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Betriebsartabhängige Anforderungen an die magnetischen Eigenschaften von NO Elektroband im Einsatz in Elektrofahrzeugen

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Abstract

Magnetkreise von elektromagnetischen Energiewandlern, wie z.B. elektrischen Maschinen haben heutzutage einen hohen magnetischen und elektrischen Ausnutzungsgrad. Dies führt dazu, dass Verbesserungen von Magnetkreiseigenschaften nur unter der Voraussetzung einer genauen Materialkenntnis erfolgen können. Zur Verbesserung von elektrischen Maschinen ist die Berechnung von örtlich verteilten Eisenverlusten mit Berücksichtigung der spezifischen Betriebsart erforderlich. Verlustrelevante Effekte können durch Separation in verschiedene Verlustkomponenten bewertet werden. Diese Vorgehensweise ermöglicht eine betriebsartabhängige Verbesserung verschiedener Eigenschaften des elektrischen Antriebs. Mit Hilfe von numerischen Simulationen können verschiedene nicht kornorientierte Elektrobandsorten unter Berücksichtigung der Betriebsarten eines Elektrofahrzeugs hinsichtlich ihres Verlustverhalten sowie Einflusses auf das Betriebsverhalten ausgewertet werden. Dadurch können Gütekriterien definiert und eine betriebsartspezifische Materialauswahl durchgeführt werden.
Dieser Beitrag stellt eine Methodik vor, die es ermöglich zwischen verschiedenen Verlustmechanismen in der elektrischen Maschine zu separieren. Eine Sensitivitätsanalyse der Modellparameter ermöglicht es solche Verlustanteile zu identifizieren, die mit Hilfe des elektromagnetischen Designs und der Materialauswahl des Antriebs beeinflusst werden können.

Operation mode dependent requirements on magnetic properties of NO electrical steel in traction drives

Magnetic circuits of electromagnetic energy converters, such as in electrical machines, are nowadays highly utilized. This proposition is intrinsic for the magnetic as well as the electric circuit and depicts that significant enhancements of electrical machines are difficult to achieve in the absence of a detailed understanding of underlying effects. The loss generating effects have to be considered and the possibility being able to distinguish between the causes of particular loss components is indispensable. Parasitic loss mechanisms additionally contributing to the total losses originating from field harmonics, non-linear material behavior, rotational magnetizations are not explicitly considered in the common iron-loss models. With this results obtained by

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numerical simulations, various grades of soft magnetic materials can be evaluated with respect to the mode of operation of an electrical vehicle. The most appropriate choice of material is possible.
This paper presents a methodology being able to distinguish between different loss mechanisms and enables to individually consider particular loss mechanisms in the model of the electric machine. A sensitivity analysis of the model parameters can be performed to obtain information about which particular loss origin for which working point has to be manipulated by the electromagnetic design or the control of the machine.

1 Introduction

The material utilization in electrical machines operated as speed variable drives is dependent on the actual working point of the machine's application. The consideration of a known drive cycle enables the knowledge to evaluate global qualities, such as the overall efficiency of the drive. As a consequence optimizing the drive for a specific working point might not lead to the best machine design for the desired application operated for a particular drive cycle. For instance, in order to determine the overall efficiency for an entire drive cycle all working points have to be considered including their frequency of occurrence. These findings are certainly not recent and are usually considered by the motor designer.
However, the detailed knowledge of the different loss mechanisms, e.g., the iron losses, can enable the possibility to exploit specific loss effects to enhance the drive in particular working points or for specific operational conditions. On the other hand the most appropriate material choice can be realized with this specific knowledge [1].
In numerical simulations of electrical motors, various material models can be employed to obtain realistic data for the iron losses. In such models, there are basically single components of hysteresis, eddy-current and excess losses [2-4] specified. Specific empiric factors calibrate such formula to the particular material operated at defined frequency and magnetic polarization. In highly utilized speed variable drives, this approach is rather inaccurate and therefore inappropriate [5].
To further enhance the properties of electrical motors the accurate determination by idealized model assumptions of the locally distributed iron losses alone is not sufficient [5, 6]. Other iron loss generating effects than hysteresis, Foucault and excess eddy-current losses have to be considered. Further on, it is indispensable to distinguish between the causes of these particular loss components.
Following the afore-mentioned reasoning, an improved estimation of iron losses is indispensable, which is applicable in a wide range of frequency and magnetic flux density [5]. In addition, parasitic loss inducing effects, particularly occurring in electrical machines, such as harmonics, dc-biased magnetizations and rotational fields need to be taken into account [6, 7].
Likewise, the mechanical properties of the soft magnetic materials attract more and more attention. This is for reasons of yield strength and for processing reasons.

