The influence of non-local eddy currents and saturation on field distribution and iron losses in electrical steel lamination

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Abstract

This paper presents the influence of non-local eddy currents and magnetic material saturation on field distribution and iron losses in electrical steel lamination. Assuming a non-conductive and non-dissipative soft magnetic material in numerical models in combination with the description of the magnetic material by a reversible magnetization curve yields the entire neglection of the iron losses in the field model. Because of the effects of eddy currents and non-linear material behavior on the flux distribution in the lamination depth, the iron losses show a dependence on eddy currents, e.g. on the frequency, and the magnetic material characteristic. Utilizing a one-dimensional eddy current model of half the sheet thickness of the lamination, the relation between the local magnetic flux density and the magnetic field strength is studied in detail.

Advanced iron-loss modeling

The common iron-loss models such as the empirical Steinmetz-Model or the physically based Bertotti-Model are sufficiently accurate for low magneic flux densities and frequencies. However, it was realized that the behavior at large fields ($B > 1.2\mathrm{T}$) is poorly represented by the Bertotti formula. Therefore the Bertotti formula is extended with an additional term containing two new parameters to

$$P = a_1 B^2 f + a_2 B^2 f^2 \left(1 + a_3 B^{a_4}\right) + a_5 B^{1.5} f^{1.5} \tag{1}$$

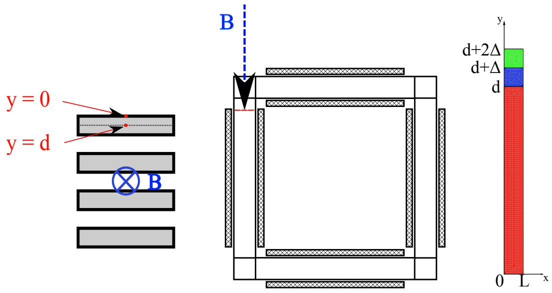
with the magnetizing frequency $f\,[\mathrm{Hz}]$, the constant parameters a_i and the magnetic flux density $B\,[\mathrm{T}]$. The quadratic in frequency character qualifies it is an eddy current term.
Assuming a linear material behavior eddy current losses with consideration of the skin effect are given by:

$$a_2 B^2 f^2 \cdot F_{skin}(\lambda), \tag{2}$$

with $\lambda = \frac{d}{\delta}$ and $\delta = \sqrt{\frac{\rho e}{\pi \cdot f \cdot \mu}}$, where d is the thickness, ρ_e the electrical resistivity and $F_{skin}(\lambda)$ the skin effect correction factor.
Bertotti's formula assumes $F_{skin}(\lambda) \approx 1$, which means that $d << \delta$ for all frequencies. This is certainly the assumption that is not fulfilled for high frequencies. At high magnetic flux densities and high frequencies, eddy current losses can be majored by about 10 percent due to material saturation. The skin effect correction is very inaccurate when material saturation cannot be neglected.

One-dimensional eddy current model

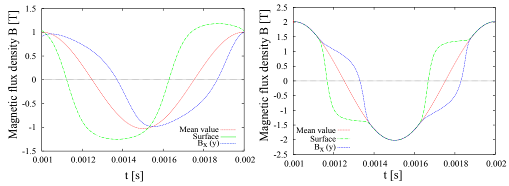
With a one-dimensional model of half the plate thickness, the relationship between the externally applied magnetic field at the surface $H_{surface}(t)$ and the internal magnetic field $H_{material}(t)$ is more precisely studied taking the influence of macroscopic eddy currents into account. This then results in an averaged field $H_{mean}(t)$ as a post-processing value.



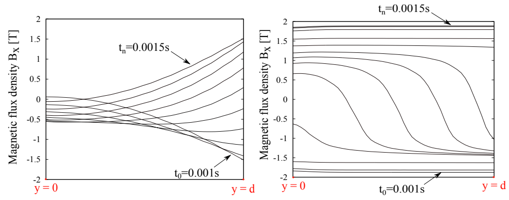
The red region with $\sigma_l \neq 0$ represents the magnetic material, where d is half the plate thickness and $L \equiv d/10$. The green region with $\mu = \mu_0$ is a region with imposed current density. The boundary conditions are as follows: $A_z = 0$ on $y = 0$ and $y = d + 2\Delta$ and $H_t = 0$ on $x = 0$ and $x = L$. The behavior of the internal and averaged magnetic flux density is investigated, which is calculated using different single-valued curves.

Field distribution inside the lamination

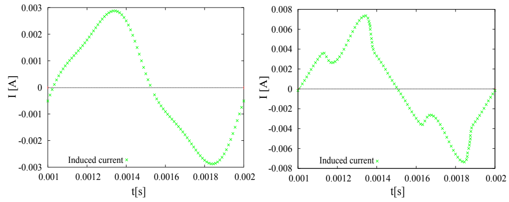
In the following, the distribution of the magnetic fields and the generation of non-local eddy currents in the sheet thickness, neglecting the variation of the magnetic field H in the plane are analyzed. For linear material behavior, i.e. μ_l = constant, the variation of the magnetic flux density of the material is assumed being sinusoidal. In this case the analytical solution (2) is valid. The field distribution and the non-local eddy currents are studied for a non-linear material magnetization behavior using an anhysteretic magnetization curve of the exemplarily chosen non-grainoriented electrical steel grade M270-35A. The excitation frequency is $f = 1000\mathrm{Hz}$ leading to a skin depth of $\delta = 0.1\mathrm{mm}$. The sinusoidal current in the coil excites a sinusoidal magnetic field at the surface of the lamination. It follows that the mean value of the flux density is also sinusoidal and the lamination responds identically.



Even at $1\mathrm{T}$, the material saturation significantly influences and varies the dynamics of the magnetic fields. In this case the linear analytical solution (2) loses its validity.
The following figures represent the magnetic flux density field lines across the lamination at different instants of time for the linear and the non-linear magnetization characteristic. The classical skin effect is clearly recognized for the linear material. In contrast to this using a nonlinear material characteristic it is realized that in case of a saturated material the skin effect disappears ($B_{surface} = B_x(y)$) and a saturation front moves through the material.



The propagating saturation front increases the inductance of the lamination sensibly as the front travels through the material. The currents induced in the material contain for those high flux densities a significant amount of harmonics. This leads to significantly larger losses and the inapplicability of the assumption of a hyperbolic eddy current distribution in the material.



Conclusion

The utilization of the 1D cross lamination model enables the nearly exact determination of the field distribution in steel laminations and improves the iron-loss calculation by considering the influence of eddy currents. The analytical solution of the linear 1D problem rapidly ceases to be accurate when the thickness of the lamination decreases and the frequency increases. In combination with a dynamic vector-hysteresis model a tightly coupled transient problem is obtained that can enable nearly the exact determination of the magnetic fields and losses under the special conditions of an Epstein frame or single sheet tester. Therewith, the initial mentioned shortcoming will be reversed.

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