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Loss estimation of a reactor with multi conductor coils by 3-D finite element analysis

***Abstract**. In this paper, the effects of the coil division on copper loss, especially eddy current loss, of a reactor are quantitatively clarified. The eddy current of the coil of the reactor is numerically computed using the three-dimensional finite element method.*

***Streszczenie.** W artykule przedstawiono wpływ podziału cewki na straty wiroprądowe w dławiku. Prądy wirowe w cewce dławika obliczane są numerycznie przy użuyciu trójwymiarowej metody elementów skończonych. (**Estymacja strat w dławiku z wieloprzewodową cewką za pomocą trójwymiarowej metody elementów skończonych**).*

Keywords: reactor, 3D-FEM, magnetic field analysis, copper loss
Słowa kluczowe: dławik, analiza pola magnetycznego, straty w miedzi

1. Introduction

Some reactors have air gaps between the cores. The leakage flux around the air gap of the reactor induces the eddy currents in the coil, and then the copper loss increases.

It is well known that the division of the cross-section of the copper wire in the coils is useful to reduce the eddy currents in the coil. But a lot of number of division of coil is not wanted because it is easy to make the coil with suitable number of division.

In Reference 1, a transformer with the divided cross-section of the copper wire in the coil was analyzed using the Three-dimensional finite element method (3-D FEM), and the usefulness of the division of the cross-section of the copper wire in the coil is clarified even though the number of division is two or four.

In this paper, the effects of the coil division on the copper loss of a reactor are quantitatively analyzed using the 3-D FEM under the condition that the number of division is four, nine and twenty-five. The division, in this paper, means a coil composed of multi conductor, and the number of division *n* means that the coil is composed of *n* conductors and the sum of squares of these conductors is the same as that of the no-division coil. At last, we clarify the usefulness of using the multi conductor of coils for reactors and the number of division, quantitatively.

2. Analysis Method

2.1 Fundamental Equations of Magnetic Field

The fundamental equations of the magnetic field used for the 3-D FEM analysis can be written using the magnetic vector potential $\boldsymbol{A}$ as follows [2]:

$$\mathrm{rot}(\nu\,\mathrm{rot}\,\boldsymbol{A}) = \boldsymbol{J}_0 + \boldsymbol{J}_e \tag{1}$$

$$\boldsymbol{J}_e = -\sigma\frac{\partial \boldsymbol{A}}{\partial t} \tag{2}$$

where ν is the reluctivity, $\boldsymbol{J}_0$ is the exciting current density, $\boldsymbol{J}_e$ is the eddy current density, and σ is the conductivity.

The analyzed model is applied by the voltage source. In order to analyze the magnetic field coupling the voltage source circuit, the following voltage equations and a set of (1) and (2) are solved simultaneously.

$$E = V_0 - RI_0 - \frac{d\psi}{dt} = 0 \tag{3}$$

$$\psi = \frac{n_c}{S_c}\int \boldsymbol{A}\cdot\boldsymbol{n}_s\,dv \tag{4}$$

$$\boldsymbol{J}_0 = \frac{n_c}{S_c}I_0\boldsymbol{n}_s \tag{5}$$

where I_0 is the exciting current, V_0 is the applied voltage, R is the effective resistance, ψ is the interlinkage flux of the coil, n_c is the number of turns, S_c is the cross-sectional area of the coil, and $\boldsymbol{n}_s$ is the unit vector along with the direction of exciting current.

2.2 Calculation of Eddy Current Loss

The eddy current loss W_{Cu} is given as follows:

$$W_{cu} = \frac{1}{\tau}\int_0^{\tau}\left\{\int_{V_c}\frac{\left|\boldsymbol{J}_0+\boldsymbol{J}_e\right|^2}{\sigma}dv\right\}dt \tag{6}$$

where τ is the period of the eddy current waveform, and V_c is the region of the conductor with the eddy current.

3. Analyzed Model and Conditions

Fig. 1 shows the analyzed model of a reactor, which is 1/8 of the whole region because of the symmetry. The 3-D finite element mesh of the coil is extremely fine to calculate the eddy currents in the copper wire in detail. The sinusoidal voltage of 60Hz is applied to the coil. The eddy currents induced in the coil are calculated by (1) and (2), and the exciting current density is simultaneously calculated by (3), (4) and (5). The copper loss is calculated by (6). Four cases of the division of the cross-section of a copper wire in the coil are analyzed as shown in Fig. 2.

