

Simulation Methodology for Transformers: Accuracy and Characteristic Analysis in Low-Frequency Wireless Power Transmission

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This work presents a novel circuit simulation method for transformers, aiming to achieve greater accuracy in their operation. This approach enables the electrical analysis of devices used in low-frequency wireless power transmission, accounting for specific characteristics such as large air gaps and eccentric geometries. By combining data from transformer tests with computationally generated information, the elements of the equivalent transformer circuit can be calculated iteratively, allowing the electrical state of the transformer to be determined at various time steps. The methodology behind this simulations is exposed and its limitations discussed.

Index Terms—Accuracy, Circuit Simulation, Electromagnetic Induction, Wireless Power Transmission.

I. INTRODUCTION

IN RECENT YEARS, wireless power transmission (WPT) has garnered significant interest due to its potential applications in key technologies, such as powering non-autonomous and autonomous electric vehicles [1], household appliances and addressing demands in hazardous environments [2]. However, most current induction devices operate at high frequencies, requiring expensive equipment, such as frequency inverters [3]. This work aims to make wireless power transmission at low frequencies viable, with the goal of reducing costs and increasing accessibility to this technology.

High-frequency WPT enables greater voltage, efficiency, and range due to stronger magnetic field variation. High-frequency applications also eliminate the need for ferromagnetic materials due to high power losses. In contrast, at low frequencies, ferromagnetic materials are essential, as the transmission range is determined by the core's shape [4]. Thus, this work focuses on optimizing induction-based transmission through the properties of the ferromagnetic core.

Transformers, particularly those with ferromagnetic cores, can be electrically modeled as a circuit where each element represents different components of its structure. These elements include components that represent the coil's behavior — its resistance and leakage inductance — and those that represent the core's behavior — magnetization inductance and resistive losses. While most circuit implementations focus on analyzing the steady-state behavior of the transformer with fixed parameters, issues involving unconventional transformer cores, like those discussed here, justify treating these elements as variable to achieve more accurate results.

II. METHODOLOGY

To obtain the instantaneous values of the components in the transformer's equivalent circuit, as indicated in Figure 1, it is necessary to have a magnetization curve of the ferromagnetic material, as well as a hysteresis curve, which is generated based on the magnetization curve and reflects the device's excitation.

Using both of these curves, it is possible to model the behavior of the magnetization inductance, with the main variable in

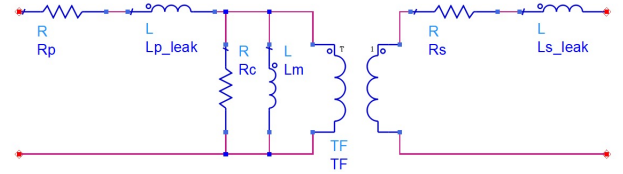


Fig. 1. Transformer's equivalent circuit made on ADS, where R_p is the primary coil's resistance, $L_p\text{'leak}$ is the primary coil leakage, R_c is the core losses resistance, L_m is the magnetization inductance, R_s is the secondary coil resistance and $L_s\text{'leak}$ is the secondary coil leakage

its calculation being the effective permeability of the material, as shown in Equation 1, which corresponds to the derivative of the magnetization curve evaluated at each time step, at the magnetic field ($H = \frac{NI}{l}$) derived from circuit excitation.

$$L_m = \frac{N^2 A \mu}{l} \quad (1)$$

The equation for the magnetization inductance, L_m , is given by Equation 1, where N represents the number of turns of the coil, A is its cross-sectional area, μ is the permeability, and l is the mean path length.

The magnetization curve is obtained through tests conducted with an Epstein frame made of the same material as the transformer's core under analysis, while the hysteresis curve is generated computationally using the Jiles-Atherton model [6], based on material-specific parameters and iterative ODE solving. This loop accounts for nonlinear distortions caused by core saturation, which generate harmonics that increase power losses. Although the IEM model only considers the fundamental frequency, hysteresis-induced harmonic losses are indirectly incorporated via the simulated B-H behavior.

