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Simplified Lamination Models for Ferromagnetic Cores

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Modeling of iron losses in electromagnetic devices containing laminated cores is still an open problem nowadays. This complex problem is of critical importance for the design of electrical machines in order to improve the machine efficiency and power density utilizing the available magnetic material properties at best, especially in modern PWM driven devices.

Iron losses in soft magnetic materials are the result of the intricate coupling of macro- and microscopic eddy currents and static hysteresis [1]. Resolving small scale interactions between eddy currents and hysteresis requires a proper modelling at the level of individual laminations solving the diffusion equation by a numerical iterative time-stepping procedure. However, direct incorporation of the 1-D diffusion equation into 2-D finite element analysis of electrical machines is rather technical and makes it necessary to modify significantly the finite element code.

Substantial simplification of the problem, while keeping sufficiently accurate solution, can be achieved by using several versions of the thin sheet model (TSM) [2, 3]. TSM models link the magnetic field at the sheet surface $H(t)$ and the mean magnetic flux density $B(t)$ over its cross section. $H(t)$ contains separate components related to the hysteretic field, classical eddy current field and excess field: $H = H_{\mathrm{hyst}} + H_{\mathrm{clas}} + H_{\mathrm{exc.}}$.

As an alternative to TSM models also the saturation wave model (SWM) can be applied, which improves the classical eddy current loss description. This model modifies the classical eddy current loss component in a magnetically linear medium in order to account for the discussed coupling of eddy currents and magnetic saturation affecting the usual skin effect. The SWM assumes a ferromagnetic material characterized by a step-like magnetization curve with maximum value $\mathrm{B}_{\mathrm{max}}$ to reproduce the layer-to-layer nature of the flux reversal.

In this paper various versions of simplified, homogenized lamination models will be compared to the solution of the 1-D diffusion equation using the parametric magneto-dynamic model (PMD) and measured data as well [5]. The hysteresis component is modeled by means of a static hysteresis model. Measured data of a non-oriented electrical steel sheet obtained under sinusoidal and non-sinusoidal, PWM-like, excitations serve for validation purposes. In this way, the ability of the simplified, homogenized models to reproduce the dynamic hysteresis loop shapes and iron losses at complex waveforms will be studied for both voltage and current driven excitation cases.

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