Measuring Magnetic Properties in Stack Structures of Non-grain Oriented Electrical Steel Laminations

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***Abstract*—The construction of electrical machines requires thin laminations shaped from electrical steel sheets. Rotating electrical machines specifically use non-grain oriented electrical steels, because they have a lower magnetic anisotropy than grain oriented steels. Electrical steels with low anisotropy are more suitable for the rotating magnetic flux patterns that are usually found in rotating electrical machines. However, when evaluating the directional dependency of the magnetic properties of non-grain oriented steels, a preferential magnetization direction can be observed which is known as the rolling direction. This paper investigates the effects on the magnetic properties of stacking the adjacent laminations in perpendicular rolling directions as opposed to stacking the laminations with parallel rolling directions. Measurements on realistic stator geometries indicate that the stacking technique has a significant impact on the magnetic properties of the stack. This effect is modelled using a simplified magnetic equivalent circuit model and the simulations support the measurements.**

I. Introduction

Electrical steel sheets are processed to achieve their desired thickness using rolling operations. The microstructure, crystallographic texture and magnetic properties of the final sheets are, to a large extent, determined by the rolling operations and the subsequent heat treatments [1]. In [5], it is stated that favourable crystallographic properties in the rolling direction (RD) of these materials make them ideal for power transformers and large rotating electrical machines, however the properties along the directions other than RD are needed for more realistic field computation at joints/teeth regions. The rolling direction is the preferential direction of magnetization in non-grain oriented electrical steel sheets, indicating that the material has a higher relative magnetic permeability in RD than in the perpendicular transverse direction (TD). When stacking the laminations parallel to their RD, the stack as a whole has a preferential magnetization direction corresponding with the RD of the individual laminations. Stacking adjacent laminations perpendicular results in a stack without preferential magnetization direction. Using an experimental setup, the differences between these two stacking approaches are investigated on a set of punched stator laminations. The experiment is repeated twice; the first set of laminations is only punched, the second set of laminations has received a heat treatment to decrease the degradation caused by the punching process. This heat treatment is known as stress relief annealing (SRA). Applying SRA decreases the core losses caused by internal residual stress.

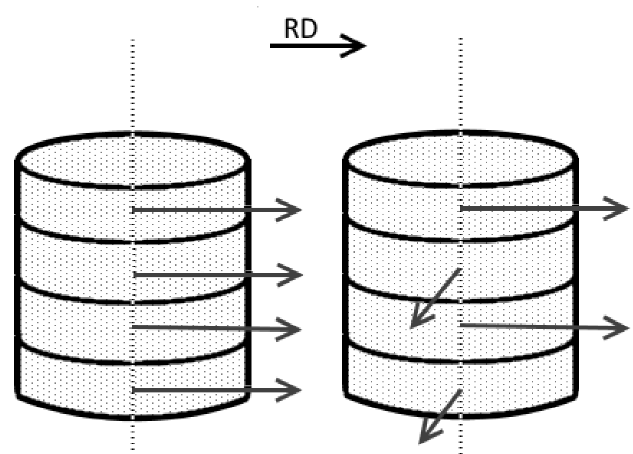

Fig. 1: left: Parallel stacking technique and right: perpendicular stacking technique

II. Methods

A. Instrumentation and Measurement Setup

The studied stator geometries consist of 4 stacks, each containing 10 punched stator laminations. SRA is applied to 2 stacks, while 2 received no SRA. In 2 stacks, the stacking is done perpendicular to the RD for adjacent laminations. In the other 2 stacks, the RD of the individual laminations are all parallel (see Fig.1). A MATLAB-based magnetic measuring setup with a National Instruments data acquisition card was used to perform the measurements. Characterizing the properties of soft magnetic materials can be done by means of global magnetic measurements. The classical two windings technique is applied, as described in [2].

B. Rolling Direction versus Transverse Direction

Epstein frame measurements were obtained from thin strips of M270-35A electrical steel in rolling direction and perpendicular transverse direction. The strips are sheared and did not

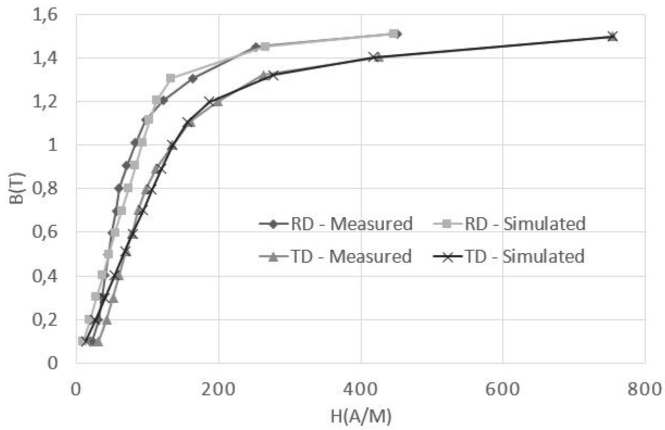

Fig. 2: Characterisation of measured and simulated data for single-valued BH-pairs using M270-35A Epstein strips in rolling direction (RD) and transverse direction (TD).

