

Homogenization Technique for Winding of Ring Core Inductor Considering Stray Capacitance at High Frequency in Finite Element Electromagnetic Filed Analysis

Xuanda Hou¹, Hiroshi Dozono¹, Kazuhiro Muramatsu¹, Keisuke Fujisaki²,
Nguyen Gia Minh Thao³, Yanhui Gao⁴, Weimin Guan⁵, Jiaxin Yuan⁵

¹Department of Electrical and Electronic Engineering, Saga University, Saga, 840-8502 Japan, xuandahou@outlook.com

²Electromagnetic Energy System Laboratory, Toyota Technological Institute, Nagoya, 468-8511 Japan, fujisaki@toyota-ti.ac.jp

³Department of Mechanical, Electrical and Electronic Engineering, Shimane University, Matsue, 690-8504 Japan, nguyenthao@ecs.shimane-u.ac.jp

⁴Division of Mechatronics, Oita University, Oita, 870-1192 Japan, gao-yanfui@oita-u.ac.jp

⁵School of Electrical Engineering and Automation, Wuhan University, Wuhan, 430072 China, guanwm@hotmail.com

To simulate the high frequency (HF) response of an inductor at the MHz range by the full-wave electromagnetic field finite element analysis (FEA), the wire of winding should be modeled directly to take account of the stray capacitance and the wire length of the winding. However, it causes high computation cost. In this paper, a homogenization technique for winding taking account of the stray capacitance and the wire length is proposed. The winding winding around the iron core is modeled to be the solid coil used in the ordinary FEA by using the equivalent conductivity and permittivity. It is shown that the HF response of the ring core inductor obtained from the proposed homogenized-winding model is in good agreement with those obtained from the real-winding model and measurement with significantly reducing the computation cost.

Index Terms—Electromagnetic field analysis, homogenization, inductor, stray capacitance, winding.

I. INTRODUCTION

IN INDUCTORS excited by the inverter using GaN power devices, the ringing phenomenon [1], which is the oscillation in the current waveform during the switching, occurs owing to the resonance at high frequency (HF), and it increases the noise and iron loss of the core [1].

In the previous research [2], the multi-resonance is represented by the full-wave electromagnetic field finite element analysis (FEA) [2, 3], and it is explained by the wave propagation in the wire, in which the stray capacitance and the wire length are required to be considered [2]. To consider these two factors, it is required that the wire of the winding is modeled directly, which leads to heavy computation cost. To save the computation cost, some homogenization techniques for winding are proposed [4, 5]. However, only the magnetic field analysis is carried out without considering the stray capacitances in [4], and the multi-resonance cannot be simulated in the case when the stray capacitances are computed as a lumped parameter in [5].

In this paper, the homogenization technique for the winding taking account of the stray capacitances and the wire length is proposed. In the proposed homogenization technique, the real-winding FEA model is transferred into the solid coil used in the ordinary FEA by the equivalent conductivity and permittivity. The proposed homogenization technique is applied to a ring core inductor. The HF characteristics of the admittance $\hat{Y}$ of the inductor in the frequency domain obtained by the homogenization FEA model is compared with those obtained by the real FEA model and the measurement. Moreover, the computation costs of both FEA models are compared with each other.

II. REAL-WINDING MODEL [2]

The measurement model of a ring core inductor is shown in Fig. 1, in which a wire is wound around a plastic case outside the ring core. The core is a magnetic solid one (JIS: SUS430) with a height h_c of 35.35 mm. The winding has a number of turns N of 254 and a total wire length l_w of 24.26 m.

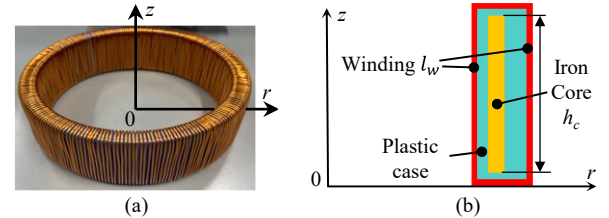


Fig. 1. Measurement model, (a) whole view, (b) sectional view.