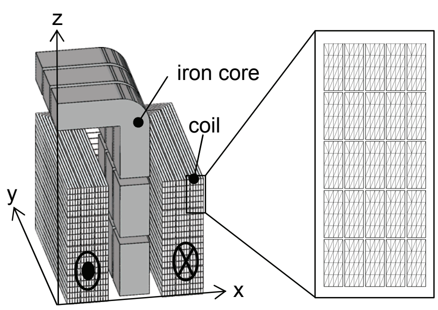

Fig.1. Analyzed model (25 division, 1/8 region).

4. Results and Discussions

Figs. 3 a) and 3 b) show the distributions of flux density vectors in the case of No-division of the cross-section of the copper wire when the current becomes the maximum. The distribution of flux density vectors is almost the same regardless of the coil division. Small differences of these cases of the coil division are caused by the eddy current in the coils. Fig. 3 c) shows the distributions of flux density vectors in the enlarged area in Fig. 3 b) in each number of divisions of the cross-section. The leakage flux around the air gap between cores intersects the coil complexly in any case. Because the input is sinusoidal voltage, the leakage flux varies sinusoidally with time and causes the eddy current in the coil.

Fig. 4 shows the distributions of eddy current density vectors in the coils in each number of divisions of the cross-section. From this figure, it is found that the distribution of the eddy current vectors in the coil is greatly difference according to the number of division. However, the tendency of the distribution is not changed according to the number of division. The eddy current density becomes small due to the division of copper wire.

Fig. 5 shows the distributions of copper loss in the coil. The copper loss concentrates near the air gap. Most of that appears on the most interior copper wire. The copper loss becomes small due to the division of the copper wire.

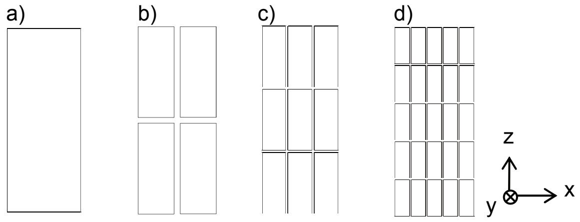

Fig.2. Division of a copper wire in coil.
a) No-division b) 4 division c) 9 division d) 25 division

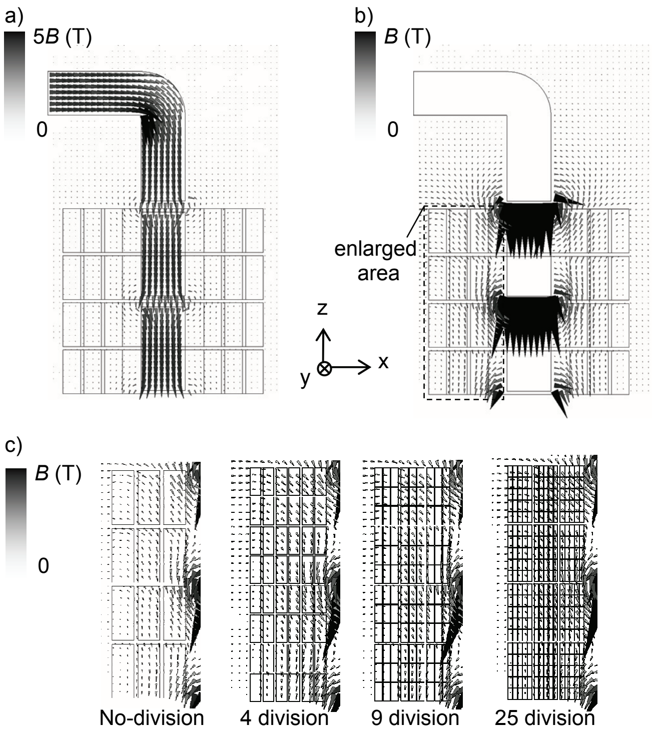

Fig.3. Distributions of flux density vectors (x-z section of center of the core). a) all view b) excluding the core (vector size is 5 times as larger as that of Fig. 3 a)) c) enlarged view (excluding the core) (vector size is 5 times as larger as that of Fig. 3 a))

