Influence of Magnetic Property of Electrical Steel Sheets of Transformer on Eddy Current Loss

Tadashi YAMAGUCHI (Mem.), Yoshihiro KAWASE (Mem.) and Shota ISHIMURA

We analyzed a three-phase transformer made of laminated non-oriented electrical steel sheets using the 3-D parallel finite element method in order to numerically investigate the influence of the magnetic properties of the electrical steel sheets on the eddy current loss. The difference of the distribution of the magnetic flux and the eddy current between non-oriented and grain-oriented electrical steel sheets are numerically investigated. Moreover, the influence of the magnetic properties of the electrical steel sheets on the eddy current loss around the lap joint parts is clarified.

Keywords: three-phase transformer, 3-D finite element method, eddy current loss

1. Introduction

It takes a lot of calculation time to analyze the magnetic field of the three-phase transformers by the 3-D finite element method (FEM) taking into account the eddy current in the electrical steel sheets [1]. In the past several years, it has become to be able to analyze the magnetic field by the 3-D parallel FEM in a practical time. We have reported the eddy current analysis of a three-phase transformer made of laminated grain-oriented electrical steel sheets using the 3-D parallel FEM [2].

There are little reports that compare the numerical calculated electrical loss of non-oriented and grain-oriented electrical steel sheets.

In this paper, we analyze a three-phase transformer made of laminated non-oriented electrical steel sheets. The influence of the magnetic properties of the electrical steel sheets on the eddy current loss is numerically investigated by comparing with the analyzed results of the grain-oriented electrical steel sheets.

Moreover, we investigate the influence of the simultaneous stacking number on the loss increase through the eddy current analysis.

2. Analysis Method

2.1 Magnetic Field Analysis

The analyzed model is calculated as a Laplace problem in order to keep the magnetic flux through the electrical steel sheets constant. The fundamental equations of the magnetic field can be written using the magnetic vector potential \( \mathbf{A} \) and the electric scalar potential \( \phi \) as follows:

\[
\text{rot}(\text{rot} \mathbf{A}) = J_e, \quad J_e = -\sigma \left( \frac{\partial \mathbf{A}}{\partial t} + \text{grad} \phi \right)
\]

where \( \nu \) is the reluctivity, \( J_e \) is the eddy current density, and \( \sigma \) is the electric conductivity.

2.2 Electrical Loss Calculation

The eddy current loss \( W_{ed} \) in the laminated electrical steel sheets is given as follows:

\[
W_{ed} = \frac{1}{T} \int_0^T \left( \int_{V_e} \frac{J_e^2}{\sigma} \right) \, dt
\]

where \( T \) is the period of the eddy current waveform, \( V_e \) is the region of the conductor with the eddy current.

2.3 Definition of Equivalent Eddy Current Loss Length

The eddy current loss in the laminated electrical steel sheets with the lap joints in the transformer increases in the lap joint parts, and is depended on size of the laminated electrical steel sheets (length, width and thickness). Therefore, it is not easy to compare with ratio of loss increase of a steel sheet and that of one made of a different material using only the value of the eddy current loss.

![Definition of equivalent eddy current loss length.](image)

Fig. 1 Definition of equivalent eddy current loss length.
In this paper, the equivalent eddy current loss length $l_{we}$ is defined by the following equation in order to compare the ratio loss increase on the transformer made of different electrical steel sheets [3]:

$$l_{we} = \frac{W_{ed} - W_{edm}}{W_{edm0}} L$$  \hspace{1cm} (3)

where $W_{ed}$ is the eddy current loss of a transformer that has joint parts as shown in Fig. 1(a), $W_{edm}$ is the eddy current loss of a transformer that doesn’t have joint parts as shown in Fig. 1(b), $W_{edm0}$ is the eddy current loss of a laminated core, which shape is straight as shown in Fig. 1(c), and $L$ is the length of that core.