Depending on the operating point of the electrical machine, copper losses and iron losses have a different share in the overall loss. For high torques, i.e., high electric currents the Ohmic losses are dominant. For high speeds, i.e., high operating frequencies the iron losses dominate. Therefore, the iron losses are one major loss component in inverter driven machines.

The local loss distribution within the machine is important. Although losses dissipated in the rotor make a small contribution of the overall losses, they have to be analyzed in particular because of the influence of temperature e.g. on the permanent magnets in PMSM. Depending on the operating point, the rotor hysteresis losses make a significant share to the rotor iron losses [7].

This paper presents a methodology being able to distinguish between different loss mechanisms and enables to individually consider particular loss mechanisms in the model of the electrical motor. With this, a sensitivity analysis of the model parameters can be performed to obtain information about the dominating loss origin for each working point. This enables to manipulate the electromagnetic design of the machine or the control of the motor's electric quantities to enhance the properties, i.e., the efficiency of the machine. Material properties required for particular application can be identified

This paper is structured as follows. Section 2 introduces the main iron-loss modeling approach.

Section 3 transfers the iron-loss modeling routine into the machine simulation and shows the machine simulation strategy focused on loss-calculation. Section 4 applies the proposed methodology to a permanent magnet synchronous machine simulation. Further on, the local loss distribution and the importance of iron losses are discussed. Section 5 discusses the influence of ferromagnetic material choice on machine characteristics in different regions of operation. Finally, Section 6 includes a discussion of the results and points out the scope for future work.

2 Prediction of Iron Losses

Soft magnetic materials are standardized by international standards [8, 9] using one value of the specific iron losses for one frequency and one magnetic flux density. Materials with a sheet thickness of 1.0 mm to 0.35 mm are graded by a loss measurement for a frequency of 50 Hz and a magnetic polarization of 1.5 T [8]. Materials with thicknesses of 0.2 mm to 0.05 mm are characterized at 400 Hz and 1.0 T [9].

For the estimation of iron losses for other values of magnetic flux density and frequency than the standard values, several iron-loss models are available. These models can be divided into empirical and physical-based approaches.

As a rule of thumb the formulation given in [2] is valid for magnetic flux density levels smaller than $B \leq 1.2\,\mathrm{T}$ and frequencies $f \leq 400\,\mathrm{Hz}$ [5]. With respect to this, an iron-loss formula (1) has been developed to improve the accuracy of a single model valid from small frequencies up to higher frequencies and magnetic flux density values [5]:

$$P_{\mathrm{IEM,5}} = a_1 B^{\alpha} f + a_2 B^2 f^2 (1 + a_3 B^{a_4}) + a_5 B^{1.5} f^{1.5} \quad (1)$$

with the material specific parameters α and a_1 to a_5. In addition, the non-linear behavior of the quasi-static loss contribution [10] as well as the definition of the non-local eddy-current loss parameter due to the simplifications [11] was identified as a source of inaccuracy.
Parameter identification is performed in line with the physical interpretation of the phenomena as described in [6].
However, the design and operation of rotating electrical machines leads to distortions of the fundamental waveform: harmonics (in time) due to iron saturation, skin effect, stator yoke slots and the use of power electronics supply (inverter, PWM) can occur, as well as vector magnetic fields (in space), the latter giving rise to so-called rotational losses.
In order to improve common iron-loss models to these conditions, rotational losses and higher harmonics can be considered by [6, 13-15]:

1. A Fourier analysis of the magnetic flux density waveform during one electrical period to identify the higher harmonics;
2. The level of magnetic flux distortion and also the magnetic saturation. Two parameters B_{min} and B_{max}, respectively the minimal and maximal magnetic flux density amplitudes over one electrical period, serve for this.
   The locus of the magnetic flux density vector over one electrical period is characterized by B_{min} and B_{max}. This enables to identify the level of magnetic flux distortion by taking the ratio between B_{min} and B_{max}. B_{max} gives an idea about the level of saturation. Zones within the stator with rotational hysteresis are those with large values of B_{min}, whereas unidirectional field corresponds with a zero value of amplitude B_{min}.