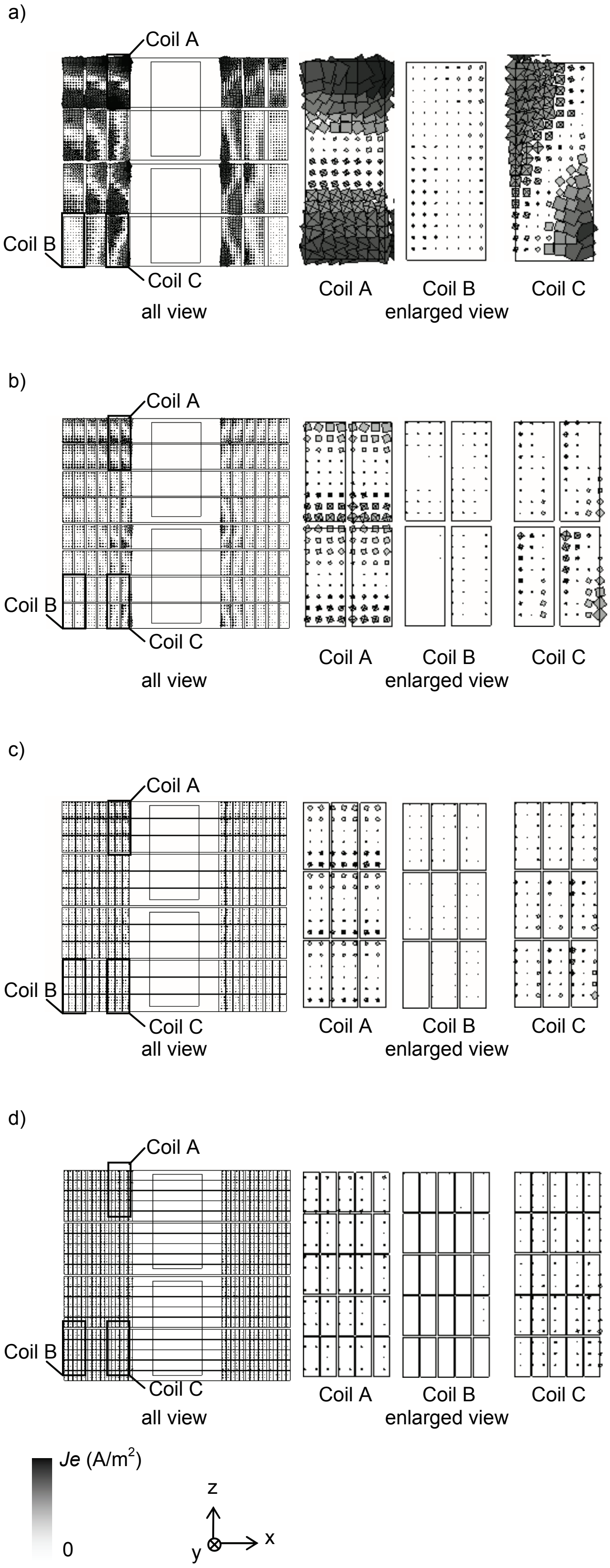

Fig.4. Distributions of eddy current density vectors (x-z section of center of the core).
a) No-division b) 4 division c) 9 division d) 25 division

Fig. 6 shows the calculated copper loss in the reactor. The values are regulated by the rated capacity of the reactor. Table 1 shows the loss vs. coil division and the ratio of eddy current loss in the copper loss. The copper loss becomes small due to the division of the copper wire. The copper loss decreases greatly in case of 4 division, and the copper loss decreases nearly half of No-division in case of 25 division. The eddy current loss is approximately a halt of copper loss in case of No-division, and the eddy current loss is approximately 6% of copper loss in case of 25 division. If this eddy current loss is allowed at the viewpoint of efficiency, temperature and so on, 25 is enough number of division in the case of 60Hz.

Table 2 shows discretization data and CPU time.

