

Recurrent Neural Network-Based Hysteresis Modeling for Magnetic Material Considering Eddy Current Loss

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This paper proposes a novel hysteresis modeling approach using a recurrent neural network (RNN) to accurately describe the hysteresis behavior of magnetic materials, incorporating eddy current losses through a Cauer circuit. The RNN-based hysteresis model is trained with measured hysteresis loops and effectively predicts untrained loops with high accuracy. The proposed model is integrated into Cauer circuit to extend its applicability to high-frequency regions, where eddy current effects become significant. Experimental results validate the model's predictions for magnetic losses and hysteresis loops, demonstrating its reliability and potential for advanced magnetic component design.

Index Terms—Cauer circuit, eddy current, hysteresis loss, recurrent neural network.

I. INTRODUCTION

MAGNETIC MODELING is a critical component in designing magnetic devices for power electronics circuits. High-frequency magnetic modeling is particularly challenging as it requires accounting for multiple loss mechanisms, including hysteresis and eddy current losses.

Recent studies have explored dynamic hysteresis modeling using the Cauer circuit. In these methods, dynamic hysteresis loops are often described by the Play and Preisach models, while the Cauer circuit represents eddy current losses. The effectiveness of these approaches has been successfully validated in previous works [1][2]. However, the Play and Preisach models necessitate a large number of B-H loops precisely measured at specific intervals. This requirement poses significant challenges, especially when dealing with low-loss magnetic materials commonly used in high-frequency applications.

Machine learning techniques have recently gained attention as an alternative to describe dynamic hysteresis behavior [3][4]. For instance, recurrent neural networks (RNNs) have been utilized to estimate DC hysteresis loops [3], while encoder-decoder transformer models have been employed to predict hysteresis loops including eddy current [4]. However, these RNN-based models are limited to loss estimation and hysteresis loop prediction and have not yet been integrated with finite element analysis (FEA).

In this paper, an RNN-based hysteresis model integrated with a Cauer circuit is proposed to overcome existing limitations. The approach combines an RNN-based DC hysteresis model with a Cauer circuit to represent eddy current losses at high frequencies. This method, based on the Cauer-based homogenization technique [5][6], is inherently compatible with finite element analysis (FEA), enabling seamless integration into advanced magnetic component design. To validate the model's effectiveness, a Sendust core with a relative permeability of approximately 30 [7], commonly used in high-

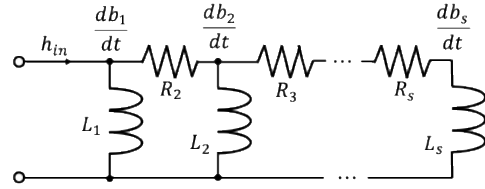


Fig. 1. Cauer circuit for homogenization model in which L_1 represents the DC hysteresis.

frequency applications, is modeled using the proposed approach.

II. PROPOSED METHOD

A. Homogenization Modeling with Cauer circuit

The homogenization modeling [5][6] of magnetic material employing the Cauer circuit is utilized to account for eddy currents in magnetic materials. The structure of the Cauer circuit is illustrated in Fig. 1. The first-stage inductance L_1 corresponds to the DC hysteresis behavior and is typically modeled using the Play and Preisach models. The other components, R_i and L_i ($i \geq 2$), represent the eddy current losses and the behavior of the material in the high-frequency range. These parameters are determined based on the actual loss and impedance characteristics obtained through measurements with a vector network analyzer.

B. Hysteresis Modeling using Recurrent Neural Network

Gated Recurrent Unit (GRU) is utilized to model the DC hysteresis behavior in the Cauer circuit. GRU is a type of recurrent neural network that is designed to efficiently capture sequential dependencies in data by using gating mechanisms. Compared to other RNN variants such as Long Short-Term Memory, GRUs have a simpler architecture with fewer parameters, making them computationally efficient while maintaining robust performance in capturing temporal patterns.

III. MODELING RESULTS

A. DC hysteresis modeling

The hysteresis behavior of Sendust with relative permeability of 30 [7] is modeled using the RNN-based hysteresis modeling approach. To construct the RNN-based model, hysteresis loops were measured, as shown in Fig. 2. A total of 13 hysteresis loops were prepared and used as training data for the GRU model. The GRU model takes the sequential data of one cycle of magnetic flux density as input and outputs the corresponding magnetic field data. The parameters used for GRU training are summarized in Table I.

