PWM-induced magnetic losses in soft magnetic composites: measurement and modeling

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This study investigates the impact of magnetizing frequency and modulation index on the losses of Fe-based soft magnetic composites under two-level and three-level PWM excitation. Working conditions were emulated using a digital hysteresisgraph-wattmeter with universal digital feedback, ensuring precise control of the magnetic induction waveform. Magnetic losses were successfully modeled using the Statistical Theory of Losses, distinguishing contributions from hysteresis, classical, and excess losses. The findings improve loss prediction accuracy and extend the applicability of soft magnetic composites in high-frequency and PWM-controlled applications.

Keywords: Soft magnetic composites; Magnetic losses; PWM

1. Introduction

Over the past decade, increasing attention has been given to soft magnetic composites as a promising alternative to traditional laminated steel in electrical machines. These materials, composed of electrically insulated particles, exhibit a heterogeneous microstructure with particle-to-particle interfaces and distributed air gaps. However, at a macroscopic scale, they behave magnetically homogeneously, offering advantages such as gradual saturation and reduced losses at high frequencies [1, 2].

The presence of insulation leads to two distinct eddy current loss scales: a microscopic scale determined by particle geometry and a macroscopic scale influenced by the sample's cross-section. In sufficiently small cross-sections, macroscopic eddy current losses become negligible [3]. This dual character of eddy currents adds complexity to loss modeling—particularly under non-sinusoidal excitation, a scenario increasingly common in modern applications.

One key source of harmonic distortions in magnetic induction waveforms is Pulse Width Modulation (PWM) control, widely used in electrical machines [4]. PWM excitation conditions present significant challenges in experimental characterization and theoretical assessment. Recent modeling efforts have primarily focused on Fe-Si laminations under complex excitation conditions [5], with limited research on soft magnetic composites and the impact of harmonic waveform distortions [3].

2. Results and discussion

This study examines the influence of magnetizing frequency and modulation index on the magnetic losses of Fe-based soft magnetic composites under both two-level and three-level PWM excitation. Experimental characterization was conducted using a broadband digital hysteresisgraph-wattmeter with universal digital feedback, complemented by fluxmeter-based quasi-static hysteresisgraph measurements to obtain initial magnetization curves and anhysteretic curves necessary for modeling.

Results indicate that while three-level PWM excitation primarily introduces ripple effects in hysteresis loops, two-level PWM excitation generates nested minor loops, contributing additional losses. Losses under PWM excitation were successfully modeled using the Statistical Theory of Losses [6] by separating contributions from hysteresis, classical, and excess loss components for both major and minor hysteresis cycles. Furthermore, static magnetic properties and hysteresis loops were effectively described using a static loss surface modeling approach [7], which requires only a limited set of experimental measurements.

This approach enhances the predictive accuracy of loss modeling and broadens the applicability of soft magnetic composites in high-frequency and PWM-driven applications.

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