Adaptation and Parametrization of an Iron Loss Model for Rotating Magnetization Loci in NO electrical steel

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Abstract – The characterization of electrical steel is typically done by measurements under the condition of unidirectional sinusoidal flux linkages. A variety of iron loss models were developed and parametrized for this unidirectional iron loss measurements. In the magnetic cross section of rotating electrical machines, the spatial magnetic flux density loci and with them the resulting iron losses strongly vary from these unidirectional cases. In this paper, an iron loss model considering the spatial magnetization course is presented and validated with measurements of circular and elliptically magnetizations.

I. INTRODUCTION

The appropriate calculation of the resulting iron loss distribution in the postprocessing of the numerical simulation of electrical machines is crucial for the design and development of electrical drives. Standardized iron loss measurements are primarily performed under sinusoidal unidirectional waveforms of the magnetic flux density at different flux densities $B_m$ and magnetization frequencies $f$. The measurements performed under these conditions only recreate the actual course of the magnetic flux density and the resulting losses in the magnetic circuit of rotating electrical machines to a very limited extent.

Rotational single sheet testers (RSST) were developed to characterize the resulting iron losses under the influence of rotating magnetization [2,3]. These magnetic sensors allow the vector-characterization of the material under the influence of varying locus curves in the sheet metal plane. The iron losses measured under these conditions differ from the material behaviour measured under one-dimensional conditions and cannot be mapped with sufficient accuracy using conventional iron loss models which were formulated and parameterized on the basis of one-dimensional measurements [1].

In this paper an unidirectional iron loss formulation based on a loss separation approach is expanded and parametrized to recreate the iron loss behaviour under the influence of rotational magnetizations.

II. ROTATIONAL IRON LOSS MEASUREMENT

The waveform of the locus of the magnetic flux density is determined by the maximum excitation $B_m$, the axis ratio $F_{Ax}$, and the angle $\theta$ between the main axis of the ellipsoid and the rolling direction (RD) as depicted in Fig. 1.

The special cases of the loci of unidirectional ($F_{Ax} = 0$) and circular courses of the magnetic flux density ($F_{Ax} = 1$) are of particular importance for the characterization of the iron loss behavior. Nonetheless, during the operation of rotating electrical machines, a variety of combinations of elliptic shapes and inclination angles occurs depending, on the respective operation point and location on the magnetic cross section of the machine. Thus, the transition between unidirectional and rotational magnetization must be considered in the magnetic characterization of the material as in the simulation of the iron loss components.

The rotational iron loss measurements depicted in Fig. 2 were performed clock- and counter-clockwise at 50, 100, 200, 400 and 800 Hz for five axis ratios $F_{Ax}$ with the main axis in parallel to the RD with a peak flux density up to 1.5 T. The sample material is a fully processed non-oriented (NO) electrical steel with a thickness of 0.24 mm. The measurements show the typical increase of the iron losses to more than double in the magnetization range of up to 1.0 T for circular rotating flux density loci ($F_{Ax} = 1.0$) in comparison to unidirectional magnetization ($F_{Ax} = 0$). The behavior in the transition is nonlinear and magnetization-dependent with regard to the losses as a function of the axis ratio. The decrease of losses in the case of circular magnetization is indicated between 1.3 and 1.5 T.

Fig.1. Different magnetic flux density loci for a) unidirectional ($F_{Ax} = 0$), b) elliptical ($F_{Ax} = 0.5$) magnetization with the angle $\theta$ between main axis and RD and circular magnetization ($F_{Ax} = 1.0$) in c) [2].

Fig.2. Measured iron losses at different axis ratios $F_{Ax}$ performed at a magnetization frequency of 200 Hz with main axis in RD.
III. IRON LOSS MODEL APPROACH

The iron loss model proposed in this work is an adaptation of the IEM iron loss separation approach presented in [4]. In addition to the previously considered hysteresis-, classical- and excess-loss component the presented model is expanded by the saturation loss component $P_{\text{sat}}$. The components $P_{\text{cl}}$ and $P_{\text{sat}}$ are not influenced by the respective locus and are calculated from the vectorial decomposition of the flux density in $B_{\text{max}}$ and $B_{\text{min}}$.

$$P_{\text{fe}} = P_{\text{hyst}} + P_{\text{cl}} + P_{\text{exc}} + P_{\text{sat}}$$

(1)

with:

$$P_{\text{hyst}} = (1 - F_{\text{Ax}}^2 \cdot r_{\text{hyst}}) B_{\text{m}}^{a+2} \cdot a_1 + F_{\text{Ax}}^{a+2} \cdot a_{1.90'} \cdot f$$

(2)

$$P_{\text{cl}} = a_2 \cdot B_{\text{m}}^{a+2} \cdot (1 + F_{\text{Ax}}^2) \cdot f^2$$

(3)

$$P_{\text{exc}} = (1 - F_{\text{Ax}}^2 \cdot r_{\text{exc}}) \cdot B_{\text{m}}^{a+2} \cdot (a_3 + F_{\text{Ax}}^{a+2} \cdot a_{5.90'}) \cdot f^{1.5}$$

(4)

$$P_{\text{sat}} = a_2 \cdot a_3 \cdot B_{\text{m}}^{a+2} \cdot (1 + F_{\text{Ax}}^{a+2}) \cdot f^2$$

(5)

The complicated behavior of the hysteresis and excess loss components with regard to the peak magnetization and the locus curve of the magnetic flux density is considered by the squared axis ratio and the additional factor $r_{\text{hyst}}$ respective $r_{\text{exc}}$. Although both loss mechanisms are based on domain wall movements, the dependencies to peak magnetization and axis ratio differs as presented in [3]. Since a distinction between these two influences can only be performed by quasi-static measurements, for the time being both components are set to:

$$r_{\text{hyst,exc}} = B_{\text{m}} \cdot \frac{P_{\text{fe}}(B_{\text{m}})}{B_{\text{e}} \cdot P_{\text{Fe,1ST}}}$$

(6)

The model parameters identified by unidirectional measurements are:

$$a_1 = 0.010845, \quad a_2 = 2.1355 \times 10^{-05}, \quad a_3 = 0.0058372, \quad a_4 = 7.8138, \quad a_5 = 0.0002$$

$$a_{1.90'} = 1.5235, \quad a_{5.90'} = 0.56487, \quad \alpha = 0.012028, \quad \beta = 0.0003$$

The simulation results depicted in Fig. 3 show the differences in the behavior of the individual loss components with unidirectional and rotating magnetization. The typical decrease in components $P_{\text{hyst}}$ and $P_{\text{exc}}$ for rotational magnetization can also be seen. In Fig. 4 the good agreement between measurement and simulation across the entire scope of $F_{\text{Ax}}$, $B_{\text{m}}$ and magnetization frequency can be seen. The rotational iron loss formulation will be applied to further NO-electrical steels and different spatial angles of the main axis will be considered and studied in more detail as well as in the application in the FE simulation of electrical machines [5].

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