

Electromagnetic Field Analysis on High-Frequency Response of Inductor Considering Frequency Dependence of Magnetic Permeability

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In inductors for power electronics, the driving source frequency becomes higher to the MHz range by applying new semiconductors (GaN/SiC). To represent the high frequency (HF) response of the inductor with the iron core of laminated electrical steel sheets by the electromagnetic field analysis (FEA), not only the stray capacitance of winding but also the frequency dependence of magnetic permeability of the steel plate is considered in this paper. The original complex permeability without the influence of the skin effect of the steel plate is determined so that the HF response of inductor obtained from FEA is matched with the measurement. It is shown that the HF response can be represented by taking account of the frequency dependence of magnetic permeability. Moreover, it is also suggested that the real part of complex permeability decreases with the frequency and its imaginary part has the peak at 10 kHz.

Index Terms—Finite element analysis, high frequency, inductor, magnetic permeability, stray capacitance.

I. INTRODUCTION

RECENTLY, to make power electronics equipment more compact and higher efficiency, the driving source frequency is increasing to MHz order by applying the new semiconductors (GaN/SiC). Therefore, to design the magnetic components, such as inductor, transformer, etc., in power electronics, the high frequency (HF) finite element electromagnetic field analysis (FEA) should be established. In the previous research [2], the measured HF response of inductor with solid iron core [1] can be represented by the electromagnetic field analysis (FEA) taking account of the stray capacitance [2, 3], and the mechanism of the multiple resonance phenomena is also clarified [2]. However, in this model, the magnetic permeability of the iron core given in FEA does not have much influence on the results because the effective permeability becomes very small due to the large skin effect in the solid iron core. Therefore, the HF behaviors of the permeabilities of magnetic materials are obscure.

In this paper, the HF response of the inductor with the iron core of laminated electrical steel sheets, in which the permeability affects the results due to its higher value and the relaxation of skin effect by laminating, is represented by considering not only the stray capacitance but also the frequency dependence of the permeability [4]. The permeability on each frequency is determined so that the HF response of inductors obtained from FEA is matched with measurement. Then, the HF behavior of the permeability is discussed.

II. EXPERIMENTAL MODEL

The experimental model of a ring core inductor is shown in Fig. 1, in which the conductive wire is wound around the plastic

case outside the iron core of laminated electrical steel sheets (JIS: 35A300). The winding has a number of turns N of 254 and the total length l_w of 18.7 m. The impedances $\hat{Z}$ of the inductor are measured at the frequencies f from 50Hz to 30MHz by the impedance spectrum analyzer (NF Corporation: ZA57630).

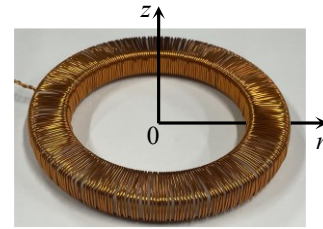


Fig. 1. Experimental model of inductor.

III. ANALYSIS MODEL AND METHOD

A. Analysis Model

The 3D analysis model for the experimental model is shown in Fig. 2. The wire is modeled directly to take account of the stray capacitances. On the other hand, to save the computation cost, the laminated iron core is modeled by the solid one with the homogenization anisotropic complex permeability $\hat{\mu}_{homo}$ and conductivity σ_{homo} . The input voltage $\hat{V}_{in}$ between the terminals (A and B) of the wire is applied by the boundary condition setting of the scalar potential ϕ_A and ϕ_B , then the input current $\hat{I}_{in}$ is calculated in the wire to obtain the input impedance $\hat{Z}$ ($=\hat{V}_{in}/\hat{I}_{in}$).

B. Electromagnetic Field Analysis

The 3D linear FEA is carried out by using the A - ϕ method (A : magnetic vector potential, ϕ : electric scalar potential) in the frequency domain taking account of the displacement current

which leads to the stray capacitance. The fundamental equations are as follows:

$$\text{rot}\left(\frac{1}{\mu} \text{rot} \mathbf{A}\right) = -(\sigma + j\omega\varepsilon)(j\omega \mathbf{A} + \text{grad} \phi) \quad (1)$$

$$\text{div}\{-(\sigma + j\omega\varepsilon)(j\omega \mathbf{A} + \text{grad} \phi)\} = 0 \quad (2)$$

where μ , σ , and ε are the permeability, the conductivity, and the permittivity, respectively, and ω is the angular frequency. Furthermore, the superscript ($\cdot$) denotes the complex number.

C. Homogenization of Laminated Iron Core

The homogenization permeability $\dot{\mu}_{homo}$, mentioned in Section III. A, is determined by the 2D linear eddy current analysis of one steel sheet model shown in Fig.3. The original permeability $\dot{\mu}_{org}$ of the steel plate is complex to take account of the hysteresis phenomenon. The conductivity $\sigma_{ano} = 3.648 \times 10^6$ S/m, which is larger than the original conductivity $\sigma_{org} = 1.92 \times 10^6$ S/m, is set in the steel sheet to consider the anomalous eddy current loss [5]. The $\dot{\mu}_{homo}$ can be obtained by dividing the average flux density $\dot{B}_{iron,ave}$ in the steel sheet by the magnetic field intensity $\dot{H}_{air}$ in the air.