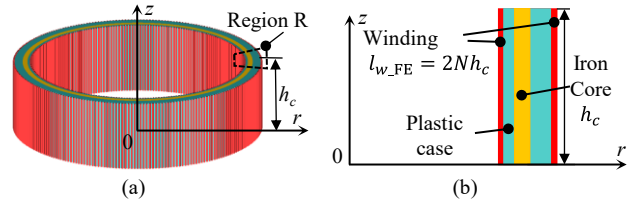


Fig. 2. Real-winding FEA model, (a) whole view, (b) sectional view.

A simplified real-winding FEA model for the measurement model is shown in Fig. 2, in which only the side parts of the winding are modeled and there is only one layer in the z direction. The wires are connected into a winding by using the numerical connection of nodes on the boundary [2].

The FEA with the A - ϕ method (A : magnetic vector potential, ϕ : electric scalar potential) in the frequency domain considering the displacement current, which leads to the stray capacitance, is performed by applying a voltage to the winding. The

magnetic characteristics of iron core are assumed to be linear, and the effect of the eddy current is considered by the complex permeability μ_c [6].

III. HOMOGENIZED-WINDING MODEL

The real-winding model is transferred into the homogenized-winding model by the combination of one turn of wire and air gap into one element as shown in the blue box in Fig. 3, which is the overhead view of the region R in Fig. 2 (a).

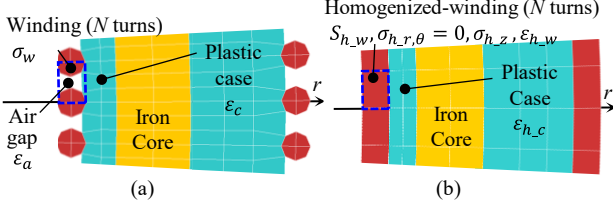


Fig. 3. Homogenization of one-turn wire and wire gap into one element, (a) real-winding, (b) homogenized-winding models in region R.

The conductivity $\sigma_a = 0$ of the air gap is considered by setting the conductivity $\sigma_{h,r,\theta}$ of the homogenized-winding in the r and θ directions to be zero. Besides, the equivalent conductivity $\sigma_{h,z}$ of homogenized-winding in the z direction is set by (1).

$$\sigma_{h,z} = \sigma_w \frac{S_w}{S_{h,w}} \quad (1)$$

where, S_w and $S_{h,w}$ are the sectional areas of the wire in real-winding and homogenized-winding models, respectively, and σ_w is the conductivity of the wire.

Fig. 4 shows the schematic diagram of the displacement current distribution of the blue part in Fig. 3. The stray capacitance C_{ww} between each turn of the real-winding can be calculated by (2). In the homogenized-winding, it can be computed by (3). Therefore, the equivalent permittivity $\epsilon_{h,w}$ of homogenized-winding can be deduced by letting (2) equal to (3), as shown in (4).

$$C_{ww} = \frac{\pi \epsilon_a h_c}{\cosh^{-1}(d_{ww}/\phi_w)} \quad (2), \quad C_{h-ww} = \epsilon_{h,w} \frac{\phi_w h_c}{d_{ww}} \quad (3)$$

$$\epsilon_{h,w} = \epsilon_a \frac{\pi d_{ww}}{\phi_w \cosh^{-1}(d_{ww}/\phi_w)} \quad (4)$$

where ϵ_a is the permittivity of the air gap, d_{ww} is the distance between the two turns of wire, and ϕ_w is the diameter of wire.