Considering this, the hysteresis losses are affected by rotational magnetization, the classical eddy-current losses are influenced by higher harmonics in the flux density and excess losses are increased by rotational magnetization as well as by higher harmonics. To include these effects, the loss contributions of (1) are extended to:

$$P_{\mathrm{Hyst}} = a_1 \cdot \sum_{\mathrm{n}=1}^{\infty} \left(\left(B_{\mathrm{n,x}}^2 + B_{\mathrm{n,y}}^2 \right)^{\alpha/2} \cdot \mathrm{n}f \right) \tag{2}$$

$$P_{\mathrm{Eddy}} = a_2 \cdot \left(\sum_{\mathrm{n}=1}^{\infty} \left(B_{\mathrm{n,x}}^2 + B_{\mathrm{n,y}}^2 \right) \cdot (\mathrm{n}f)^2 \right) \tag{3}$$

$$P_{\mathrm{Exc}} = a_5 \cdot \left(1 + \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}} \cdot \left(r_{\mathrm{Exc}}(B_{\mathrm{max}}) - 1 \right) \right) \cdot \left(\sum_{\mathrm{n}=1}^{\infty} \left(B_{\mathrm{n,x}}^2 + B_{\mathrm{n,y}}^2 \right)^{0.75} \cdot (\mathrm{n}f)^{1.5} \right) \tag{4}$$

$$P_{\mathrm{NL}} = a_2 \cdot a_3 \cdot B_{\mathrm{max}}^{2+a_4} \cdot f^2 \tag{5}$$

with B_{max} the maximum value of the flux density during one period, B_{n} the amplitude of the n-th harmonic component of the magnetic flux density, n the order of harmonic, f the fundamental frequency, and the material specific parameters $\alpha,\ a_1 - a_5$. This model (2-5) is validated in [7, 12] and will be used to analyze the iron losses in the studied IPMSM.

3 Machine simulation scheme

In order to understand the influence of machine design of e.g. a traction drive it is not sufficient to consider a single operating point. Therefore, the entire operating range of the machine is simulated.
The operating behavior is determined by the interaction of the stator- and the rotor flux linkage. In case of a permanent magnet synchronous machine, the length and direction of the rotor excitation flux vector is defined by the permanent magnets.
In order to depict the complete operation space the stator flux vector, respectively the stator current vector must be varied during simulation. For this purpose the rotor-flux-fixed dq-reference frame is used to perform a variation of the direct and the quadrature current.

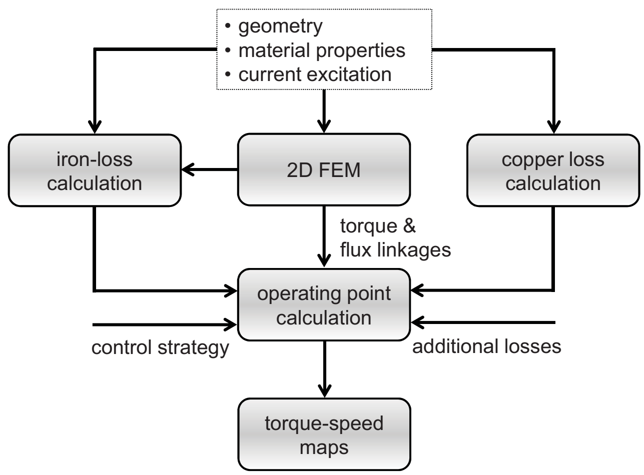

Figure 1: Machine simulation scheme.

