Magnetic performance of step-lap joints in distribution transformer cores

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ABSTRACT

The magnetic characteristics of cores with step-lap joints are analyzed by using the finite element method taking into account eddy current and magnetic saturation. The effects of the following factors on the magnetic characteristics such as flux and eddy current distributions and magnetizing current are clarified quantitatively.

1)step-lap length
2)length of air gap at the joint
3)number of laminations per one stagger layer
4)flux density (magnetic saturation)

Obtained results give useful suggestions improving the design of the joints of transformer cores.

1. INTRODUCTION

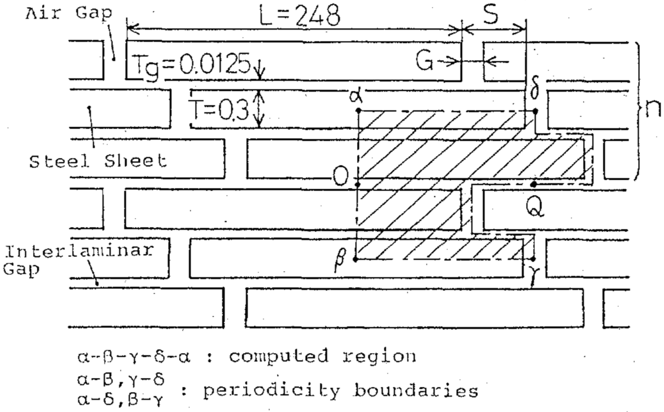
Recently, in Japan, step-lap joints were introduced for distribution transformer cores. This structure is superior to the conventional butt-lap joint with respect to the magnetic characteristics such as magnetizing current, core losses and sound level.

Little is known about magnetic characteristics such as the localized flux and eddy current distributions in step-lap jointed core. Ellis [1] compared total loss in various types of joints qualitatively. In this paper, the magnetic performances of the step-lap joints are evaluated quantitatively by using the finite element method taking into account the magnetic saturation and the eddy current which is generated by the flux crossing between plates.

2. ANALYSIS

Figure 1 shows an example of the section of analyzed stacking configurations. The two-dimensional finite element method is applied to the hatched region αβγδα. We need not analyze the whole region because of symmetry [2],[3]. The number of the so called gradϕ's [3] following eddy current problems is decreased considerably by introducing the periodicity conditions [4]. The boundary conditions [5],[6] are shown in Fig. 1.

As only a few conductors occupy almost the whole part of the analyzing region, the coefficient matrix becomes nearly full because of the gradϕ. A new technique by which the coefficient matrix is modified into a banded matrix with edges is developed [4].



α-β-γ-δ-α : computed region
α-β, γ-δ
α-δ, β-γ : periodicity boundaries

Fig. 1. Analyzed model of a laminated core (n=3).

By using these methods, the laminated core can be analyzed taking account of eddy current with little increase of the CPU time and the memory sizes. In Fig. 1, S, G and n denote the step-lap length, the air gap length and the number of laminations per one group, respectively. The distance Tg between the layers is chosen to be 0.0125 mm which is equivalent to 96 % of the space factor. The core is made of 0.3 mm thick grain oriented silicon steel (Grade:AISI-78 M-4).

The initial magnetization curve is used as the magnetization curve for non-linear calculation. In order to reduce the computing time, a newly developed method which is called the "time periodicity finite element method [7]" is used.

3. RESULTS AND DISCUSSIONS

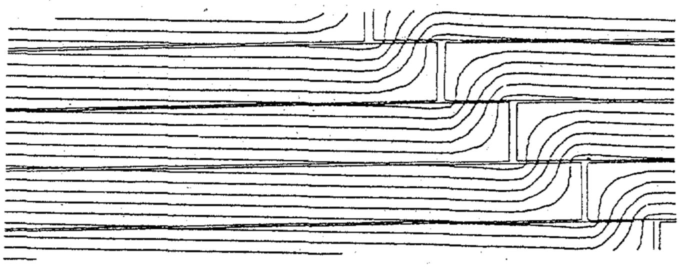
All the results shown in this section are obtained for 50 Hz .

Figure 2 shows the flux distribution for the infinite lamination (the number n of laminations per one group is infinite). The step-lap length S, the gap length G and the average flux density B are 11 mm, 1.0 mm and 1.0 T or 1.73 T respectively. The average flux density B is defined by the following equation.

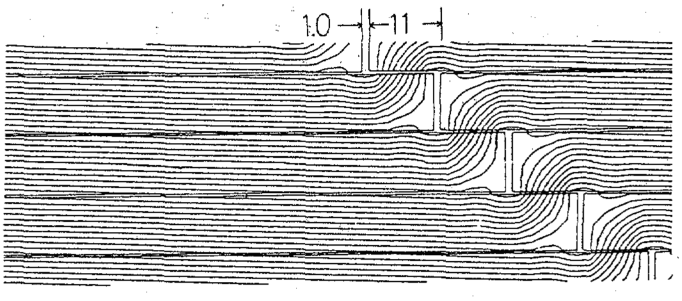
B=(the maximum value of the flux passing through the section far from the joint in one plate)/(the sectional area of the plate)

In the case when the notation B is used, the eddy current is neglected. If the eddy current is taken into account, the flux distribution is influenced by the wave form of applied voltage. In this paper, when the notation Bm is used instead of B, the eddy current is taken into account and the wave form of flux is sinusoidal.

