

Equivalent Circuit Model of Printed Circuit Board-Based Magnetic Components with High-Aspect Coils

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This paper proposes a fast equivalent-circuit-based analysis method for PCB-based magnetic components with high-aspect-ratio coils. Circuit parameters were derived using quasi-static and homogenized FE analyses, significantly reducing computation time compared to full-wave FE analyses. The method effectively modeled dielectric losses by incorporating parasitic resistance into the equivalent circuit, achieving high accuracy in frequency-dependent resistance simulations.

Index Terms—Equivalent circuit, homogenization, printed circuit board, parasitic resistance

I. INTRODUCTION

RECENTLY, high-frequency operation and high-power density have become essential requirements for power electronic circuits. Consequently, miniaturization of the magnetic components is required to meet these demands. Printed circuit board (PCB)-based magnetic components have attracted attention for miniaturization [1][2]. The use of PCBs allows the simultaneous fabrication of coils along with other circuit traces. Additionally, leveraging the layered structure of a PCB enables the realization of a high inductance density.

However, coils are extremely thin, ranging from tens to hundreds of micrometers in size. To reduce DC loss, the coils require a high-aspect ratio. However, this design choice leads to increased AC losses owing to skin and proximity effects. Therefore, an accurate evaluation of the AC losses in PCB-based coils is crucial during the coil design stage.

Parasitic capacitances potentially exist in PCB-based coils because of the presence of insulation layers with thicknesses of tens to hundreds of micrometers within PCBs. Therefore, it is essential to accurately estimate these parasitic capacitances simultaneously. Moreover, the dielectric loss of the insulation layers is affected by the losses at high frequencies.

These challenges can be addressed through a full-wave finite element (FE) analysis and Darwin approximation [3], which employs a fine mesh designed to account for the skin depth and structure of the PCB-based coils. However, FE analysis is inherently time-consuming.

In this study, an equivalent-circuit-based method is proposed to rapidly analyze PCB-based magnetic components. In this method, the circuit parameters are calculated using a FE analysis in a quasi-static field and a homogenized FE analysis, significantly reducing the computation time compared to full-wave analyses. In this study, an equivalent circuit of an inductor with a PCB-based coil and magnetic core was constructed, and the effectiveness of the proposed method was validated.

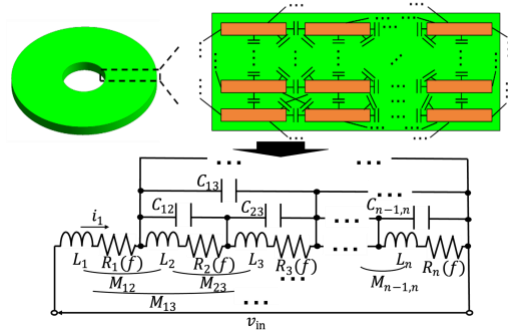


Fig. 1. Equivalent circuit model of a PCB-based coil.

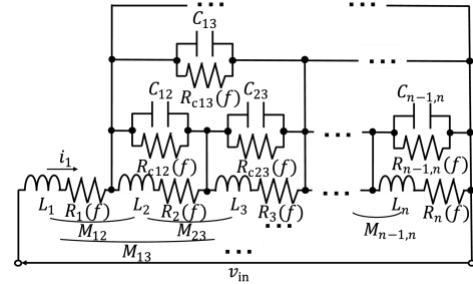


Fig. 2. Equivalent circuit model of a PCB-based coil considering dielectric loss.

II. PROPOSED METHOD

A. Equivalent Circuit

The PCB-based coil is represented by the equivalent circuit shown in Fig. 1, where R_i , L_i , M_{ij} , and C_{ij} represent the resistance, self-inductance, mutual inductance, and parasitic capacitance, respectively. In this circuit, L_i , M_{ij} , and C_{ij} were calculated using magnetostatic and electrostatic FE analyses.

However, this structure did not account for the dielectric loss in the insulation layer of the PCB. To address this limitation, the circuit was extended to the configuration shown in Fig. 2. In this extended circuit, resistance R_{cij} is introduced in parallel with C_{ij} , representing the dielectric loss. The resistance value can be computed through an electro-quasi-static FE analysis.

The resistance R_i changed significantly with frequency owing to the skin and proximity effects. Therefore, AC characteristics should be incorporated into each R_i . In this study,

a homogenized FE analysis based on [4] was employed to determine the frequency-dependent resistance values.

B. Homogenized FE analysis

The homogenization method assigns the macroscopic complex permeability $\langle \mu_r \rangle$ in the coil region shown in Fig. 3, which describes the proximity effect of the coil. For a circular coil, we can analytically derive $\langle \mu_r \rangle$, whereas $\langle \mu_r \rangle$ for a rectangular coil needs to be computed by a unit cell approach [5]. By employing the homogenization method, it becomes unnecessary to create a mesh that accounts for the skin depth, enabling faster FE analysis to determine R_i shown in Fig. 1.