undergo SRA. M270-35A is a non-grain oriented grade, but by cutting and measuring the strips in both directions (TD and RD), some significant differences in the magnetic properties can be observed (see Fig. 2). From the measurements, it is clear that for a given value for the magnetic field, the magnetic flux density is higher in RD than in TD. The single-valued non-linear constitutive relation displayed in Fig. 2 can be modelled using three parameters B_0, H_0, and ν, following equation 1 [2]. The data obtained from the epstein measurements is fitted and the results are depicted in Fig.2. The magnetic properties of M270-35A in rolling directions can be characterized with the identified material parameters $B_0 = 1.45$, $H_0 = 132.9$, and $\nu = 21.4$. In transverse direction, these parameters are identified as; $B_0 = 1.38$, $H_0 = 183.4$, and $\nu = 13.6$. These fitted data are used in the construction of two magnetic equivalent circuit (MEC) models, which are related to the different stack structures.

$$\left(\frac{H}{H_0}\right) = \left(\frac{B}{B_0}\right) + \left(\frac{B}{B_0}\right)^{\nu} \tag{1}$$

C. Stack Structures

The two stacking techniques are applied to laminations of a stator geometry (see Fig. 4). One stack has its laminations oriented with parallel rolling direction, while the other one has its adjacent laminations oriented perpendicularly (see Fig.1). All stacks are equipped with an excitation coil (n=120) around the stator yoke. On 8 locations along the stator yoke, search coils (n=10) are applied to measure the magnetic flux (see Fig. 4). Using the magnetic measuring setup, the magnetic field generated by the excitation coil was controlled to achieve a sinusoidal flux density with an amplitude of 1T in each measuring coil. The amplitude of the magnetic field relates to the magnetic permeability of the magnetic material on this location on the stack.

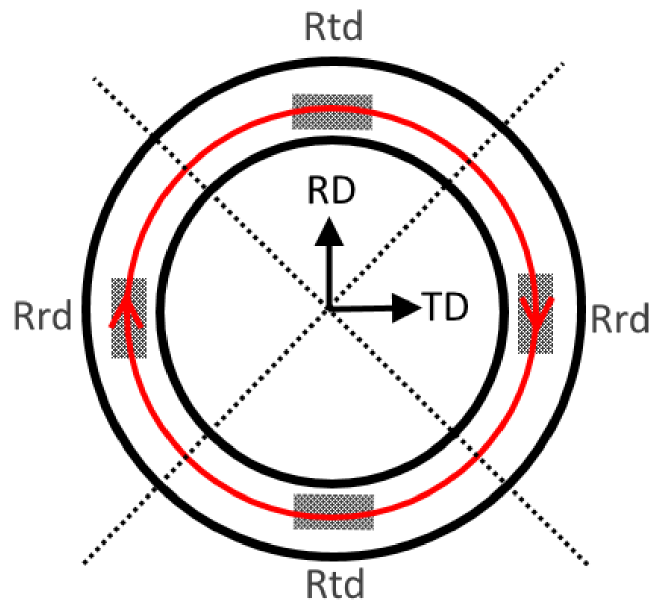

Fig. 3: Simplification for MEC model construction of a ring core sample using 4 magnetic reluctances in series

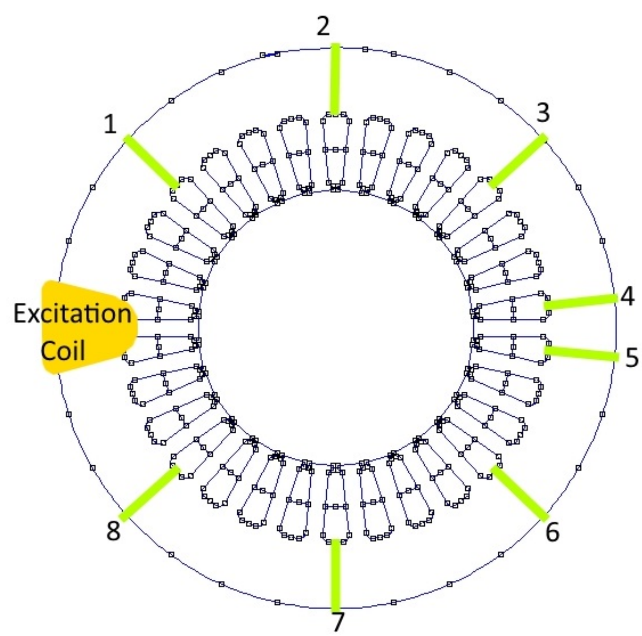

Fig. 4: Stator lamination measurement setup with 1 excitation coil and measuring coils on 8 different positions around the stator yoke