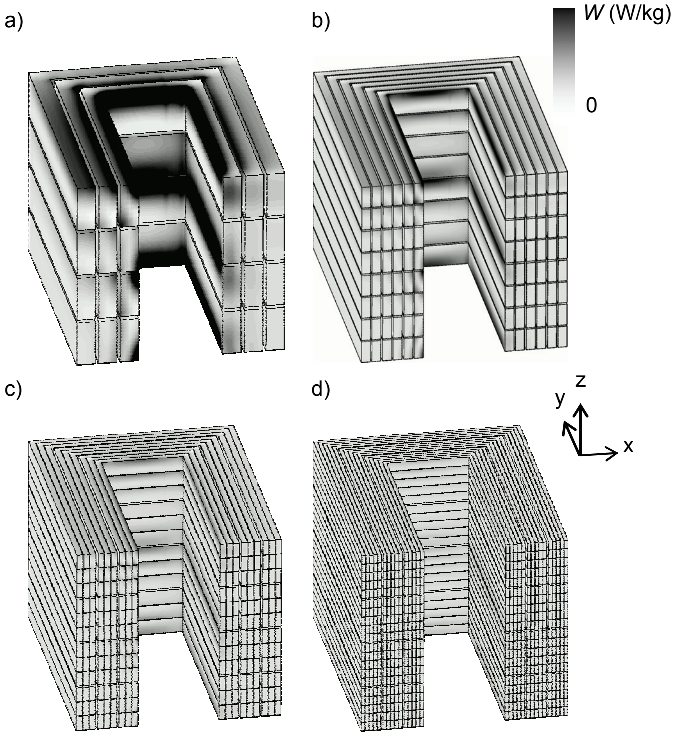

Fig.5. Distributions of copper loss.
a) No-division b) 4 division c) 9 division d) 25 division

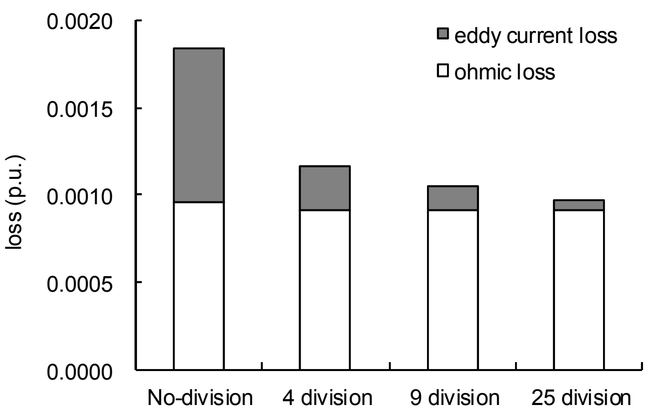

Fig.6. Copper loss of reactor.

Table 1. Loss characteristics.

	No-division	4 division
Copper loss	100%	64.8%
ratio of eddy current loss	49.4%	21.9%

	9 division	25 division
Copper loss	58.2%	53.5%
ratio of eddy current loss	13.1%	5.4%

Table 2. Discretization data and CPU time.

	No-division	4 division
Number of elements	1,465,644	6,934,620
Number of nodes	252,450	1,176,520
Number of edges	1,782,456	8,633,677
Number of unknown variables	1,759,632	8,576,362
Number of time steps	80	
Elapsed time / step (min. / step)	9.62	36.1

	9 division	25 division
Number of elements	10,328,994	19,686,720
Number of nodes	1,748,768	3,323,362
Number of edges	12,471,456	24,001,856
Number of unknown variables	12,279,040	23,919,760
Number of time steps	80	
Elapsed time / step (min. / step)	89.4	313.2

Computer used : Core 2 Duo (3.16GHz) PC × 16 [3]

5. Conclusion

The effects of the coil division on the copper loss, especially eddy current loss, of a reactor are quantitatively analyzed using the 3-D FEM under the condition that the number of division is four, nine and twenty-five. And we clarify the usefulness of using the multi conductor of coils for reactors and the number of division, quantitatively.

The copper loss in the case of 9 division is much smaller than that in the case of no-division. The copper loss in the case of 25 division is slightly smaller than that of 9 division. So if this eddy current loss is allowed at the viewpoint of efficiency, temperature and so on, 25 is enough number of division in the case of 60Hz.

For the future, we will analyze this same model under the condition that the frequency of the exciting current is the order of PWM career frequency. So, we will clarify the number of conductors to reduce the eddy current loss of reactors with the LCL filter and the PWM inverter.

REFERENCES

[1] M. Sawada, Y. Shindo, Y. Kawase, T. Yamaguchi, S. Ukai and Y. Shibayama, 3-D Finite Electrical Loss in Winding of Transformer, Proceeding of the Asia Pacific Symposium of Applied Electromagnetics and Mechanics, (2010), pp. 112-113
[2] S. Ito and Y. Kawase, Computer Aided Engineering of Electric and Electronic Apparatus Using Finite Element Method, (2000) (in Japan), Morikita Publishing Co.
[3] T. Nakano, Y. Kawase, T. Yamaguchi, M. Nakamura, N. Nishikawa, and H. Uehara, Parallel Computing of Magnetic Filed for Rotating Machines on the Earth Simulator, IEEE Trans. Magn., (2010), vol. 44, no. 8, pp. 3273-3276

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