Iron Loss Calculation of High Frequency Machine Including Excess loss

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In this paper, the modeling method of the stacked structure of iron cores combining a 3D solid core analysis with a 1D steel plate analysis is improved to include the excess loss. The main cause of excess loss, which is considered to be the domain wall bowing is considered in the 1D steel plate analysis because the iron loss along the thickness direction of the stack is dominant compared with that in the surface direction. In the 1D analysis, the eddy currents and the stack structure are taken into account, and the domain wall bowing is taken into account by introducing an initial bowing flux. The improved method is applied to the iron loss calculation of a simple single-phase reactor working under 500 Hz. The iron loss considering the excess loss shows around 15% increase.

***Index Terms*—Excess losses, high frequency machine, numerical analysis, silicon steel sheet.**

I. Introduction

HIGH FREQUENCY electric machines is used more and more extensively with the development of space industry and vehicle industry, etc. For the iron loss calculation of power frequency machines, the stacked structure of iron cores are normally neglected in magnetic field analysis because of the low proportion of eddy current loss in the iron loss. Whereas, it needs to be taken into account in high frequency machines because of the high proportion of eddy current loss in the iron loss. A modeling method of the stacked structure of iron cores combining a 3D solid core analysis with a 1D steel plate analysis has been proposed in [1] and proved to be effective in saving computation cost. Furthermore, it was applied to the iron loss calculation and reduction of a reactor under inverter power supply [2]. However, discrepancy exists between the calculation and measurement because the excess loss was not included in the calculation.

In this paper, the modeling method of the stacked structure of iron cores is improved to include the excess loss. The main cause of excess loss, which is considered to be the domain wall bowing [3], [4], is considered in the 1D steel plate analysis. In the 1D analysis, the eddy currents and the stack structure are taken into account, the domain wall bowing is taken into account by introducing an initial bowing flux [5]. The improved method is applied to the iron loss calculation of a simple single-phase reactor. The iron losses with and without excess loss are compared in detail.

II. Method of Loss Calculation

A. Method of magnetic field analysis

The stack of iron core is modeled combining a 3D solid core analysis with a 1D steel plate analysis as shown in Fig. 1. In this analysis, the flux density in each gauss point of the 3D solid one is applied to the 1D plate model as boundary condition. The equivalent permeability is obtained from the 1D model with computational homogenization approach similar to [7] and return to each element of the 3D analysis. The eddy currents within the sheet along the thickness direction of the stack is not considered in the 3D solid core analysis but in the 1D steel plate analysis, thus free from the subdivision within the sheet along the thickness direction of the stack and save computation cost.

1) 3D solid core analysis

The nonlinear 3D eddy current finite element analysis is applied to calculate the electromagnetic field distribution in the solid core model. The fundamental equations are:

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

$$\mathrm{div}\left\{-\sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \mathrm{grad}\,\phi\right)\right\} = 0 \tag{2}$$

where $\boldsymbol{A}$ and ϕ are the magnetic vector potential and the electrical scalar potential, respectively. $\boldsymbol{J_o}$ is the exiting current vector. ν and σ are permeability and conductivity, respectively.

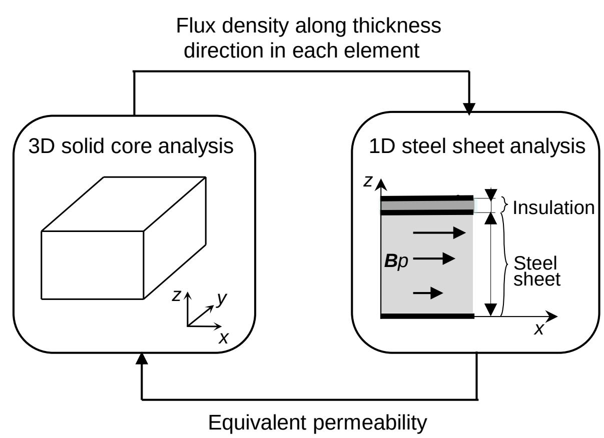

Fig. 1. Simple block diagram of the stack of iron core modeling method.