III. RESULTS

The proposed equivalent circuit for a nine-turn PCB-based coil with a magnetic core shown in Fig. 4 was constructed, and the relative permeability of the core was set to 2000. To evaluate the effect of dielectric loss, the relative permittivity of the PCB insulation layer was set to 4.0 and $4.0-j0.4$. For comparison, a circuit-based model employing Ahmed's method, recognized for its effectiveness in estimating AC losses in high-aspect-ratio coils, was utilized [6]. Additionally, a 2D axial magneto-quasi-static FE analysis with a fine mesh and a 3D full-wave FE analysis with a coarse mesh were performed.

Figure 5 shows the frequency-dependent resistance characteristics without considering the dielectric loss in the PCB, where the red line, green line, black dots, and black dashed line were obtained by the proposed method, analysis with Ahmed's model, full-wave FEM, and quasi-static FEM, respectively. The first resonant peak at approximately 10 MHz simulated by the proposed method was in good agreement with that obtained via the full-wave FEM. The resistance characteristics up to 3 MHz simulated using the proposed method agreed with those of the quasi-static FEM. However, the simulation using Ahmed's model did not agree with that of the quasi-static FEM. This is because the Ahmed model does not consider the magnetic material surrounding the coil.

Figure 6 shows the frequency-dependent resistance characteristics, considering the dielectric losses in the PCB. The resistance characteristics at frequencies above 1 MHz simulated using the proposed method showed good agreement with those obtained using the full-wave FEM. These results demonstrate that, by incorporating R_{cij} , a parasitic resistance connected in parallel with the equivalent circuit can effectively reproduce the dielectric losses in a PCB.

Finally, the computational times were compared. The construction of the equivalent circuit required approximately an hour, and the circuit analysis of Figs. 4 and 5 required less than one second at 101 frequency points. In contrast, the magneto-quasi-static and full-wave analyses require approximately 13 h. These results validate the efficiency and effectiveness of the proposed model in significantly reducing the computation time.

In this study, we will fabricate an inductor with a PCB-based coil and magnetic core, and compare its characteristics with the measurement results to further validate the proposed approach.

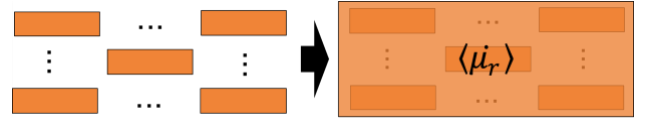


Fig. 3. Homogenization of the coil region.

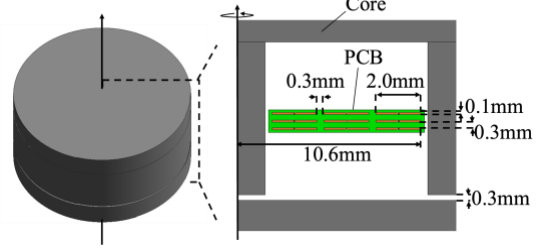


Fig. 4. 3D model and 2D axial model of the analyzed model.

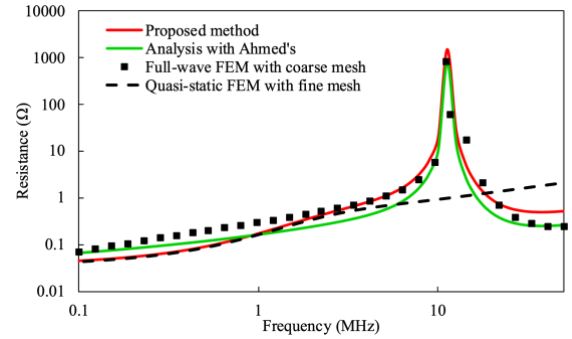


Fig. 5. Frequency-dependent resistance characteristics: simulated by the proposed method (red), analysis with Ahmed's model (green), full-wave FEM (black dots), and quasi-static FEM (black dashed line).

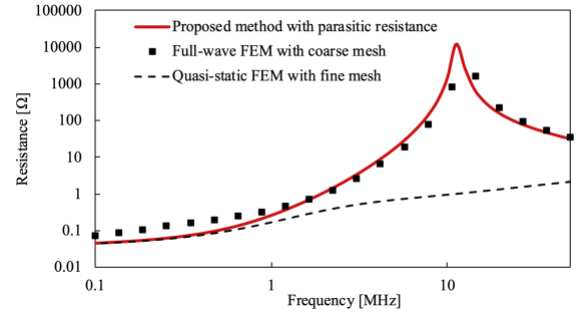


Fig. 6. Frequency-dependent resistance characteristics considering losses in the PCB simulated by the proposed method (red), full-wave FEM (black dots), and quasi-static FEM (black dashed line).

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