Magnetic Field Analysis of Reactors for Power Conditioner System Taking Account of Hysteretic Property

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This paper describes the analysis method for inductance and iron loss taking account of magnetic hysteresis property in reactors. We calculate inductance based on magnetization curves and hysteresis loops. Then, we discuss the difference between the 2 methods. Furthermore, we propose iron analysis method under AC excitation with high-frequency ripples.

Index Terms— **Computational electromagnetics, finite element analysis, inductance, magnetic hysteresis**

I. Introduction

GENERALLY, a reactor in a power conditioner is used under DC or AC excitation with high-frequency current ripples. Under DC-biased situation, the magnetic field analysis of the reactor based on a magnetization curve is not sufficiently accurate because the operating point of the reactor is on minor loops. Additionally, it requires a lot of time steps to analyze the reactor excited by commercial-frequency AC with high-frequency ripple in order to consider harmonic components accurately, which results in large computational cost.

In this paper, we investigate two inductance calculation methods: one is based on a magnetization curve, and the other is based on the play model in order to take account of hysteretic property. Furthermore, we propose a practical method for calculating iron loss under AC excitation with high-frequency ripple. In this proposed method, the fundamental and harmonic iron losses are calculated separately. In order to verify the validity of the proposed method, the iron loss analysis of an AC reactor is performed.

II. Inductance Calculation Method

A. Inductance calculation method based on hysteresis property by play model

Minute-amplitude AC waveform superimposed on DC component is shown in Fig. 1. I_m denotes the amplitude of minute-amplitude AC, and I_0 denotes the DC component. I_0 is sufficiently large compared to I_m. In addition, the minor loop corresponding to the situation in Fig. 1 is shown in Fig. 2. Points A and B in Fig. 2 coincide with those in Fig. 1, respectively. $\Delta\mu_s$ is defined as a slope passing through points A and B. In this situation, inductance L_1 is represented as

$$L_1 = \frac{\Phi_a - \Phi_b}{i_a - i_b} = \frac{\Phi_a - \Phi_b}{2I_m}\,, \tag{1}$$

where Φ_a, Φ_b, i_a, i_b are total flux linkage of a reactor and current at points A and B, respectively. Hereafter, this calculation method is called method 1.

In this method, the inductance is calculated from incremental permeability ($\Delta\mu_s$). In this paper, we use the play model [1], [2] to represent minor loops. This method is expected to be accurate because hysteretic property is considered directly.

B. Inductance calculation method based on a magnetization curve

The operating points on a magnetization curve corresponding to Fig. 1 are shown in Fig. 2. Point C in Fig. 1 coincides with that in Fig. 2, which is not on the minor loop but the magnetization curve. The differential permeability is defined as a slope passing through the point A and C. Inductance L_2 based on the differential permeability is given by:

$$L_2 = \frac{\Phi_a - \Phi_c}{i_a - i_c} \tag{2}$$

where Φ_c and i_c are total flux linkage of the reactor and current at point C, respectively. Hereafter, this calculation method is called method 2.

On the other hand, inductance L_3 based on usual permeability is given by:

$$L_3 = \frac{\Phi_a}{i_a} = \frac{\Phi_a}{I_0 + I_m} \tag{3}$$

Hereafter, this calculation method is called method 3.

III. Iron Analysis Method under AC Excitation with High-frequency Ripple

The basic concept of the proposed method is shown in Fig. 3. In principle, a current waveform of Fig. 3(a) should be inputted. In this case, many different minor loops are drawn on major loop. In order to reduce the computational cost, the waveform shown in Fig. 3(a) is separated into fundamental component (Fig. 3(b)) and several harmonic components with different DC offset (Fig. 3(c)). In Fig. 3(c), the 5 high-frequency current waveforms with different DC offsets are depicted as an example. The harmonic iron loss is approximated by the average of the loss generated by the current waveforms. The total iron loss is the sum of the fundamental (calculated from Fig. 3(b)) and the harmonic loss. In this paper, 9 high-frequency current waveforms are considered to obtain harmonic loss of the reactor.

The hysteresis loss (W_h) is calculated from the area of hysteresis loop drawn by the play model. The eddy current loss (W_e) is calculated from the time series date of the flux density in each element as post-processing of the finite element analysis [4]-[5].

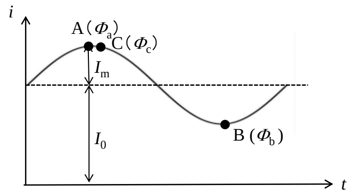

Fig. 1. Minute-amplitude current waveform with DC-biased current.