Fig. 1 gives an overview of the machine simulation scheme. Starting from the geometry of the studied machine in combination with its material properties (remanent induction of permanent magnets, magnetization behavior of soft magnetic material, iron-loss parameters), the direct- and quadrature-axis-currents are varied during simulation. For each combination of direct and quadrature-axis-current the corresponding electro-magnetic torque, magnetic flux-linkage and local magnetic flux density distribution is calculated.
Based on the local magnetic flux density distribution the iron-losses are calculated according to (2-5). Finally, combining the modeled iron losses with additional losses (copper, air friction, bearing, …), the operation point of the machine is calculated in line with the used control strategy, i.e., maximum-torque-per-ampere (MTPA) or maximum-torque-per-voltage (MTPV). Boundaries resulting from voltage or current limit are taken into account.
Using this detailed information, the iron-loss distribution is calculated and analyzed in each working point versus the torque-speed map of the machine.
In the following section this scheme is exemplarily applied to an interior permanent-magnet synchronous machine designed for an automotive traction application.

4 Permanent-magnet synchronous machine

The IEM-Formula (2-5) in combination with the simulation scheme (Section 3) is exemplarily employed to a permanent magnetic synchronous machine for automotive application (Fig. 2).

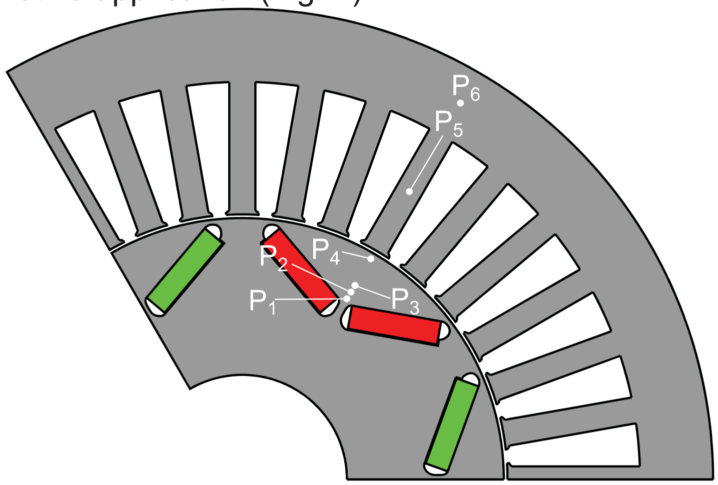

Figure 2: Cross section of the studied machine.

The studied machine with V-shaped permanent-magnets inside the rotor has a maximum rotational speed of $n_{\text{max}} = 18{,}000\ \text{rpm}$, a maximum torque of $M_{\text{max}} = 140\ \text{Nm}$, a maximum current of $I_{\text{max}} = 300\ \text{A}$, and operates at a dc-link voltage of $U_{\text{dc}} = 400\ \text{V}$.
In particular, in highly utilized electrical machines operation such as traction, iron losses are important. This will be discussed in detail in this section. Depending on torque, rotational speed and frequency the dominating loss terms change. Single-valued magnetization curves have been used in the 2D FEM simulation to consider saturation effects originating from the non-linear material behavior. Second-order effects, originating from hysteresis behavior, are neglected. Pure hysteresis, classical eddy-current, excess as well as saturation losses (2-5) in the laminated stator and rotor cores are estimated a posteriori from the field simulation.
In order to apply the described iron-loss model the spatial vector field and the parasitic effects through harmonics need to be taken into account. For this purpose the local waveforms of the magnetic flux densities at different positions in the electrical machine are analyzed.

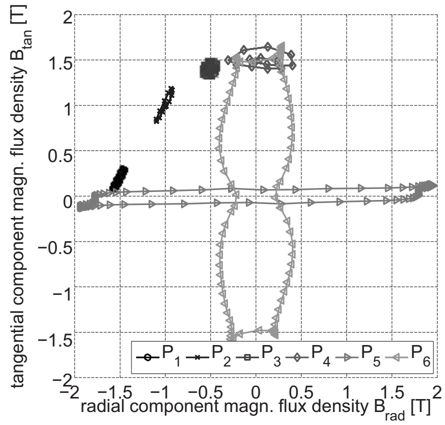

Figure 3: Locus of magnetic flux density during one period in different points of interest.