3. Analyzed Model and Conditions

Fig. 2 shows the analyzed model of a three-phase transformer. Owing to the symmetry in the $z$-axial direction, the analyzed region is a part of the whole region. As shown in Fig. 2(a), the magnetic vector potentials $A_u$, $A_v$, and $A_w$ are given as Dirichlet boundary conditions in order to generate the three-phase magnetic field in the electrical steel sheets. The electrical steel sheets shown in Fig. 2(b) are stacked alternately. Fig. 2(c) shows a cross section $\alpha$-$\beta$ shown in Fig. 2(a). The thickness of the electrical steel sheets is different by the magnetic property of the electrical steel sheets. The number $n$ in the captions are the simultaneous stacking number. For example, in case of $n=1$, the steel sheets I and II shown in Fig. 2(b) are stacked alternately every one sheet, if $n=3$, those are stacked alternately every three sheets. In this paper, we analyze the three-phase transformer under the conditions of $n=1$, 3 and 5.

Table 1 shows the properties of two materials used as the electrical steel sheets.

Table 3 shows the B-H curves of two materials.

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**Table 1** Materials properties.

| Magnetic property | Non-oriented | Grain-oriented |
|-------------------|--------------|----------------|
| Thickness (mm)    | 0.35         | 0.23           |
| Interlaminar gap  | 0.007        | 0.013          |
| Lamination factor (%) | 98          | 95             |
| Saturation flux density (T) | 1.4 | 1.7 |
4. Analyzed Results and Discussion

The distributions of the flux density vectors, the eddy current density vectors and the eddy current loss in this chapter are those on the surfaces I and II shown in Fig. 2(c).

4.1 Comparison between Non-oriented and Grain-oriented

In this section, the three-phase transformer is analyzed when the simultaneous stacking number is one. We investigate the influence of the magnetic properties of the electrical steel sheets on the distributions of the flux and the eddy current density vectors.

Table 2 shows the analysis condition. The analysis has been done under the condition of two patterns of the average flux density: 1.0T and the saturation flux density, which is 1.4T as the non-oriented material and 1.7T as the grain-oriented one. The distributions of the flux and the eddy current density vectors shown in this section are the analyzed results under the condition that the saturation flux density.

Fig. 4 shows the distributions of the flux density vectors. From these figures, we can see that the distribution in the steel sheet I almost same with that in the steel sheet II regardless of the magnetic properties. We can also see that there is much difference between the distributions of the non-oriented electrical steel sheets and the grain-oriented ones. The flux density vectors of the non-oriented electrical steel sheets vertically distribute to the gap of the lap joint parts, on the other hand, those of the grain-oriented ones distribute in the rolling direction even around the lap joint parts.

Fig. 5 shows the distributions of the eddy current density vectors. From these figures, we can see that the eddy current vectors of the non-oriented electrical steel sheets distribute parallel to the gap of lap joint parts, on the other hand, that of the grain-oriented electrical steel sheets distribute in a transverse direction around the lap joint parts. This difference is owing to the distributions of the flux density around the lap joint parts as shown in Fig. 4 and the property that the eddy current flows perpendicularly to the magnetic flux. It is not easy to theoretically explain about the difference so that it is necessary to investigate experimentally in order to confirm the validity of the analyzed result.

Fig. 6 shows the distributions of the eddy current loss. From these figures, we can see that the eddy current loss is concentrated around the lap joint parts regardless of the magnetic properties of the electrical steel sheets. This is because of the transverse magnetic flux around the lap joint parts in the z-axis direction. Moreover, we can also see that the eddy current loss of the non-oriented electrical steel sheets around the area γ shown in Fig. 2(a) is larger than that of the grain-oriented ones.

Fig. 7 shows the equivalent eddy current loss length. From these figures, we can see that the eddy current loss on the lap joint parts of the non-oriented electrical steel sheets is larger than that of the grain-oriented ones regardless of the flux density.

Table 3 shows the eddy current loss density. Table 4 shows the discretization data and the elapsed time. The number of finite elements is the same for each magnetic property of the electrical steel sheets. We can see that the elapsed time of the grain-oriented electrical steel sheets is longer than that of the non-oriented ones.