III. Model

A. Assumptions for building the MEC models

Some reasonable assumptions are made to simplify the MEC model building. First, the stator measurement setup with excitation coil around the yoke is assumed to be equivalent to a ring core sample with corresponding inner and outer diameter. Secondly, because the magnetic flux propagates through the ring core equidistantly in RD and in TD, the ring core sample can be modelled with 4 magnetic reluctances with equal magnetic path length, equal cross section but different magnetic permeabilities related to the direction of the reluctance (see Fig. 3). The different permeabilities for RD and TD result from the measurements and simulations in Fig.2. Finally, it is assumed that in the parallel stack, there are no interlaminar magnetic fluxes, while for the perpendicular stack, the magnetic flux can propagate through the insulation between adjacent laminations.

B. Building the MEC Models

The Magnetic Equivalent Circuit method is a numerical method for the analysis of nonlinear magnetic fields in electromagnetic devices [8]. Using the assumptions from the previous section, two different MEC models are proposed that capture the different magnetic behaviour for parallel and perpendicular stacks. The parallel MEC is very simple, and similar to the simplification made in Fig.3. In this model, the total magnetic path length is 0.377m and the magnetic cross section for each reluctance is calculated from the width of the stator yoke (23mm), the lamination thickness (0.35mm) and the number of laminations (10). For the perpendicular stack, the MEC model is more complex; the magnetic flux propagates through two parallel reluctances, either in RD (R_{rd}) or in TD (R_{td}). After each section, the flux can travel through the insulation (R_i). This R_i reluctance has a relative permeability of 1, a magnetic cross section width equal to the width of the yoke (23mm) and a magnetic path length equal to the thickness of the isolation layer between two laminations (0.013mm). In this configuration, the magnetic flux can propagate through the ring core via the more favourable (R_{rd})-reluctances, however the (R_i)-reluctances significantly increase the total reluctance of this flux path. The MEC models for parallel stacking and perpendicular stacking are displayed in Fig. 5.

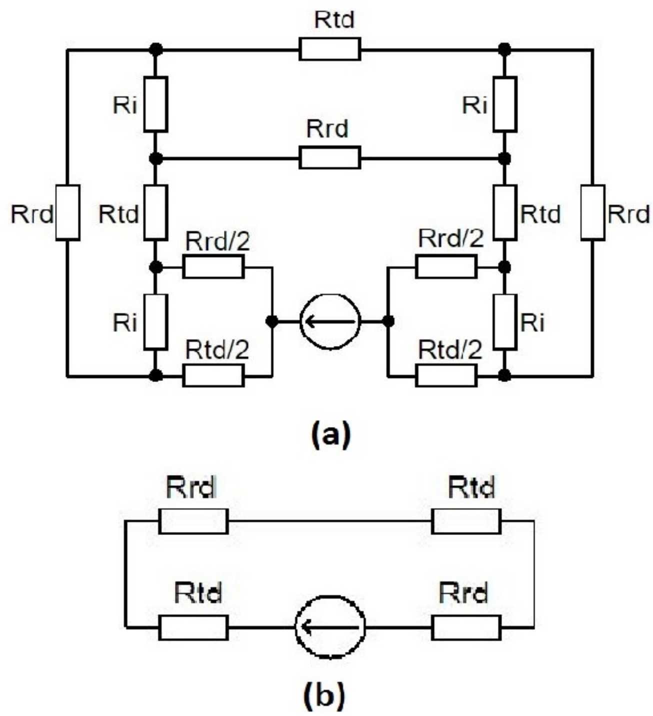

Fig. 5: (a) MEC model for perpendiculary stacked laminations and (b) MEC model for parallel stack laminations

IV. Results and Discussion

A. Measurement Results

Figure 6 shows the results of the global magnetic measurements. Two stacks are processed with SRA, two have not. Two stacks have been stacked perpendicularly, the other two are in parallel. In each of the 4 stacks, the required magnetic field is highest for the positions furthest away from the excitation coil. This due to the leakage flux. To measure a sinusoidal flux density with amplitude 1T, the magnetic field generated by the excitation coil needs to be significantly higher because a bigger portion of the magnetic flux closes via the air. The measurements confirm the positive effect of the SRA, because for both the parallel and perpendicular stacks, the required magnetic field decreases significantly. In both cases, with and without SRA, the required magnetic field decreases when the stacking is done perpendicular. The average decrease in magnetic field is 2% for stacks without SRA, and 5% for stacks with SRA.

