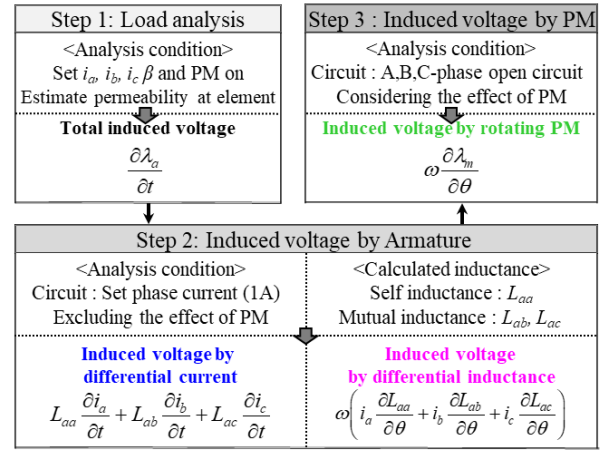


Fig. 2 Decomposition process of induced voltage.

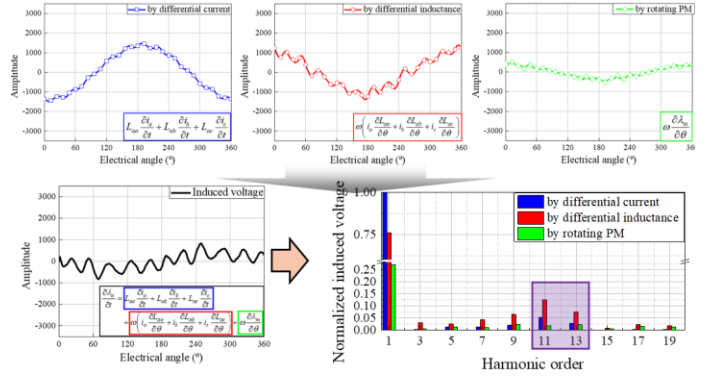


Fig. 3. Induced voltage components of the initial model obtained from FEA.

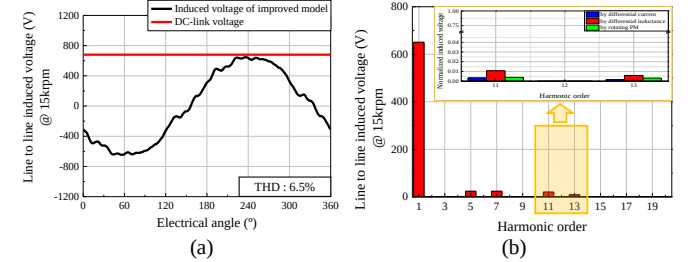


Fig. 4. DC-link voltage and line to line induced voltage obtained from FEA of improved model (a) waveform and (b) harmonic analysis.

decomposition method, identifying the primary harmonic causes. Detailed decomposition, analysis methods, and the improved design process will be included in the full paper. Additionally, the improved model has been manufactured, and the load test setup is in progress. The results will be presented in the full paper to validate the effectiveness of this research.

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