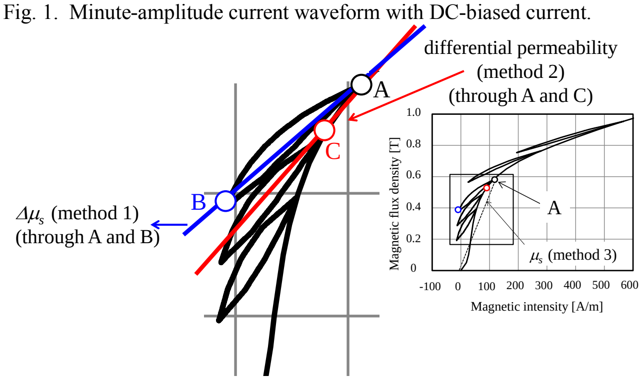

Fig. 2. Operating points on minor hysteresis loop.

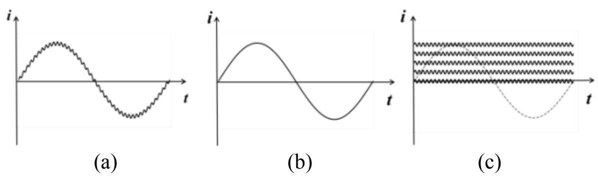

Fig. 3 Input current for proposed iron loss estimation method. (a)real waveform, (b) fundamental component, (c) harmonic component superposed on DC component.

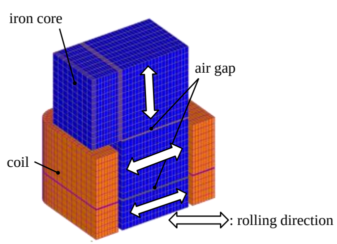

Fig. 4. Analysis model of reactor.

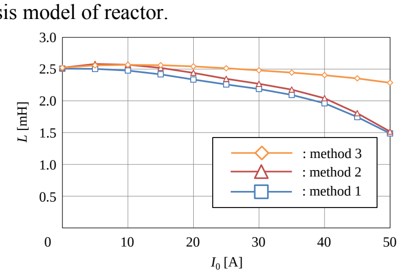

Fig. 5. DC-biased inductance property.

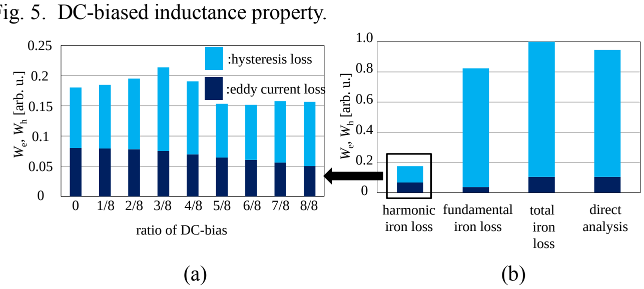

Fig. 6. Comparison of iron losses between separate and direct calculation. (a)DC-biased high frequency iron loss, (b)sum of the harmonic and fundamental losses.

IV. Numerical Results

A. Analysis model

The analyzed reactor is shown in Fig. 4. Because of the symmetry, the analysis domain is 1/8 part of the entire model. The coils whose number of turns is 41 are wound on each leg of the core.

B. Inductance calculation results

The numerical result is shown in Fig. 5. In this analysis, the input current is DC with minute-amplitude AC whose amplitude and frequency are 1.0 A and 10 kHz, respectively. As shown in Fig. 5, the result of method 2 is closer to that of method 1, which is regarded as the reference solution in this paper. A difference of the differential permeability and $\Delta\mu_s$ is small in the reactor because the magnetic resistance of the air-gap has a dominant influence on the resultant magnetic property of the reactor. The analysis times are 1643 sec in method 1, 18 sec in method 2 and 12 sec in method 3 at I_0=10 A, because calculation of method 1 is based on the play model. As a result, method 2 is considered to be a practical method from standpoints of computational cost and accuracy.

C. Iron loss calculation results

In order to investigate the validity of the proposed method, the iron loss analysis of the reactor shown in Fig. 4 is carried out. The normalized iron loss is shown in Fig. 6. In this analysis, the amplitude of fundamental (sinusoidal) current is 38.89 A and the frequency is 60 Hz. The amplitude and frequency of high-frequency ripple is 1.9 A and 1.8 kHz, respectively. Fig. 6(a) shows an iron loss when high-frequency AC current is superimposed on DC current. The harmonic iron loss in Fig. 6(b) is an average of the 9 iron losses in Fig. 6(a). The total iron loss in Fig. 6(b) is the sum of the harmonic and fundamental iron losses. According to Fig. 6, the proposed method can obtain almost the same total iron loss as the direct analysis. The computational times of the proposed method and the direct analysis are 6975 and 16390 sec, respectively. From the above-mentioned results, the effectiveness of the proposed method can be confirmed.

In the full paper, the detail of the proposed method and the comparison in inductance and iron loss between numerical and experimental results will be included.

V. References

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