B. MEC Results

The measurements on the stator stacks are confirmed by the MEC models. The top graph in Fig. 7 displays the simulated flux density B as a function of the input current I for both MEC models. Because the difference is quiet small, the graph below shows the difference between the two MEC models more clearly, as the bottom graph displays the difference in magnetic permeability $\Delta\mu$ for both MEC models. The $\Delta\mu$ is 0.035 for input current 0.1A, implying that for the perpendicular stacking model the magnetic permeability is 3.5% higher than for the parallel stacking model. At input current level 0.4A, the flux density is approximately 1T, and the difference in permeability equals $\pm$ 2%. This corresponds very well to the measurements displayed in Fig.6, because the difference in magnetic permeability to obtain a 1T flux density is also 2% on average over the 8 measured positions. From the MEC simulations, it is clear that the difference in stack permeability decreases for higher input currents.

V. Conclusion

The measurement results show that when laminations are stacked perpendicularly with respect to the rolling direc-

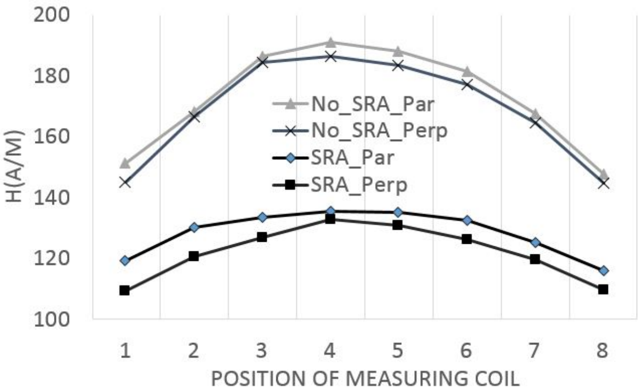

Fig. 6: Measurements on 4 different stacks and 8 different positions around the stator yoke of the amplitude of the magnetic field strength required to obtain a flux density amplitude of 1T.

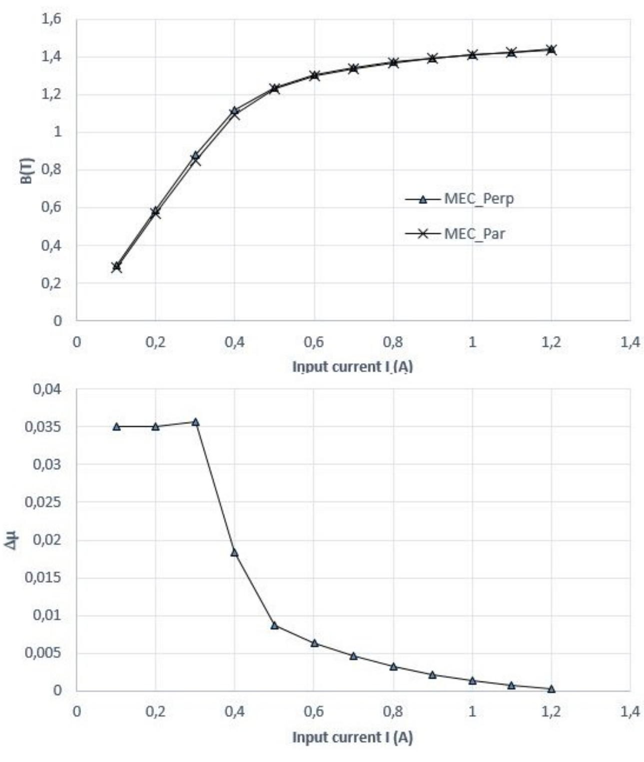

Fig. 7: Results of the MEC model simulations. Top; Flux density as a function of excitation current. Bottom; percentage deviation of the magnetic permeability between MEC model 1 and 2

tion, the permeability of the stack is higher than when the laminations are stacked parallel. The MEC models support the measurements and show that the perpendicularly stacked laminations require a smaller magnetic field to achieve a flux density of 1T, thus having a higher magnetic permeability. However, the simulations show that the difference between the two stacking techniques decreases for higher flux densities.

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