

Computationally Efficient Conductor Design for WFSM with Hairpin Windings Considering AC Ohmic Loss

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This paper presents a computationally efficient and reliable method for designing conductor shapes in wound field synchronous motors (WFSM) with hairpin windings to enhance efficiency considering AC ohmic loss. First, a hybrid method combining magneto-static analysis and analytical modeling is proposed for the accurate and practical estimation of AC resistance and loss. The proposed method is validated through detailed comparisons with conventional transient analysis, demonstrating high accuracy and consistency. Additionally, the optimal conductor shape is designed by applying the previously proposed method. The optimization framework considers variations in conductor geometry and their impact on iron loss. Motor parameters, including current vectors and field current, are analyzed to minimize total losses across various operating conditions. Finally, the optimal conductor shape and motor design are determined to achieve maximum efficiency.

***Index Terms*—AC ohmic loss, hairpin winding, wound field synchronous motor.**

I. INTRODUCTION

THE GROWING demand for electric vehicles (EVs) has led to significant advancements in traction motor technologies, with a focus on achieving high efficiency and reliable performance across diverse operating conditions. Among the available motor types, permanent magnet synchronous motors (PMSMs) and wound-field synchronous motors (WFSMs) are prominent candidates, each with strengths and limitations [1].

PMSMs are widely regarded for their high efficiency, power density, and compact design, driven using rare-earth permanent magnets. These magnets ensure constant magnetic flux without additional field current, making PMSMs a preferred choice for modern EVs. However, their reliance on rare-earth materials such as neodymium (Nd) and dysprosium introduces significant cost challenges and supply chain vulnerabilities. Additionally, PMSMs exhibit limited flux control at high speeds, leading to increased inverter loads and higher voltage requirements.

In contrast, WFSMs offer greater flexibility and operational versatility by generating magnetic flux through field current, allowing dynamic adjustment to varying system demands. This adaptability makes WFSMs suitable for variable-speed applications, and their elimination of rare-earth materials provides a more sustainable and cost-effective alternative [2]. As a result, manufacturers like Renault and BMW have adopted WFSMs as replacements for PMSMs in certain EV applications. However, the lower efficiency of WFSMs remains a key challenge. To address these limitations, hairpin winding technology has emerged as a promising solution. With its high fill factor, reduced DC resistance, and superior thermal management, hairpin winding enhances the power density and efficiency of WFSMs under high-current and high-frequency conditions [3]. Nevertheless, it introduces significant AC ohmic losses due to skin and proximity effects, requiring accurate modeling and optimization to fully realize its benefits.

This study seeks to address the challenges associated with WFSM efficiency and hairpin winding implementation. By

introducing a computationally efficient framework for estimating AC ohmic losses, this research contributes to the advancement of WFSMs for EV applications. The primary contributions of this research are as follows:

- Development of an accurate and efficient method for estimating AC resistance and loss.
- Design strategies for optimizing conductor geometry to improve overall efficiency in WFSMs with hairpin windings.

II. ESTIMATION METHOD FOR AC OHMIC LOSS OF WFSM

AC ohmic loss is a key factor in the design of WFSMs with hairpin windings, influenced by skin and proximity effects from armature and field currents. These losses exhibit nonlinear characteristics dependent on the armature current vector, field current, and frequency. Accurate estimation of AC ohmic loss is critical for optimizing motor performance, and three primary methods are used as follows: First, analytical modeling estimates AC resistance by considering slot leakage flux and skin depth, providing efficient trend analysis for design variables. However, it lacks accuracy in complex magnetic circuits or under magnetic saturation. Second, finite element analysis (FEA) offers precise modeling of leakage flux and skin effects but is computationally intensive, especially for transient analysis. Third, hybrid approaches combine the accuracy of FEA with the computational efficiency of analytical methods, using techniques such as magneto-static post-processing to achieve accurate and resource-efficient AC ohmic loss estimation.

In this study, as shown in Fig. 1, a hybrid method is adopted to provide a computationally efficient framework for AC ohmic loss estimation, enabling accurate and practical solutions for the design and optimization of WFSMs with hairpin windings.

The magnetic vector potential from magneto-static analysis can be used to calculate AC copper loss, assuming the eddy current-induced magnetic field is negligible compared to the main magnetic field. The governing equation for magneto-static analysis is expressed as:

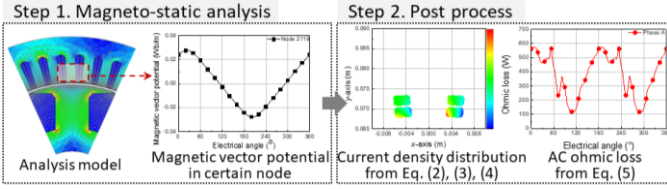


Fig. 1. Magneto-static analysis-based postprocessing method

$$\nabla \times \left[\frac{1}{\mu} (\nabla \times \mathbf{A}) \right] = \mathbf{J}_a + \mathbf{J}_f \quad (1)$$

where μ is the magnetic permeability; $\mathbf{J}_a$ and $\mathbf{J}_f$ are the armature and field current density, respectively. The electric field intensity, $\mathbf{E}_e$, causing eddy currents in the conductors is computed using Faraday's law, and the time-dependent eddy current density, $\mathbf{J}_e$, is derived as:

$$\nabla \times \mathbf{E}_e = -\frac{\partial \mathbf{B}}{\partial t} = -\frac{\partial (\nabla \times \mathbf{A})}{\partial t} \quad (2)$$

$$\mathbf{J}_e = \sigma \mathbf{E}_e = \sigma \frac{\partial \mathbf{A}}{\partial t} \quad (3)$$

where $\mathbf{B}$ is the magnetic flux density; σ is the electrical conductivity of conductor. A practical method for calculating AC copper loss using FEA is as follows. The eddy current density represents only the eddy current and excludes the instantaneous input current. Therefore, the actual armature current density, incorporating both the input current and eddy current for each element, is calculated based on the known input current under the given conditions and can be expressed as:

$$J_a^{i,j}(t) = J_e^{i,j}(t) + \left(\frac{I_a(t)}{N_p} - \sum_{m=1}^{N_e} J_e^{i,m}(t) \cdot S^{i,m} \right) / \sum_{m=1}^{N_e} S^{i,m} \quad (4)$$

where $J_a^{i,j}$ and $J_e^{i,j}$ is the actual armature current density and eddy current density for conductor i and element j , respectively; I_a is the instantaneous input current; N_p is the parallel circuit of armature winding; S is the area of element; N_e is the number of elements; Finally, the AC copper loss can be calculated as:

$$W_{AC}(t) = \sum_{n=1}^{N_e} \sum_{m=1}^{N_e} J_a^{n,m}(t) \cdot S^{n,m} \quad (5)$$

where N_e is the number of conductors. Fig. 2 illustrates the comparison of current density distribution and ohmic loss in phase A, obtained using transient analysis and the proposed method under load conditions. The current density distribution and AC ohmic loss results derived from the proposed method demonstrate high consistency with those from transient analysis validating its accuracy.

III. CONDUCTOR DESIGN OF WFSM WITH HAIRPIN WINDING

In this section, the AC ohmic loss for various conductor shapes is calculated and analyzed using the previously introduced method. Fig. 3 shows the design procedure for identifying the optimal conductor shape of the WFSM. Initially, conductor shapes are evaluated based on variations in conductor width and height while maintaining a constant slot fill factor and current density. Variations in conductor shape result in changes to slot geometry, which subsequently alter the tooth and yoke dimensions of the stator core. These variations lead to changes in iron loss. Therefore, iron loss is also considered alongside AC ohmic loss for various conductor shapes to esti-

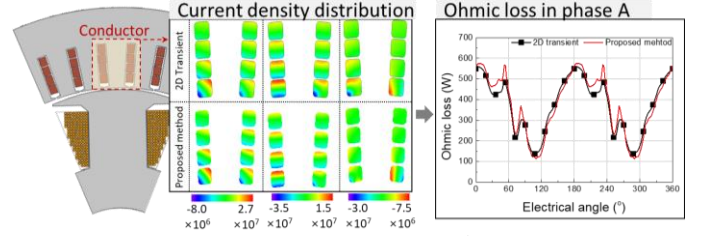


Fig. 2. Current density distribution and ohmic loss of WFSM

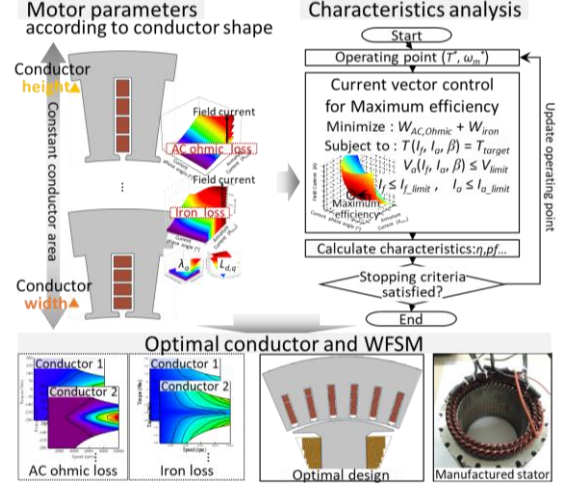


Fig. 3. Optimal conductor design process

mate the total loss. Furthermore, motor parameters are analyzed based on the armature current vector and field current. The current vector and field current are optimized to minimize losses depending on operating conditions, and characteristics such as losses and efficiency are evaluated. Finally, among the various conductor shapes, the optimal conductor shape and WFSM design that maximize efficiency are determined.

IV. CONCLUSION AND FUTURE WORK

This paper proposed a method to effectively design the conductor shape of WFSM with hairpin windings to maximize efficiency by considering AC ohmic loss. The study introduced a computationally efficient approach that integrates magneto-static analysis with an analytical method, enabling quick and accurate calculations of AC ohmic losses. The reliability of the proposed method was validated through comparisons with conventional transient analysis results. In future work, the proposed method will be extended to include the analysis of AC ohmic loss for various conductor shapes. This comprehensive analysis will be applied to optimize the conductor shape of WFSM with hairpin windings to enhance efficiency. Finally, the proposed methods will be validated through the experimental tests on manufactured WFSM design.

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