2) 1D steel plate analysis with domain wall bowing

The iron loss along the thickness direction of the stack is dominant compared with that in the surface direction, thus the domain wall bowing is only considered in the 1D analysis. To take into account the wall bowing, the 1D nonlinear eddy current finite element analysis is performed introducing an initial flux distribution $\boldsymbol{B}_p$ along the sheet thickness direction, which is assumed to represent the bowing generated by pinning effect. The fundamental equation is

$$-\frac{\partial}{\partial z}\left(\nu\left(\frac{\partial \boldsymbol{A}}{\partial z}-\boldsymbol{B}_p\right)\right)+\sigma\frac{\partial \boldsymbol{A}}{\partial t}=0 \qquad (3)$$

where $\boldsymbol{B}_p$ is the flux distribution along the sheet thickness in the analyzed model. $\boldsymbol{B}_p$ is assumed to take the shape of parabola, which follows the function of $\boldsymbol{B}_p^{(ie)} = az^2+b$, where $\boldsymbol{B}_p^{(ie)}$ is the flux density of each element *ie* and *z* is the coordinate of element center in the thickness direction. a and b are constants, which can be determined with certain domain wall bowing degree. The applied values of $\boldsymbol{B}_p$ are shown in Fig. 2.

The equivalent permeability in parallel direction of the plate is calculated using the field distribution obtained from the 1D analysis above including the effects of the stack structure, the eddy currents and the domain wall bowing along the thickness direction. That in thickness direction is calculated using the length and permeability of the 1D analysis above. The equations are the same as in [2].

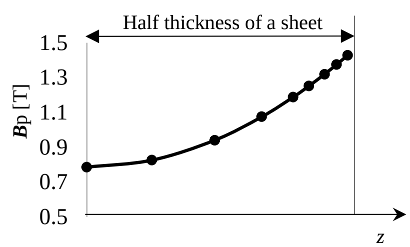

Fig. 2. The applied initial bowing flux in the 1D steel sheet analysis.

B. Method of loss calculation

The iron loss is calculated using the flux density and eddy current density obtained from the eddy current FEA directly. The equation is as the following with two terms: the hysteresis loss W_h and the eddy current loss W_e [6].

$$W_i = W_h + W_e$$
$$= \sum_{i=1}^{Ne}\left\{K_{h,B_{max}}^{(i)} f + \left(\sum_{j=1}^{Ns}\frac{Je^{(i,j)2}}{\sigma}\right)\Big/ Ns\right\}V^{(i)} \qquad (4)$$

where *Ne* is the total element number, $K_{h,Bmax}$ is the hysteresis coefficients varying with the amplitude of the flux density B_{max} in each element, which is obtained by using the iron-loss characteristics of the steel plate with *f* of 50 Hz and 60 Hz in the catalogue data, *Ns* is the total time step, *Je* is the eddy current density, σ is the conductivity of the sheet and *V* is the volume of each element in the 3D analysis and length of each element in the 1D analysis.

III. ANALYSIS OF A SIMPLE ONE-PHASE REACTOR

A. Analyzed model and conditions

The analyzed simple single-phase reactor constructed by stacked iron cores and coil is shown in Fig. 3. Only1/8 of the whole region is analyzed due to symmetry. The cores with gaps are stacked by steel sheets (thickness 0.35 mm) in the *z* direction, and the space factor *F* is 0.95. The current with a frequency of 500 Hz is imposed inside the coil so that the average flux density in the cross section of the stack is around 0.5T.

B. Losses

The classified iron losses with and without the excess loss of the reactor is shown in Fig. 4. Both the hysteresis loss and the eddy current loss are increased by considering the excess loss and the total iron loss with the excess loss shows about 15 % increase compared with the one without. More detail about the method and comparison with measurement will be reported in the full paper.

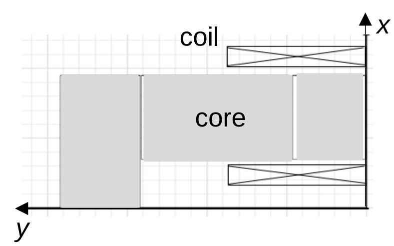

Fig. 3. The analyzed simple sing-phase reactor.

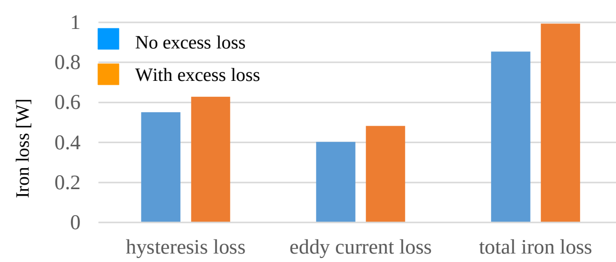

Fig. 4. Comparison of losses with and without the excess loss in detail.

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