Modeling of scalar dependencies of soft magnetic material magnetization for electrical machine finite element simulation

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The magnetization behavior and thus, the form of the magnetization curve of an electrical steel strongly depends on the direction of the magnetic field, frequency of excitation, external mechanical stress and cut edge effect. These factors influence the performance of electrical machines and need to be considered in advanced machine contemplation, e.g. design processes or numerical modeling. Most of the before mentioned effects occur locally in the machine, and therefore need to be described locally. It is crucial to characterize the material under realistic conditions for adequate identification and quantification of the influences. In this paper, modeling and simulation of soft magnetic material is performed based on a detailed magnetic characterization, considering magnetization amplitude, angle in respect to rolling direction of magnetization, mechanical stress and cut edge effect. The dependent soft magnetic material characteristics are derived from the magnetic measurement data and concluded into interpolation surfaces. Subsequently, these surfaces are used to simulate a synchronous machine designed for a traction drive of an electric vehicle by finite element simulation. One of the main challenges is the correct determination of the local material properties, depending on the operating point, which influence global quantities, such as losses and torque. This paper provides a methodology to consider different local influences on the magnetization behavior of electrical steel in a finite element simulation, thus offering potential for improving electromagnetic circuit design.

***Index Terms*—Soft magnetic material, material properties, electromagnetic measurements, electromagnetic modeling, finite element analysis.**

I. Introduction

THE designs of wide-range applicable electrical machines require accurate knowledge of the soft magnetic material properties. The production process of non-oriented (NO) electrical steel sheets leads to an anisotropy of magnetic properties. Crystallographic texture and residual stress from the rolling process are sources of the anisotropy [1]. As a result, even NO materials possess a preferred direction of magnetization [2], i.e., resulting magnetic polarization for a distinct magnetic field depends on the direction of excitation. The processing from electrical steel sheets to motor laminations, for example by shear cutting, induces plastic deformation as well as residual stress in the materials, which leads to the so-called cut edge effect. The effect describes the decrease of permeability in the vicinity of the cut edge which essentially decreases the magnetizability [3], [4]. Motor laminations are then stacked, packaged and fit into a housing to form the magnetic core. Furthermore, a high mechanical centrifugal force during operation of the machines lead to additional mechanical stress contributions. All of the mentioned production and processing influences alter the magnetization behavior of NOs, mainly due to the mechanical stress [5]. Hence, using regular magnetization curves obtained from unprocessed sheet material in finite-element (FE)-simulations will lead to inaccurate results. Although, there is usually a compensation in the post processing by calculating the iron losses. In this paper, a material simulation model, which includes the dependency on mechanical stress, cut edge effect and magnetic anisotropy is implemented in order to improve the accuracy of machine design. The error from the simulation with one single nonlinear magnetization curve compared with the simulation results considering the applied dependencies locally in each element is examined in detail. Consequently, it is necessary to build material models to represent the material properties. By means of a sufficient database a general applicable method to consider different scalar dependencies of soft magnetic material magnetization can be applied to finite element simulations. Although, this paper focuses on the magnetization curve, the presented methodology is adaptable to the anhysteretic curve of hysteresis models. In this paper, the required magnetic measurements for the identification routines and database are presented and the applied material models for the effects are derived. A comparison of magnetization properties from the material models to the measurements is given. The influence of magnetic materials under different dependencies on electrical machines is discussed by results of FE simulation.

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II. Processing of material measurements

In this study, the magnetization behavior of an industrial non-oriented M300-35A electrical steel is performed on a standard uni-axial single-sheet-tester (SST). In order to determine the scalar relationship between magnetization properties and the studied dependencies different measurements are proceeded. The different magnetic characterization conditions are collected in Table I. The samples are excited from a sinusoidal unidirectional magnetic flux density of 0.1T to 1.8T in steps of 0.1T. To account for the material's saturation polarization, an extrapolation to higher polarizations up to 2.03T is used. The measurements are performed at the excitation frequency of 50Hz. Due to SST set-up the sample can only be excited in one direction. The magnetic field strength and magnetic polarization are considered to be parallel. In order to determine the anisotropic properties, sample cuts of an angle from 0° to 90° relative to the rolling direction are used. In this way the magnetization properties in each direction can be obtained with SST. With the help of equipping a hydraulic pressure cylinder to a SST, the stress response of the material can be obtained. A maximum tensile or compressive force of 5kN can be applied. The applied stress is collinear to the magnetic field. The sample for stress measurements has a length of $600\mathrm{mm}$ and a width of $100\mathrm{mm}$. In this paper, the measured range is limited from -8MPa to $25\mathrm{MPa}$. In order to simulate the magnetic field in dependency of wider range of stresses in electric machines, a stress model based on these measurements needs to be built for $\pm 400\mathrm{MPa}$. To characterize the cut edge effect, a set of electrical steel samples of $120\,\mathrm{mm} \times 120\,\mathrm{mm}$ is cut into strips with different widths N according to [6] to increase the proportion of cut surface per fixed sample volume. For instance, a sample with N = 8, is composed of 8 strips of $15\mathrm{mm}$ in width. The specimen with different N of cuttings are measured then with the help of SST.

