Eddy Current Analysis of Three-Phase Transformer Made of Grain-Oriented Electrical Steel Sheets Using 3-D Parallel FEM

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We analyzed a three-phase transformer made of laminated grain-oriented electrical steel sheets using the three-dimensional parallel finite element method. The magnetic flux and eddy current distribution of the transformer are clarified in detail. Moreover, it is clarified that the eddy current loss of the transformer is affected by the build-up method of the laminated electrical steel sheets.

***Index Terms*—transformer, eddy current, three-dimensional parallel finite element method, grain-oriented electrical steel sheets**

I. INTRODUCTION

It takes a lot of calculation time to analyze the three-phase transformer by the 3-D finite element method taking into account the eddy current in the steel sheets. Therefore, in the past, only a part of the transformer has been analyzed [1],[2]. In these days, it becomes to be able to analyze full transformers using the 3-D parallel finite element method (FEM) in a practical time.

In this paper, we analyzed a three-phase transformer made of grain-oriented electrical steel sheets using the 3-D parallel FEM with prismatic edge elements. The flux and eddy current distribution of the transformer are clarified in detail. In addition, we clarified the effects of the build-up method of laminated electrical steel sheets on the eddy current loss of the transformer.

II. ANALYSIS METHOD

A. Magnetic Field Analysis

The fundamental equations, which is solved as Laplace equations of the magnetic field considering the eddy current $\boldsymbol{J}_e$, can be written using the magnetic vector potential $\boldsymbol{A}$ and the electric scalar potential ϕ as follows:

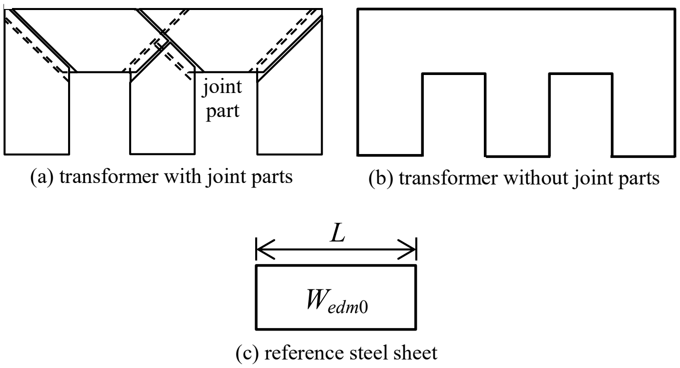
$$\mathrm{rot}\left(\nu\,\mathrm{rot}\,\boldsymbol{A}\right)=\boldsymbol{J}_e,\quad \boldsymbol{J}_e=-\sigma\left(\frac{\partial \boldsymbol{A}}{\partial t}+\mathrm{grad}\,\phi\right) \tag{1}$$

$$\mathrm{div}\,\boldsymbol{J}_e=0 \tag{2}$$

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

B. Definition of Length Equivalent to Eddy Current Loss

The eddy current loss of the laminated steel sheets with lap joints in the transformer is increased in the lap joint parts, and depended on size of the laminated steel sheets (length, width, thickness). It is difficult to compare the rate of increase in the loss of the laminated steel sheets using the value of the eddy current loss. Therefore, in this paper, the equivalent eddy current loss length l_{we} is defined by the following equation in order to introduce for easy understanding of the measure of the increased eddy current loss [3].



(a) transformer with joint parts (b) transformer without joint parts

(c) reference steel sheet

Fig. 1. Definition of equivalent eddy current loss length.

$$l_{we}=\frac{W_{ed}-W_{edm}}{W_{edm0}}L \tag{3}$$

where W_{ed} is the eddy current loss of a transformer, which has joint parts of the laminated steel sheets as shown in Fig. 1(a), W_{edm} is the eddy current loss of a transformer, which does not have joint parts of the laminated steel sheets as shown in Fig. 1(b), and W_{edm0} is the eddy current loss of a reference steel sheet, which length is L, as shown in Fig. 1(c).