Figure 2 shows the influence of magnetic saturation. There is little difference between Fig. 2(a) and (b).



(a) Low flux density (B=1.0T).



(b) High flux density (B=1.73T).

Fig. 2. Flux distributions ($S=11, G=1.0, n=\infty$).

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Figure 3 shows the influence of the number of laminations n per one group in the high flux density region. When the number is small, the parts facing the air gaps of the joint are saturated, and some of the fluxes pass through the air gap. However, when n is increased, the percentage of the flux passing through the gap is decreased.

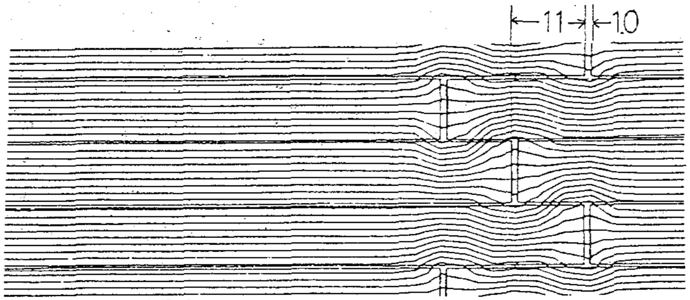
The equivalent magnetizing current length lh and the equivalent eddy current loss length lwe are defined by the following equations and are introduced for easy understanding of the measure of the increased magnetizing current and the eddy current loss.

lh=(magnetizing current with joints - magnetizing current without joint)/(magnetizing current per unit length without joint)

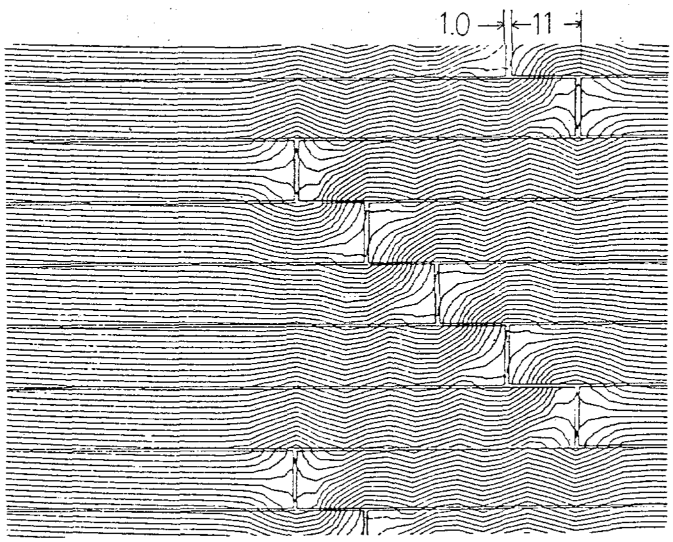
lwe=(eddy current loss with joints - eddy current loss without joint)/(eddy current loss per unit length without joint)

Figures 4 and 5 show the influence of the step length S on the equivalent current and loss lengths lh and lwe. When the flux density is low, both lh and lwe are decreased with the increase of the step-lap length S. However, when the flux density is high, and S is increased, lh is increased considerably, but lwe is increased toward saturation.

Figures 6 and 7 show the influence of the air gap length G on the equivalent current and loss lengths lh and lwe. When the flux density becomes higher, both lh and lwe are increased with the increase of the gap length G, but lwe is not increased so much. When the flux density is low, both lh and lwe are remarkably unchanged.



(a) n=3



(b) n=5

Fig. 3. Flux distributions (s=11,G=1.0,B=1.73T).

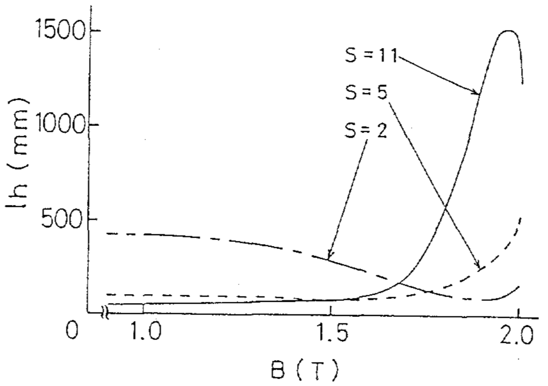


Fig. 4. Equivalent magnetizing current length (G=1.0,n=∞).