TABLE I
MEASURING PROCEDURE

dependencies	measurements
stresses	-8MPa, -4MPa, -3MPa, 0MPa, 3MPa, 5MPa, 10MPa, 15MPa, 20MPa, 25MPa
cut edge	60mm, 30mm, 15mm, 7.5mm, 5mm
directions	0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 45°, 60°, 65°, 70° 75°, 80°, 85°, 90°

III. Material Modeling Approaches

As presented in section II the measurements can not be performed up to saturation or carried out a continuous data base in consideration of various dependent parameters. For this reason, continuous material models are implemented to represent the relationship of J(H,σ), J(H,x) and J(H,θ). In order to examine the local permeability during the simulation, these material models have been integrated in FE solver. The polarization of each material model is extrapolated to 2.03T.

1) Stress consideration

Considering the machine construction and operation conditions, the rotor lamination bears a compressive stress until $-70\mathrm{MPa}$ due to assembly and at the same time a centrifugal tensile stress up to 400 MPa. Different models have been published, representing locally magnetic behavior according to stress distribution in electric machines [7], [8]. Here it is assumed that the polarization is degraded symmetrically and quadratically in tensile and compressed direction. With this assumption, the J(H,σ) is interpolated from the measurements and extrapolated to the range of $\pm 400\mathrm{MPa}$ as showed in Fig. 1. To simulate the stress dependent magnetic field, the simulation model should at first be calculated in a mechanical solver while considering the assembly and operating point in order to assign each element to a certain stress. Afterwards, with the polarization surface the magnetization curve for each element can be determined during FE simulation for electric magnetic fields.

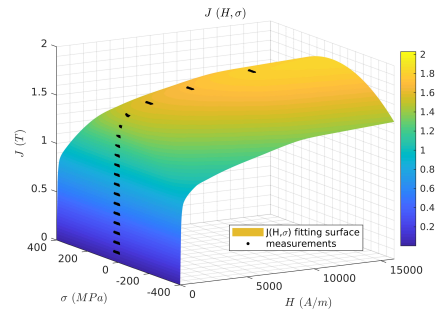


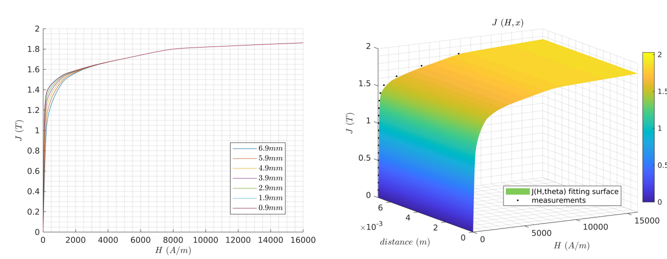
Fig. 1. Polarization in dependent with stresses and magnetic field strength

2) Cut edge consideration

Fig. 2a depicts the magnetic polarization curve decreased with narrower strips. The difference is obvious with a polarization from 1.4T to 1.5T. Several cutting edge modeling approaches are presented in [9], [10]. The cut edge model here represents magnetization properties in a relationship with the distance x to the cutting edge.

$$\mu_r(H,x) = \mu_r(H,N=0) - \Delta\mu_{cut}(H)\cdot\eta(x) \qquad (1)$$

$\mu_r(H,N=0)$ represents the undamaged permeability from the sample with a size of $120\,\mathrm{mm} \times 120\,\mathrm{mm}$. $\eta(x)$ is the degradation profile corresponding to x. It takes the influence from depth of the sample and slope of deterioration into account. For the material sample used in this paper it turns out to be $\eta(x = 6.32\mathrm{mm})$ = 0. Which means, the permeability of the position with a distance to cut edge exceed $6.32\mathrm{mm}$ should equal to $\mu_r(H,N=0)$, as the undamaged specimen. This is depicted in Fig. 2b. The $\Delta\mu_{cut}(H)$ is the maximum change between permeability from undamaged specimen and specimens with different widths of cutting strips, which describes the relationship between permeability, distance to cut edge and strip width. With algorithms, assigning each element a distance to the cut edge, the J(H,x) relationship in Fig. 2b can be applied to FE-solver to examine the local magnetization behavior of each element.