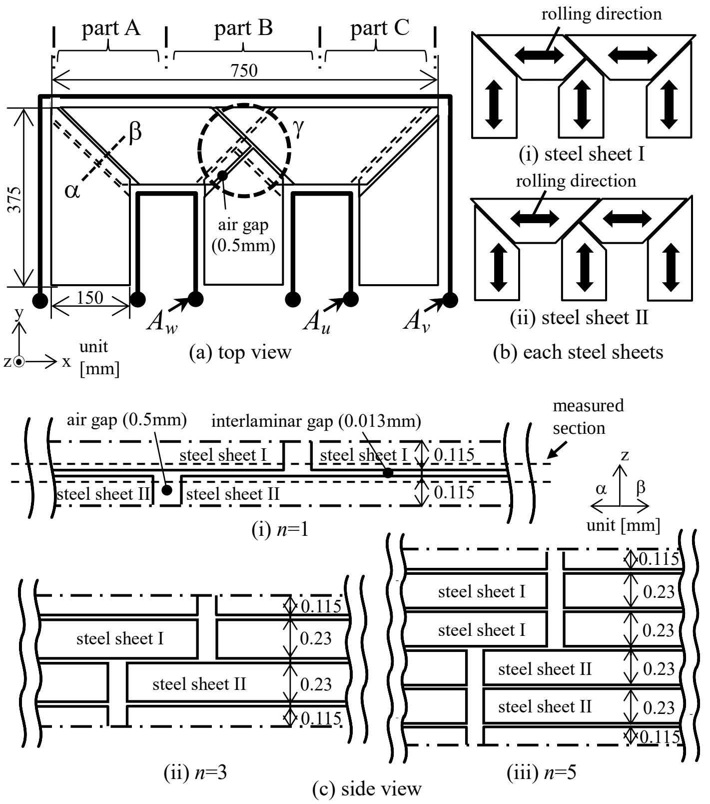
The eddy current loss is calculated by $\boldsymbol{J}_e$ in (1).

III. ANALYZED MODEL AND CONDITIONS

Fig. 2 shows the analyzed models of a three-phase transformer. In this paper, for the model simplification, triangular parts at the corners of the transformer are omitted as shown in Fig. 2(a). The steel sheets shown in Fig. 2(b) are laminated alternately. The area γ in Fig. 2(a) is used when discussing the analyzed result.

The Dirichlet boundary conditions A_u, A_v, and A_w are shown in Fig. 2(a) so that those give three-phase magnetic field.

Fig. 2(c) shows a cross section α-β shown in Fig. 2(a). Owing to the symmetry in the z-axial direction, the analyzed region is a part of the whole region. n in Fig. 2(c) is the number of the same steel sheets, which are laminated to the z-direction. For example, when n=1, the steel sheets I and II shown in Fig. 2(b) are laminated alternately one by one, and if n=3, those are laminated alternately by three.



(a) top view (b) each steel sheets (i) steel sheet I (ii) steel sheet II

(i) n=1 (ii) n=3 (iii) n=5 (c) side view

Fig. 2. Analyzed model of three-phase transformer.

