

Computationally Efficient Calculation of AC Copper Losses with PWM Current in EV Propulsion Motors

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The increasing demand for high-efficiency propulsion motors to enhance the energy efficiency of electric vehicles (EVs) necessitates accurate efficiency estimation during the design stage. When evaluating AC copper losses in propulsion motors, neglecting losses caused by PWM current-based calculations, particularly at high-speed and low-torque operating points, can result in an overestimation of motor efficiency. However, incorporating PWM currents into optimization for enhancing motor efficiency at the design stage is often impractical due to the significant computational time required. To address the challenge of accurately calculating AC copper losses in propulsion motors, this study proposes a method that combines analytical models and FEA. The method efficiently accounts for proximity and skin effects while incorporating PWM current harmonics alongside sinusoidal currents. This approach significantly reduces computation time, enabling the practical integration of PWM currents into motor design. Additionally, it provides a framework for significantly reducing the time required to construct motor efficiency maps.

Index Terms—AC copper losses, current diffusion, hairpin winding, proximity effect, pulse with modulation (PWM) current, skin effect.

I. INTRODUCTION

THE propulsion motor of a high-performance electric vehicle (EV) requires high-speed and high-power capabilities. Hairpin winding offers several advantages, such as a high slot fill factor, low DC resistance, and enhanced thermal robustness due to increased heat dissipation surface area. Therefore, hairpin winding has been widely adopted in EV propulsion motors that demand high power density. However, because of the large cross-sectional area of the conductor, the skin effect and proximity effect exacerbate the non-uniformity of the current density distribution, increasing AC copper losses, which accelerate the degradation of motor efficiency. Therefore, it is crucial to consider AC copper losses when designing propulsion motors with hairpin windings [1], [2]. Nevertheless, calculating AC copper losses during the design stage is challenging due to the high computational cost of transient analysis, especially with PWM current harmonics requiring a small time step.

To address these challenges, numerous studies have introduced methods to reduce the computational time for calculating AC copper losses. These methods include the analytical method, finite element analysis (FEA), partial element equivalent circuit (PEEC), and the hybrid method, which combines analytical and FEA approaches. The analytical method represents the losses caused by skin effect through Ampere's law and Faraday's law [3]. However, it is derived using assumptions such as magnetic field saturation, transverse leakage flux, and geometric simplification. These assumptions result in computational inaccuracies, which do not fully reflect the characteristics of the reaction field. The PEEC method reduces computational cost compared to transient FEA by representing FEA field values as an equivalent circuit [4]. However, it remains more complex than analytical methods due to the need for extensive discretized information about the conductor. The hybrid method achieves a balance between accuracy and computational efficiency. It calculates AC copper losses using

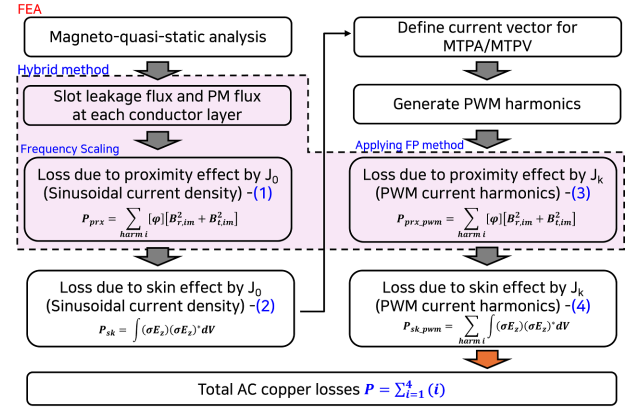


Fig. 1. The method for calculation AC copper losses considering PWM harmonics.

field values from magneto-quasi-static FEA and analytical equations for skin and proximity effects [5]. However, previous studies have neglected the skin effect induced by PWM current harmonics, leading to larger errors, particularly in rectangular conductors with large cross-sectional areas.

In this article, we propose a method for efficiently estimating AC copper losses caused by skin and proximity effects while considering PWM harmonics. This method demonstrates a reduction in the time required to construct motor efficiency maps.