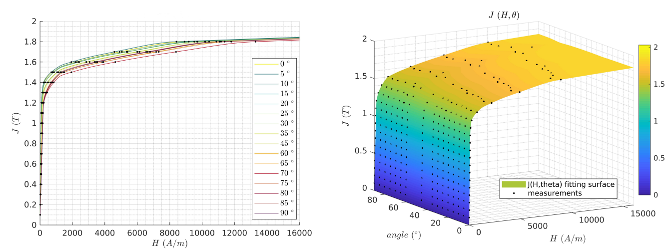


(a) J(H,width) (b) J(H,x)

Fig. 2. Magnetzation properties affected by cut edge effect.

3) Anisotropy consideration

Besides the cut edge effect on the magnetizability during production of electric magnetic sheets, anisotropy is another phenomenon, that appears through mechanical deformation. To achieve a certain polarization in different excitation directions, different magnetic field strengths are required. Fig. 3a reveals the magnetization behavior by interpolating the measured data from rolling to transverse direction in 2D. At lower polarization, the anisotropy induced from domain wall pinning, which is decided by micro structure of the material [11], [12]. From 1.4T to 1.8T the magnetization differs from each direction conspicuously. In this range, the magnetizing is caused predominantly by domain rotation. The domains align along the external field faster in magnetic easy direction and slower in hard direction. In this hard direction with an angle of 70° to rolling direction the material is the most difficult to magnetized than in other directions. Increasing the magnetic field strength, the anisotropic characteristic vanishes by saturation. Fig. 3b depicts the polarization surface in relation to magnetic field strength and excitation direction. With the J(H, θ) it is also able to simulate the vector anisotropy of the material [13].



(a) J(H,θ) in 2D (b) J(H,θ) surface

Fig. 3. Polarization in different angles relative to rolling direction

IV. Nonlinear finite element model

Consecutively to the modeling of the different nonlinear material characteristic in electrical machines, the finite element method (**FEM**) in combination with the magnetic vector potential formulation is employed. The magnetoquasistatic formulation of the FEM originates from the Ampères law, which describes that the rotation of **H** is equal to the current density.

$$\nabla \times \nu(\nabla \times \boldsymbol{A}) = \boldsymbol{J} \tag{2}$$

J represents the current density, **B** is the magnetic flux density and **A** the magnetic vector potential. The material behavior is represented by ν, which is a function of **B**. Depending on the material that should be modelled it can have an additional dependency on the stress σ, the distance x to the cutedge or the direction of the magnetic flux density. Even though the material is more nonlinear compared to the standard isotropic approach, it is still considered to be a scalar value. Especially for the anisotropy this is a simplification. Therefore, the named material characteristics can be easily included in every FEM code and the scalar Newton Raphson formulation can be used to consider nonlinear phenomena.

V. Application on electric motor

In this paper, a permanent magnet synchronous machine (**PMSM**) with buried v-shaped magnets is studied. The shown machine is employed in automotive applications. The machine characteristics are summarized in Tab. II .

TABLE II
Characteristics of the simulated PMSM.

Rated power P_{N}	30kW
Rated torque T_{N}	100Nm
Rated speed n_{N}	3000min^{-1}
Maximum speed $n_{\max}$	14000min^{-1}
Polepairs	3
Number of phases	3

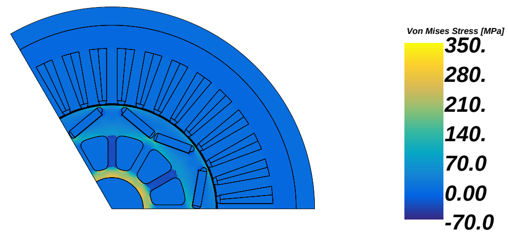


Fig. 4. Stress distribution at maximum speed.