IV. RESULTS AND DISCUSSION

The frequency characteristics of impedances $\dot{Z}$ of the inductor obtained from FEA are compared with the measured one in Fig. 4. In FEA, two types of the original permeabilities $\dot{\mu}_{org,const}$ and $\dot{\mu}_{org,var}$ with the frequency independent and dependent, respectively, are set. The permeability $\dot{\mu}_{org,const}$ is determined at 50 Hz so that the impedance $\dot{Z}$ obtained from FEA is only well matched with the measured one at 50 Hz. On the other hand, the $\dot{\mu}_{org,var}$ is determined by each frequency. Fig. 4 shows that the frequency characteristics of the impedance $\dot{Z}$ of the inductor can be represented by taking account of the frequency dependent $\dot{\mu}_{org,var}$ of the original permeability.

Fig. 5 shows the original permeabilities $\dot{\mu}_{org,const}$ and $\dot{\mu}_{org,var}$ determined by FEA. It is suggested that the real part of the original permeability $\dot{\mu}_{org,var}$ decreases with frequency and its imaginary part has the peak at 10 kHz. The behavior of $\dot{\mu}_{org,var}$ will be discussed in the full paper.

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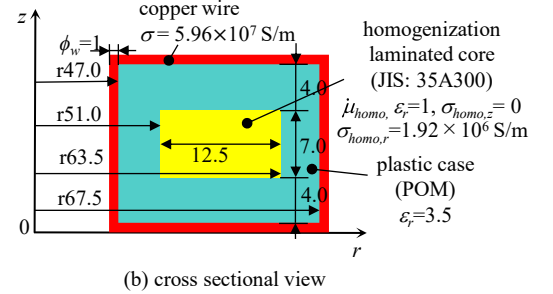
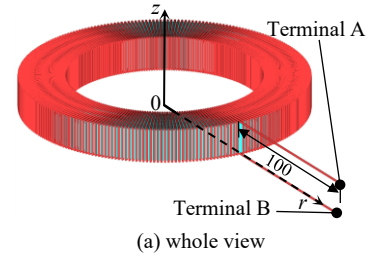


Fig. 2. 3D analysis model of inductor.

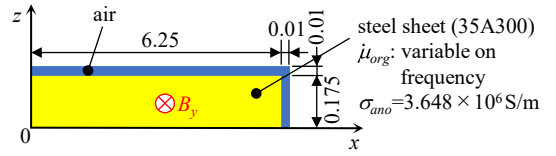


Fig. 3. 2D analysis model of one steel sheet (1/4 region).

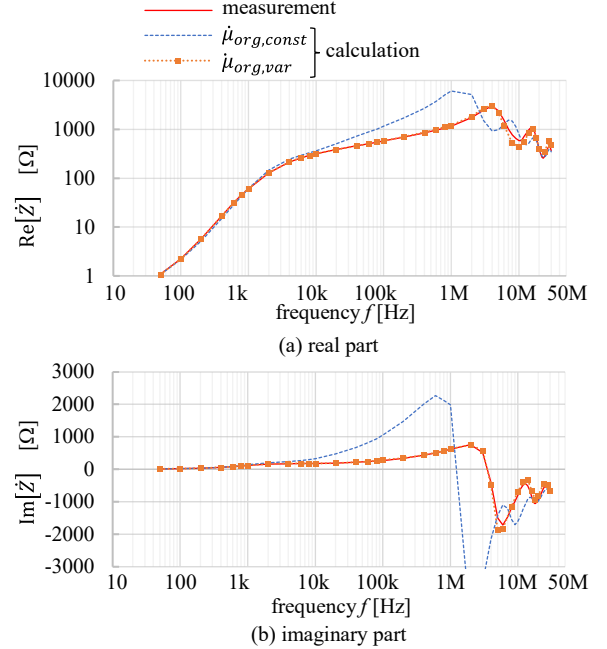


Fig. 4. Frequency characteristics of input impedance $\dot{Z}$ of the inductor.

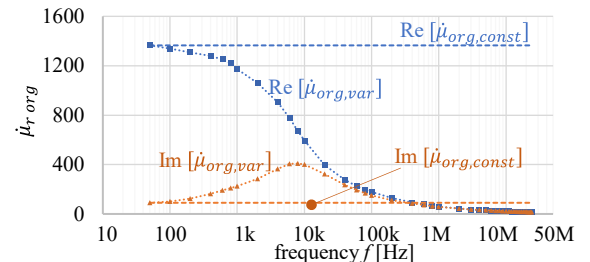


Fig. 5. Frequency dependency of original complex permeability $\dot{\mu}_{org}$ of steel sheet.