

Computationally Efficient Calculation of PWM-Induced AC Copper Losses in Concentrated Winding Axial Flux Machines

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This paper proposes a computationally efficient method for evaluating pulsedwidth modulation (PWM)-induced alternating current (AC) copper losses. The conductive coils are simplified into equivalent magnetic domains using complex permeability modeling. Time-stepping finite element analysis (FEA) and time-harmonic FEA are conducted to compute the AC copper losses under the sinusoidal envelope currents and PWM-induced current ripples, respectively. The proposed approach is validated using a case study model of a 12slot 10pole axial flux permanent magnet synchronous machine. Results demonstrate good agreement with those obtained from the pure time-stepping FEA, which requires significantly higher computational resources.

Index Terms—Axial flux permanent magnet machines, complex permeability, AC copper losses, pulsedwidth modulation.

I. INTRODUCTION

AXIAL flux permanent magnet (AFPM) motors have gained significant attention in pump and propulsion applications due to their high-power density and compact, disc-shaped design. Prototypes widely employ fractional slot concentrated windings in 12-slot 10-pole and 24-slot 20-pole machines that offer reduced end-winding length and efficient space utilization, thereby improving power density and efficiency [1].

The selection of wires for AFPM machines is primarily guided by the maximum allowable direct current (DC) density. Furthermore, alternative current (AC) copper losses are critical considerations for high-speed operations, particularly in higher-pole machines [2]. These losses arise from the combined effects of the low frequency (LF) envelope and high frequency (HF) ripple fed by a pulsedwidth modulation (PWM) voltage source inverter (VSI). Accurate and efficient evaluation of these losses poses a significant challenge, as pure time-stepping simulations require an enormous number of time steps to fully address the large time-scale differences between LF and HF components.

Many studies have proposed two-step finite element analysis (FEA) for evaluating PWM-induced AC copper losses [3]. In the first step, a nonlinear magnetostatic or time-stepping FEA is performed to consider the non-linearity depending on load conditions under sinusoidal excitation. Then, a time-harmonic simulation is conducted using the stored incremental magnetic permeability obtained from the previous magnetostatic or time-stepping analysis, referred to as frozen permeability method, at various frequencies. Copper losses obtained from the time-harmonic simulation are then scaled based on current spectra driven from an equivalent circuit simulation to evaluate the losses caused by PWM-induced current ripples.

Nonetheless, FEA-based evaluations face challenges in the efficient implementation for three-dimensional (3-D) models, especially when all individual wires are modelled explicitly. Consequently, most studies are limited to two-dimensional (2-D) radial flux machine models [3] or quasi-3D AFPM machine models. However, these approaches inherently neglect the effects of the end region and are not directly applicable to coupled magnetic-thermal simulations.

This paper proposes a computationally efficient method for calculating PWM-induced AC copper losses using complex permeability modeling (CPM). The proposed algorithm is outlined while the identification procedure for CPM parameters is detailed in the extended paper. A single-sided AFPM machine is employed to validate the method. The calculated results demonstrate its effectiveness in evaluating not only PWM-induced AC copper losses but also their distribution within the winding, which can be directly extended to system-level and the coupled thermal evaluation.

II. PWM-INDUCED AC COPPER LOSSES

A. Proposed calculation algorithm

Fig. 1 illustrates the flowchart for calculating PWM-induced AC copper losses. The algorithm is divided into four parts, with two parts dedicated to generating a lookup table (LUT) for extracting frequency-dependent copper losses based on a given wire arrangement (LUT1) and load-dependent electric machine characteristics (LUT2). Using the data from LUT 2, a coupled inverter–motor model is constructed to derive the PWM-induced current waveform for a specified reference torque.

To evaluate AC copper losses under sinusoidal current I_l , the fundamental frequency f_l is selected. The magnetic field vector $\mathbf{h}(t)$ and current density vector $\mathbf{j}(t)$ within the winding region are exported from time-stepping FEA. Then, $\mathbf{h}(t)$ vector is then transformed into the local field vector $\mathbf{h}_{loc}(t)$ using $\mathbf{j}(t)$ vector,

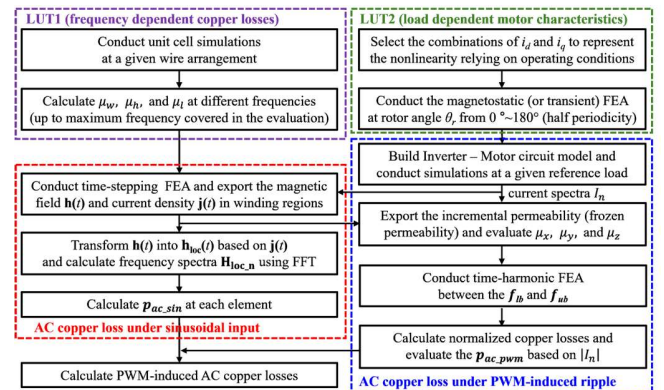


Fig. 1. Flowchart for evaluating PWM-induced AC copper losses.

and the field spectra $\mathbf{H}_{loc,n}$ at n -th harmonic are derived through a fast Fourier transform (FFT). Consequently, the sinusoidal AC copper losses p_{ac_sin} at each element can be computed.