1) Stress consideration

The mechanical stress that the machine at the maximum speed needs to withstand is depicted in Fig. 4. It can be clearly seen that the highest stress occurs in the bridges, due to centrifugal forces. A comparison between the simulation with stress consideration and a reference simulation is shown in Fig. 5. Even though the biggest load is in the bridges, the difference between both simulation shows no difference in the bridges, which is because of the high magnetic saturation in these areas. The other areas are more influenced, and the deviation shows compliance with the mechanical stress in the machine. Especially the fitting shows an impact on the magnetic behaviour at the contact of the shaft and the rotor as well as in the stator due to the shrink fitting.

2) Cut-edge effect

Next to the mechanical load due to rotation, which is dependent on the speed, and the fitting of the stator, there is always the effect of the material degradation caused by the cutting of the laminations. This degradation, which is a function of the distance to the cut-edge, is modelled here. The distance is depicted in Fig. 6 and the effect takes places if the distance is smaller than x. Evaluating the influence on the flux density distribution in Fig. 7 clearly indicates the necessity to consider the material degradation. Especially for small machines with many teeth, this effect is not neglectable. This

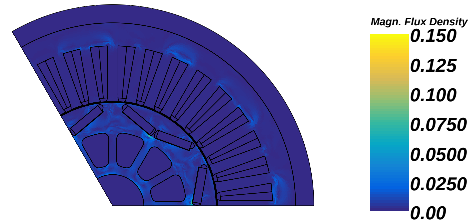


Fig. 5. Flux density difference between stress consideration and without stress consideration

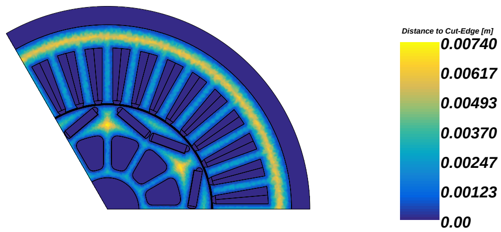


Fig. 6. Distance to cut-edge of the steel lamination.

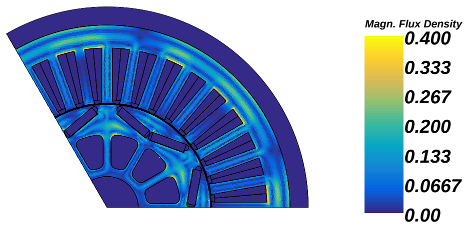


Fig. 7. Influence of the material degradation due to cutting.

effect is therefore antiproportional to the machines dimension.

3) Directional dependency

The scalar consideration of directional dependencies is an academic investigation of a non-intrusive anisotropic simulation. For this purpose, the easy direction of the material is placed in the x-axis, leading to a preferred direction of the magnetic flux. The resulting difference in the magnetic flux density distribution is presented in Fig. 8. It is obvious that the flux experiences an anisotropy, which has its maximum in 60° to 70° direction. This results in a global deviation of the flux density compared to the reference. Although in reality the influence of ferromagnetic anisotropy can be generally diminished by reasonable stacking of the laminations for general machine designs with distributed windings the effect is necessary to be modelled in machines with concentrated windings and with segmented stator designs or with grain oriented material.

VI. Conclusion

Electrical steel sheets, such as M300-50A, which are used for electrical machines, have been measured by means of SST, taking different dependencies into account. Relying on the measured magnetization curves, various material models have been implemented to determine the local magnetizability J(H), with consideration of various dependencies. The implemented approach opens a possibility to calculate the permeability with local distributions of different dependencies. Furthermore, by applying these material models into FE simulation, a comparison study to reference model was carried out.

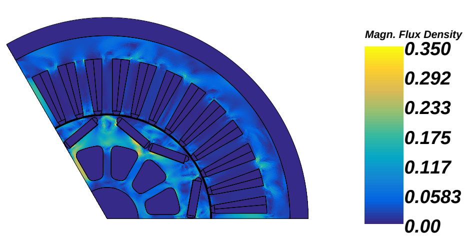


Fig. 8. Influence of the directional dependency on the flux densitiy distribution compared to reference simulation

Acknowledgment

This work is funded by the Deutsche Forschungsgemeinschaft(DFG, German Research Foundation) 255713208 and carried out in the research group project "FOR 1897 Low-Loss Electrical Steel for Energy-Efficient Electrical Drives".

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