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(i) surface I (a) non-oriented

(ii) surface II

(b) grain-oriented

Fig. 4 Distributions of flux density vectors. ($\omega t=0^\circ, n=1$)

(i) surface I (a) non-oriented

(ii) surface II

(b) grain-oriented

Fig. 5 Distributions of eddy current density vectors. ($\omega t=0^\circ, n=1$)

(i) surface I (a) non-oriented

(ii) surface II

(b) grain-oriented

Fig. 6 Distributions of eddy current loss. ($n=1$)

(i) surface I (a) non-oriented

(ii) surface II

(b) grain-oriented

Fig. 7 Distributions of equivalent eddy current loss. ($n=1$)
4.2 Influence of Simultaneous Stacking Number

In this section, we analyze the three-phase transformer when the simultaneous stacking number 3 or 5 in order to investigate the influence of the simultaneous stacking number on the equivalent eddy current loss length.

![Fig. 7](image)

**Fig. 7** Equivalent eddy current loss length $l_{we}$.

Table 5 shows the analysis condition.

**Table 5 Analysis condition.**

| Magnetic property | Non-oriented | Grain-oriented |
|-------------------|--------------|----------------|
| Flux density (T)  | 1.0, 1.4     | 1.0, 1.7       |
| Simultaneous stacking number | 1, 3, 5 | 1, 3, 5 |
| Element type      | Triangular prism | Triangular prism |
| Frequency (Hz)    | 50           | 50             |
| ICCG convergence criterion | $1.0 \times 10^{-7}$ | $1.0 \times 10^{-7}$ |

![Fig. 8](image)

**Fig. 8** Distributions of flux density vectors. ($\omega t=0^\circ$, $n=3$, 5)
Fig. 9 shows the distributions of the eddy current density vectors. From these figures, we can see that the eddy current density vectors distribute parallel to the gap of the lap joint parts regardless of the magnetic properties. This is because of the transverse magnetic flux around the lap joint parts in the z-axial direction. Moreover, we can also see that the eddy current density vectors around the lap joint parts increase as the simultaneous stacking number increases. This is because that the transverse magnetic flux around the lap joint parts in the z-axial direction increases as the simultaneous stacking number increases.

Fig. 10 shows the distributions of the eddy current loss. From these figures, we can see that the eddy current loss is concentrated in the lap joint parts regardless of the magnetic properties. Moreover, we can also see that the eddy current loss around the lap joint parts increases as the simultaneous stacking number increases.

Fig. 11 shows the equivalent eddy current loss length in case of the simultaneous stacking number $n=1, 3$ and 5. From these figures, we can see that the equivalent eddy current loss length increases as the simultaneous stacking number increases regardless of the magnetic properties and the flux density. Moreover, the equivalent eddy current loss length of the grain-oriented electrical steel sheets is smaller than the non-oriented ones when the simultaneous stacking number is 1 as shown in the section 4.1, on the other hand, that of the grain-oriented ones is larger than the non-oriented ones when the simultaneous stacking number is 5.

Table 6 shows the eddy current loss density.

Table 7 shows the discretization data and the elapsed time.

**Fig. 9** Distributions of eddy current density vectors. ($\omega t=0^\circ$, $n=3, 5$)

**Fig. 10** Distributions of eddy current loss. ($n=3, 5$)
4. Conclusion

We analyzed a three-phase transformer made of laminated non-oriented electrical steel sheets using the 3-D parallel finite element method in order to investigate the influence of the difference of the magnetic properties of the electrical steel sheets on the eddy current loss.

It is analytically clarified that the difference of the distribution of the flux and the eddy current density vectors between made of the non-oriented electrical steel sheets and the grain-oriented ones.

We found that the equivalent eddy current loss length of the grain-oriented electrical steel sheets is smaller than the non-oriented ones when the simultaneous stacking number is 1. On the other hand, that of the grain-oriented ones is larger than the non-oriented ones when the simultaneous stacking number is 5. These results mean that the loss increased by the lap joint in the three-phase transformer made of the non-oriented steel sheets is smaller than that made of the grain-oriented steel sheets if the simultaneous stacking number is large. Because it is not easy to explain the phenomena qualitatively with only this model, we will investigate several models in future research.

References

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