Fig. 5 shows the schematic diagram of displacement current distribution between the iron core and winding in Fig. 3. The stray capacitance C_{cw} between the iron core and the real-winding can be calculated by (5). In the homogenized-winding, it can be computed by (6). Thus, the equivalent permittivity $\epsilon_{h,c}$ of the plastic case in the homogenized-winding model can be deduced by letting (5) equal to (6), as shown in (7).

$$C_{cw} = \epsilon_c \frac{\pi r_{cw} h_c}{d_{cw}} \quad (5), \quad C_{h-cw} = \epsilon_{h,c} \frac{2\pi h_c}{N \ln \left(\frac{r_{cw} + d_{cw}}{r_{cw}} \right)} \quad (6)$$

$$\epsilon_{h,c} = \epsilon_c \frac{r_{cw} N \ln \left(\frac{r_{cw} + d_{cw}}{r_{cw}} \right)}{2 d_{cw}} \quad (7)$$

where ϵ_c is the permittivity of the plastic case, d_{cw} is the distance between the iron core and wires.

The other techniques to overcome the difference between the

total wire lengths l_w and l_{w_FE} of the measurement and FEA models, respectively, and reduce the number of elements more will be demonstrated in the full paper.

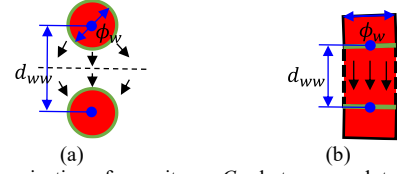


Fig. 4. Homogenization of capacitance C_{ww} between each turn of wire, (a) real wires, (b) homogenized wires.

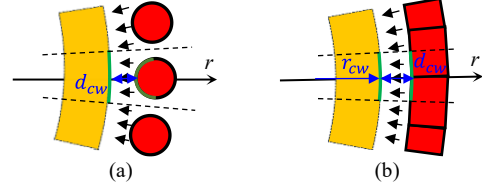


Fig. 5. Homogenization of capacitance C_{cw} between iron core and wires, (a) real wires, (b) homogenized wires.

IV. RESULTS AND DISCUSSION

The HF characteristics of the amplitudes of the input admittance $|\dot{Y}|$ obtained from the measurement, the real-winding and homogenized-winding model are shown in Fig. 6. Both calculation models can simulate the multi-resonance phenomenon of the ring core inductor observed by the measurement. Moreover, the results from the homogenized-winding and the real-winding models have similar resonant frequencies of 8MHz, 16MHz, and 25MHz.

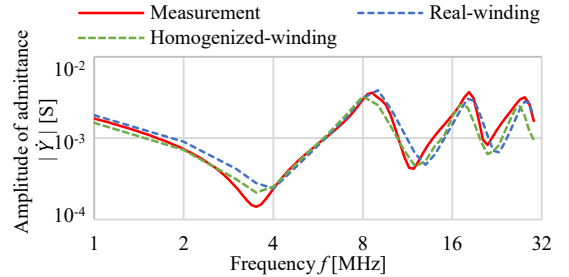


Fig. 6. Amplitude of the input admittance $|\dot{Y}|$ of the ring core inductor.

The average CPU time for each frequency is about 4 hours for the real-winding model with the number of elements of 17,526. While the average CPU time of the homogenized-winding model is only about 7 minutes because the number of elements can be reduced to be 5,355, moreover, the convergence characteristics of the matrix solver, CICC method, are also much improved by removing the thin elements.

It can be concluded that the proposed technique can reduce the computation cost significantly with keeping the accuracy.

REFERENCES

- [1] N. G. M. Thao, et al., *Proc. of the 2021 Int. Symp. on Electrical and Electronics Engineering*, pp. 232-237, 2021.
- [2] X. Hou, et al., "Electromagnetic field analysis on resonance phenomenon of inductor driven by inverter considering stray capacitance", *International Journal of Applied Electromagnetics and Mechanics*, 2025 (in press).
- [3] Y. Zhao, et al., *IEEE Trans. on Magn.*, vol. 53, no. 6, #7400905, 2017.
- [4] H. Igarashi, *ibid.*, vol. 53, no. 1, #7400107, 2017.
- [5] Y. Sato, et al., *ibid.*, vol. 60, no. 3, #7400804, 2024.
- [6] Y. Gao, et al., *ibid.*, vol. 45, no. 3, pp. 1044-1047, 2009.