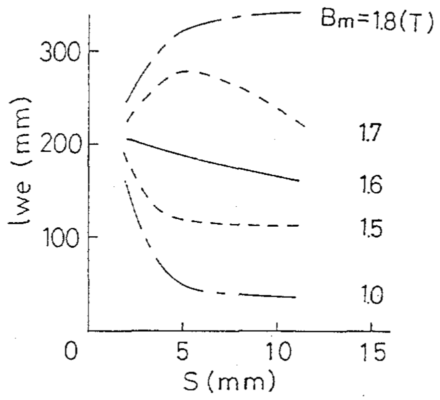


Fig. 5. Equivalent eddy current loss length (G=1.0,n=∞).

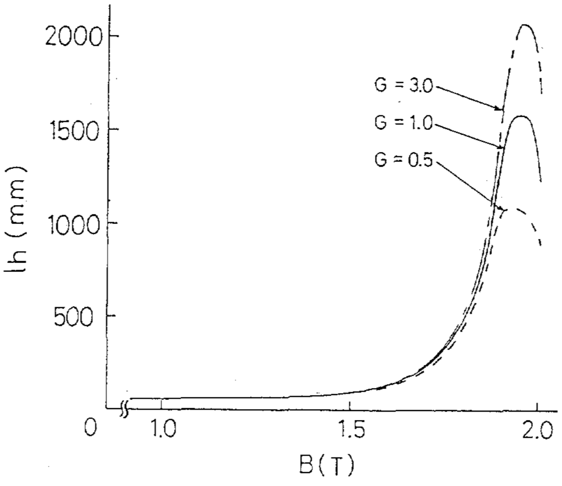


Fig. 6. Equivalent magnetizing current length (S=11,n=∞).

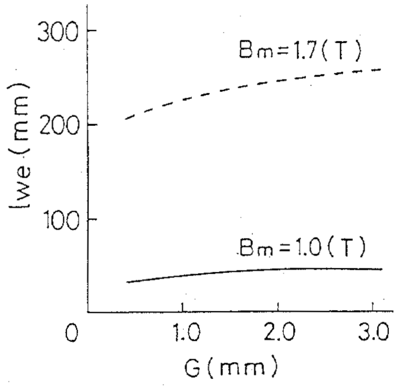


Fig. 7. Equivalent eddy current loss length (S=11,n=∞).

Figure 8 shows the influence of the number of laminations per one group n on lh. With the decrease of the number n, the maximum value of lh becomes larger and the corresponding flux density moves lower. When the flux density is low or extremely high, lh is nearly equal to zero. As the magnetic characteristics of the saturated silicon iron are nearly the same as those of the air gap, the joint has little influence on the magnetizing current of the core.

Figure 9 shows the influence of the number n on lwe. When n is increased, the eddy current loss is increased because of the increase of the normal flux. When the flux density Bm is increased, some of the fluxes pass through the air gap because of the saturation. Therefore the normal flux is not increased so much. Consequently lwe is decreased a little.

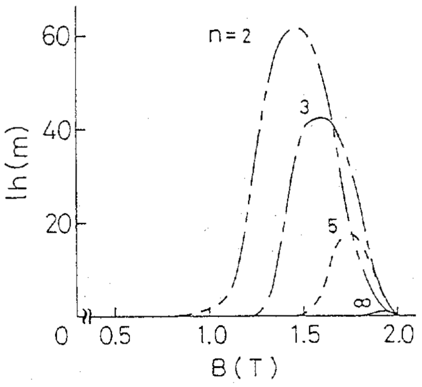


Fig. 8. Equivalent magnetizing current length (G=1.0,S=11).

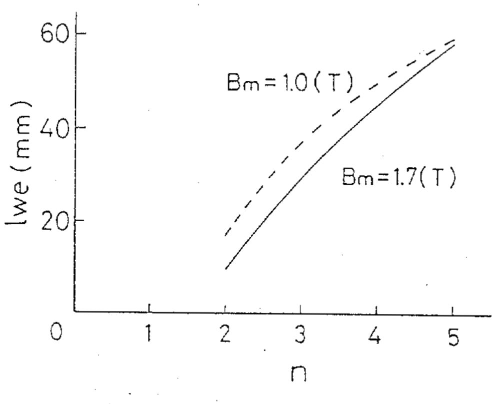


Fig. 9. Equivalent eddy current loss length (G=1.0,S=11).

4.CONCLUSIONS

The magnetic characteristics of the step-lap joints have been quantitatively analyzed taking into account the eddy current and magnetic non-linearity. The following techniques were especially powerful to reduce computing time: 1) use of the time periodicity finite element method, 2) effective use of periodicity boundary conditions, and 3) skillful use and management of the symmetry of gradϕ.

The obtained results can be summarized as follows

1) When the number of laminations per one group is increased, the exciting current is considerably decreased, but core losses are slightly increased.

2) If the number of laminations per one group is small, the effect of gap length on magnetic characteristics is significant.

3)In the lower flux density region, when the step-lap length is long, the core performance is improved as compared with the case when the length is short.

However, in the higher flux density region, the above mentioned behaviour is reversed.

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