Fig. 3 compares the measured and predicted hysteresis loops at a peak magnetic field H_m of 700 A/m. Here, the measured loop is not included in the training dataset. It is found that the predicted hysteresis loop closely matches the measured loop, demonstrating the accuracy of the proposed model. Furthermore, Fig. 4 illustrates the hysteresis loss versus the magnetic flux density. The predicted losses are in good agreement with the measured values over the entire range, implying the reliability of the GRU-based model for hysteresis loss estimation.

B. Homogenization with GRU-based Hysteresis model

The hysteresis model constructed in Section III.A is incorporated into the first-stage inductance of the Cauer circuit to extend its applicability to high-frequency regions. The circuit parameters R_i and L_i ($i \geq 2$) for Cauer circuit were optimized to match the actual losses measured using a BH analyzer.

Fig. 5 illustrates the magnetic loss against the frequency at $B_m=10$ mT. It is observed that the loss remains nearly constant up to 100 kHz, indicating that eddy current losses are negligible within this frequency range. Beyond this frequency, however, the magnetic loss begins to increase, reflecting the onset of significant eddy current losses. The predictions made by the proposed model show good agreement with the experimental measurements.

In the presentation, we provide a detailed explanation of how the DC hysteresis model is constructed and demonstrate how the proposed homogenized model is incorporated into FEA for inductor analysis.

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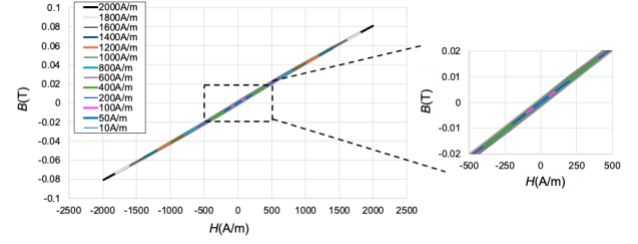


Fig. 2. DC hysteresis loops used for GRU training.

Number of layers	6	Learning ratio	0.001
Batch size	32	Optimizer	Adam
Loss function	MSE		

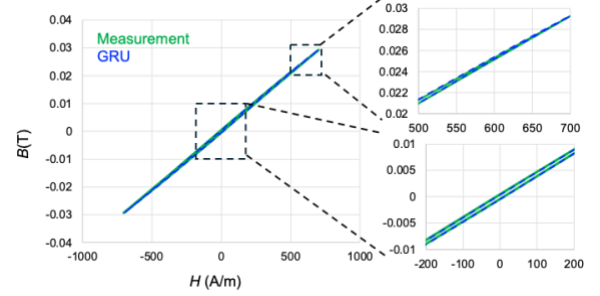


Fig. 3. DC hysteresis loops where the green and blue lines are measured by BH analyzer and predicted by the GRU-based model, respectively.

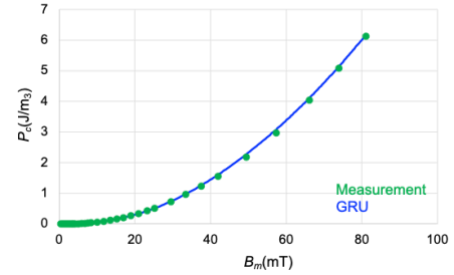


Fig. 4. DC hysteresis loss against the peak magnetic density obtained by the measurement and prediction by the proposed model.

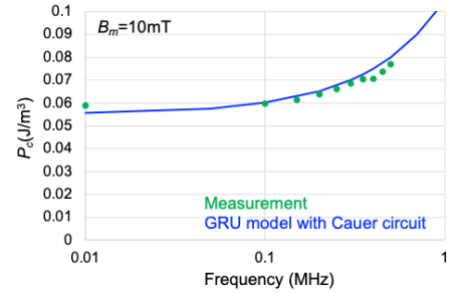


Fig. 5. Loss against the frequency at $B_m=10$ mT obtained by the measurement and prediction by the proposed model.