II. CALCULATION OF AC COPPER LOSSES

The harmonics of the PWM current vary depending on the modulation region, which is categorized into linear modulation and over-modulation. The operating points of the motor determine the input conditions, which in turn define the modulation region and lead to changes in the current waveform. To calculate the PWM current waveform under operating conditions, motor parameters must first be determined based

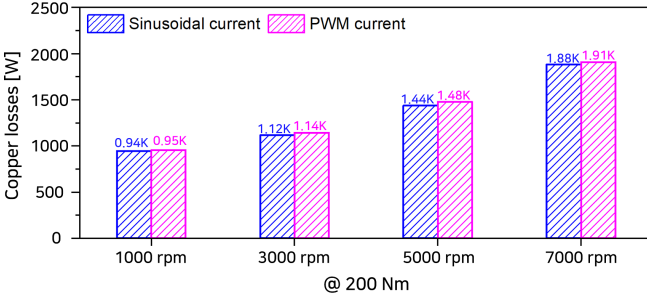
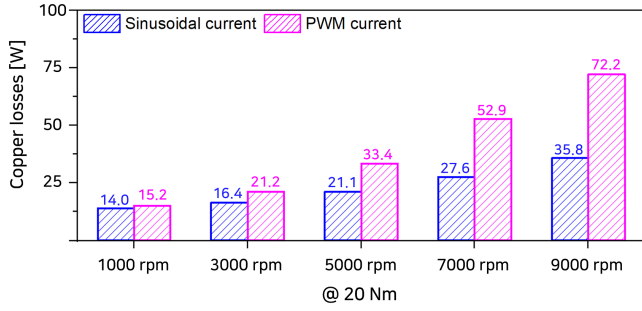


Fig. 2. Comparison of AC copper losses under sinusoidal and PWM current inputs at (a) 20Nm and (b) 200Nm with speed variation.

on sinusoidal currents. PWM current harmonics are derived using an inverter model in Matlab/Simulink. Subsequently, the commercial electromagnetic FEA software JMAG is used to calculate AC copper losses based on the PWM current.

The comparisons of AC copper losses under sinusoidal and PWM current inputs are shown in Fig. 2 for various speeds at two different constant torque conditions. The results in Fig. 2(a) show that, at low torque, AC copper losses caused by PWM currents increase dramatically as the rotational speed rises. In contrast, Fig. 2(b) indicates that under high torque conditions, the larger input current magnitude results in higher copper losses dominated by the fundamental current. Consequently, the contribution of PWM current harmonics to the total losses becomes relatively smaller. Therefore, calculating losses induced by PWM current harmonics is crucial, particularly under low-torque and high-speed conditions.

III. ESTIMATION OF AC COPPER LOSSES INDUCED BY PWM CURRENT HARMONICS

In this section, the proposed method is applied to EV propulsion motors to evaluate its computational efficiency and accuracy. FEA is used to extract field values while considering magnetic saturation, and AC copper losses are calculated using analytical equations. The process, shown in Fig. 1, determines the AC copper losses caused by PWM current harmonics. The slot leakage flux and the PM field are the major causes of losses due to the proximity effect. It is analyzed as a reactance-limited transient magnetic diffusion problem using diffusion equations to calculate the losses under sinusoidal and PWM currents[6], [7]. However, the slot leakage flux induced by PWM current harmonics is relatively minor and has a limited contribution to

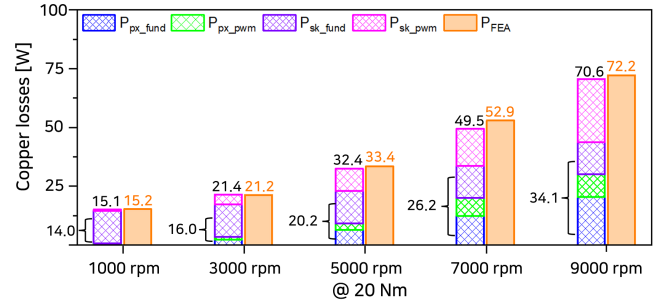


Fig. 3. Comparison of AC copper losses between FEA and the hybrid method under varying RPM and PWM current harmonics conditions.

the overall losses. Similarly, the skin effect is analyzed by solving the two-dimensional current distribution under reactance-limited conditions, incorporating the impact of eddy currents [8]. Additionally, the skin effect caused by PWM current harmonics in the conductor amplifies losses, highlighting the need for its evaluation. Fig. 3 validates the proposed method by comparing sinusoidal and PWM harmonic-induced skin and proximity effect losses with those obtained through FEA. This approach enables the calculation of individual eddy current losses and provides a cost-efficient solution for analyzing PWM harmonic-induced losses. Furthermore, it provides a valuable framework for understanding loss mechanisms and their factors.

In this manuscript, we present a detailed process and an analytical model for calculating AC copper losses induced by sinusoidal and PWM currents. The proposed method is validated by comparing motor efficiency maps obtained through FEA and the proposed approach, demonstrating a significant reduction in computational costs. Finally, experimental results validating the calculated PWM AC copper losses are presented.

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