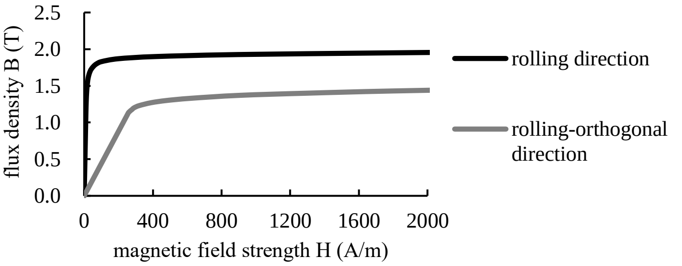


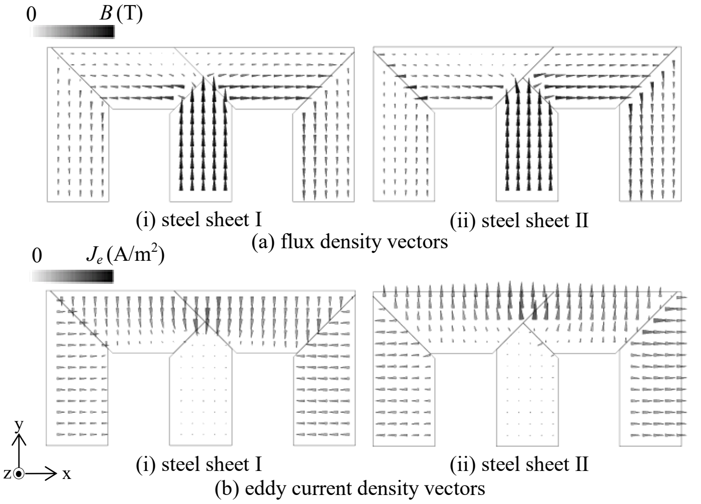
Fig. 3. B-H curve.

The magnetic nonlinearity of the laminated steel sheets, which has anisotropy, is taken into account using the B-H curve shown in Fig. 3. The analysis was conducted so that the maximum average flux density in the steel sheets was 1.7 T.

IV. RESULT AND DISCUSSION

Fig. 4 shows the distribution of flux and eddy current density vectors in the steel sheets I and II when n=1. We can see that there is no major difference between the distributions of flux density vectors in the steel sheets I and II. On the other hand, there is clear difference between distributions of eddy current density vectors in the steel sheets I and II. There are particular large eddy current density vectors at near the air gap in the area γ. Those vectors are generated by the flux through the interlaminer gap close to the air gap.

Fig. 5 shows the relationship of n and l_{we}, the analyzed model divided in parts A, B and C shown in Fig. 2(a). The length l_{we} of each part are defined as l_{weA}, l_{weB}, l_{weC} respectively. In all cases of n=1, 3, 5, the l_{weB} is the largest in length l_{we} of each part, and the l_{weA} is equal to the l_{weC}.



(i) steel sheet I (ii) steel sheet II
(a) flux density vectors
(i) steel sheet I (ii) steel sheet II
(b) eddy current density vectors

Fig. 4. Distributions of flux and eddy current density vectors (n=1, ωt=0°).

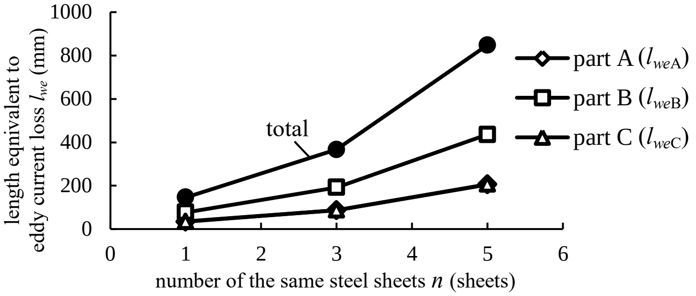


Fig. 5. Relationship of n and l_{we}.

TABLE I
DISCRETIZATION DATA AND ELAPSED TIME

Analyzed model	n=1	n=3	n=5
Number of elements	4,796,924	14,390,772	23,984,620
Number of nodes	2,635,464	7,467,148	12,298,832
Number of unknown variables	9,121,578	35,835,825	48,298,615
Elapsed time (hours)	89.1^{*1}	422.9^{*2}	850.3^{*2}

Computer used:^{*1}Intel Xeon 3.4GHz PC×16, ^{*2}Intel Xeon 3.5GHz PC×16

Therefore, the eddy currents are distributed concentrated in the joint of the area γ. The length l_{we} of total at n=3 and n=5 are about 2.5 and 5.8 times larger than that at n=1, respectively.

Table I shows the discretization data and the elapsed time.

V. CONCLUSION

In this paper, we analyzed a three-phase transformer made of grain-oriented electrical steel sheets by the 3-D parallel FEM, and clarified the flux and eddy current distributions of the transformer in detail. Consequently, the eddy current is distributed concentrated in the joint of the center of the model, and increase in the eddy current loss caused by joint part is get higher as the number of laminations of steel sheets.

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