Thus, the effective permeability of the material can be determined by using the magnetization curve along with the corresponding magnetic flux density value. When an air gap is present in the transformer, a magnetization curve for the entire system is generated for analysis. To model the core loss resistance, Equation 2 is used for a given flux density value, where V is the voltage applied to the transformer and P is the

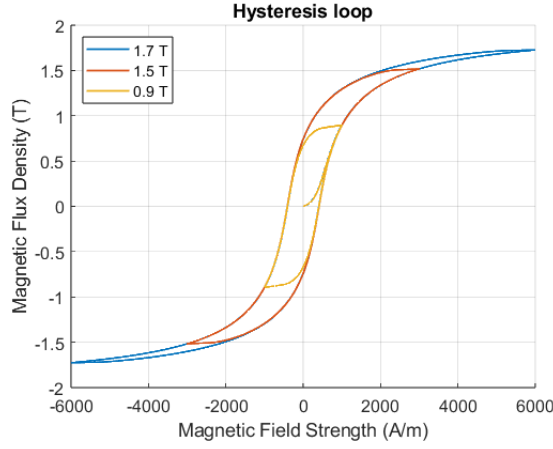


Fig. 2. Hysteresis Loop using Jiles-Atherton model, is represented by the relationship between the Magnetic Flux Density B and the Magnetic Field Strength H

core loss, given in Watts.

$$R_c = \frac{V^2}{P} \quad (2)$$

To estimate the core losses, the IEM-5 parameter iron-loss model [7] is implemented, as indicated in Equation 3. The parameters of the equation can be determined either through semi-physical procedures or mathematical curve fitting based on the material's loss curve. The model includes hysteresis losses, classical eddy current (Foucault) losses and excess losses, represented by the terms a_1 , a_2 , and a_3 , respectively. Additionally, it includes a higher-order B term.

$$P = a_1 \hat{B}^2 f + a_2 \hat{B}^2 f^2 (1 + a_3 \hat{B}^{a_4}) + a_5 (\hat{B} f)^{1.5} \quad (3)$$

Given the close relationship between the leakage inductance and the geometry of the ferromagnetic core at low frequencies, it is essential to perform a spatial and temporal electromagnetic simulation of the transformer. By analyzing the magnetic flux paths [5], this approach allows for the accurate calculation of leakage inductance, which can then be integrated into the device's macrosimulation with acceptable precision. The leakage inductance inherently accounts for air gap and geometric eccentricities, as these features alter the field distribution from which the permeance is derived.

A planar B-field is obtained from CST and exported to MATLAB for processing. In MATLAB, flux lines are generated from the field vectors, as illustrated in Fig. 3.

Each flux line is filtered to include only the segments outside the core, then classified as a circle, ellipse (with unequal radii), line, or a combination of these geometric shapes. After classification, curves are merged when they meet specific criteria regarding their geometric profile and proximity, forming a 2D figure. This process is repeated across different planes, generating sufficient data to be integrated into various volumes, which are then treated as magnetic elements to calculate their magnetic permeance, P . Next, this value is used to calculate the inductance using Equation 4.

$$L_{leak} = N^2 P \quad (4)$$

The total leakage inductance is determined by the equivalent inductance of all the inductances from the 3D forms. Finally,

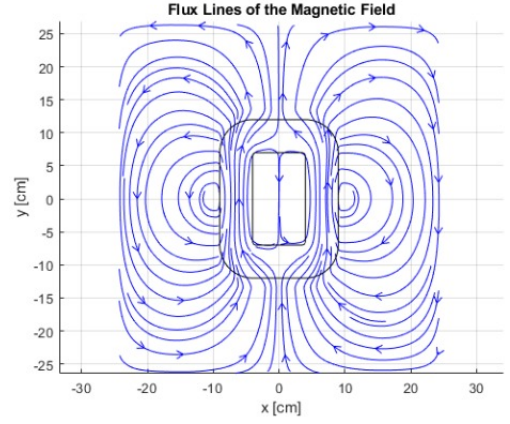


Fig. 3. Flux lines generated in MATLAB

with all the elements in place, an iterative simulation of the transformer can be conducted to achieve more accurate results.

III. EXPECTED RESULTS AND DISCUSSION

Although the presented code can simulate a transformer with improved accuracy, accounting for air gaps and other specific features, it remains limited to tests, stable operation with no remanent magnetization, and isotropic materials. Future works aims to include anisotropic materials, the effects of remanent magnetization, and, most importantly, to predict the impact of the air gap on the magnetization curve. This would reduce the dependence on tests and make the simulations more applicable to optimization processes.

The computational modeling of the transformer, as presented in this work, is a significant advancement in the development of solutions for efficient wireless power transmission. The simulations and calculations discussed provide a solid foundation for the development of the complete system, which in future works will include practical tests and experimental validation.

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