For PWM-induced losses, the current spectra resulting from the PWM are obtained through coupled inverter–motor circuit simulations. The sideband components at each carrier harmonic, ranging from f_c to $5f_c$ are obtained. The pre-calculated magnetic field and current density vectors from the time-stepping study are employed to assign incremental permeability in the stator and rotor cores and complex permeability in the winding. The anisotropic complex permeability (μ_w , μ_h , μ_l) in local coordinates are converted into global counterparts (μ_x , μ_y , μ_z).

A time-harmonic FEA with a 1 A current input is performed to calculate normalized losses in the winding across several frequencies between a lower bound f_{lb} and an upper bound f_{ub} . Loss values at arbitrary frequencies can be obtained through interpolation. Finally, AC copper losses under PWM-induced current ripple p_{ac_pwm} are determined by superimposing the contributions from each harmonic component.

B. Complex permeability modeling

The calculation of AC copper losses is based on the CPM of conductors. Each conductive wire must be finely discretized to represent the skin effect, significantly increasing computational costs. The CPM addresses this challenge by modeling the eddy current phenomenon using equivalent diamagnetic domains to replace the conductors, as illustrated in Fig. 2. The application of CPM to AFPM motors was introduced in a previous study [4], where details of the complex permeability were discussed.

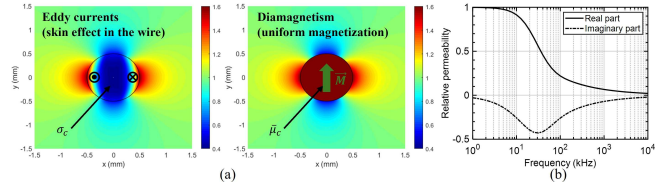


Fig. 2. (a) The equivalence of the eddy current and diamagnetism which can be represented in (b) the frequency-dependent complex permeability.

In the post-processing phase, magnetic field spectra within each volume element (i -th element) of the winding are used to evaluate the AC winding losses for each harmonic. The losses are calculated using the following expression:

$$p_{ac,i} = \sum_{n=1}^{\infty} \frac{2\pi f_n}{2} \text{Re}(\bar{\mu}_{w,n}) |\bar{\mathbf{H}}_{i,n}|^2 \Delta V_i \quad (1)$$

where $\bar{\mu}_{w,n}$ the complex permeability tensor of the winding for the n -th harmonic, f_n is the frequency of the n -th harmonic, $\bar{\mathbf{H}}_{i,n}$ the n -th harmonic of the magnetic field intensity tensor at the i -th element, ΔV_i is the volume of the i -th element. In the extended paper, the detailed formulation and its application to the calculation of AC copper losses will be explained further.

III. CASE STUDY

The proposed algorithm is validated using a case study model of a 12-slot 10-pole AFPM motor. Conducting pure time-stepping 3D FEA with a PWM current waveform requires impractically high computational time. Previous validation of the methodology under sinusoidal current conditions has been reported in [4]. To validate the proposed calculation, the 3D

AFPM motor model is simplified to a 2D linear motor, with all individual wires modeled in detail (pure time-stepping) and homogenized based on CPM (proposed), as shown in Fig. 3(a).

The inverter–motor circuit model was developed using the 3-D AFPM machine, and the PWM-induced current waveform is obtained simulations implemented in the Simulink environment. These current waveforms are directly applied to the simplified 2D model, and the resulting loss waveforms, with and without PWM excitation, are illustrated in Fig. 3(b). The inclusion of PWM excitation increases both the envelope of the loss and the ripple in the loss waveform.

Table I compares the calculated results obtained from pure time-stepping FEA and the proposed algorithm. The simulations are conducted at a rotational speed of 2000 rpm and a load torque of 1.25 Nm. The DC-link voltage is set to 300 Vdc, and the carrier frequency is 6 kHz. The AC copper losses are evaluated under both sinusoidal and PWM excitations, with the impact of PWM excitation quantified as the ratio of losses between the two conditions. When the proposed algorithm is applied to the 3D AFPM model, the resulting ratio is lower than that of the 2D model due to end-winding effects. Nevertheless, the result still indicates an approximate 45% increase in AC copper losses under PWM excitation in the case study motor.

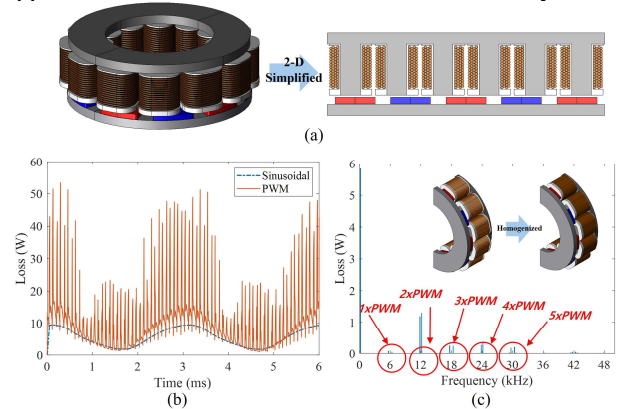


Fig. 3. (a) The case study AFPM motor, (b) copper loss waveform and (c) loss spectra from the pure time-stepping and proposed simulation, respectively.

TABLE I. COMPARISON OF CALCULATED AC COPPER LOSSES

Model	Method	w/o PWM	w/ PWM	Ratio
Simplified 2-D model	Pure time-stepping	5.42 W	10.10 W	1.86
	Proposed	5.58 W	9.94 W	1.78
3-D model	Proposed	5.58 W	8.20 W	1.45

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