Fig. 3 presents the magnetic flux density in different loci of the machine cross-section (Fig. 2) exemplarily at 100 Nm in the speed of 6,000 rpm (base speed). P_1 to P_4 are located inside the rotor of the machine. It is apparent that the magnetic flux density behavior is shifted with a dc-bias offset due to the remanent magnetic flux density of the permanent magnets and the magnetic field from direct axis current. Point P_1 is directly related to the bypass-flux of the permanent magnets. Point P_4 represents the tangential pre-magnetization due to quadrature current, whereas points P_2 und P_3 depict a mixture of the afore-mentioned components.

In [7] it is shown that neglecting of minor-loop hysteresis losses inside a permanent magnet synchronous machine leads to an underestimation of rotor iron losses of about 50%. On that account, it should be stressed that an accurate iron-loss calculation in a permanent-magnet synchronous machine rotor needs to include minor-loop hysteresis [7].

Points P_5 and P_6 are located in the stator. At P5 located in the center of a stator tooth the magnetic flux density is almost entirely directed along the radial direction. The tangential component is significantly smaller, i.e., B_{rad} reaches a maximum of 1.95 T, whereas the tangential component B_{tan} reaches less than 0.13 T. It is apparent that in the base of a tooth (P_6), i.e., in the region where the magnetic flux heads from the yoke to the tooth or vice versa, to some extent rotational magnetization processes occur with B_{tan} of 1.65 T and B_{rad} of 0.4 T.

Next to this, the influence of the machine operation is discussed in detail. The machine is modeled in a rotor-flux fixed dq-reference frame. In order to calculate the operating points of the machine the maximum torque per ampere (MTPA) control strategy for the base speed range (n < 6,000 rpm). For the field weakening range (n > 6,000 rpm) the MTPA formulation with an additional speed depending upper boundary for the stator flux linkage is used [12, 16].

In Fig. 4 the operational characteristics of the studied machine, including the operating points at different rotational speeds, are given. When going to higher rotational speeds an increased field-weakening is necessary, i.e., increased negative direct current and decreased quadrature current to reach the same torque.

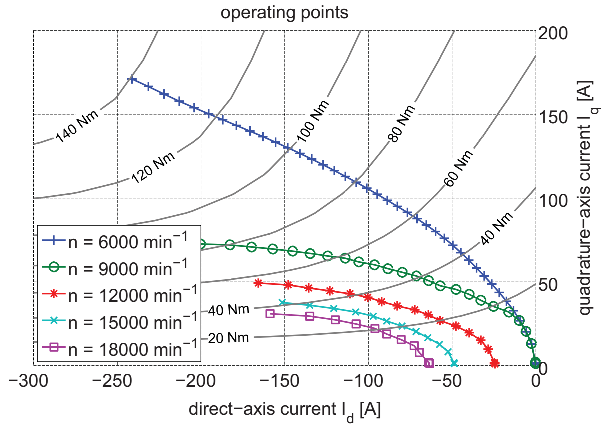

Figure 4: Operating points of the studied synchronous machine.

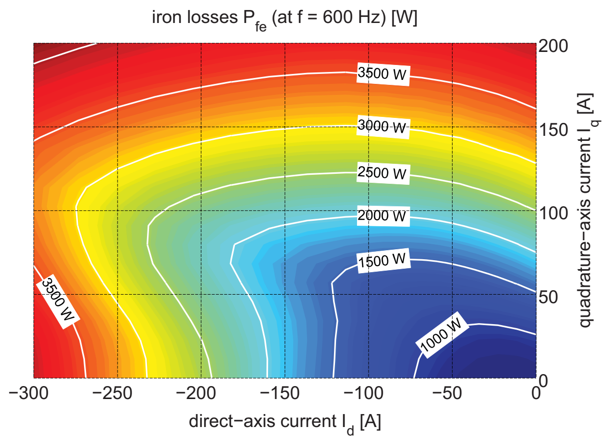

Figure 5: Iron losses at a fixed fundamental frequency of 600 Hz (12,000 rpm).

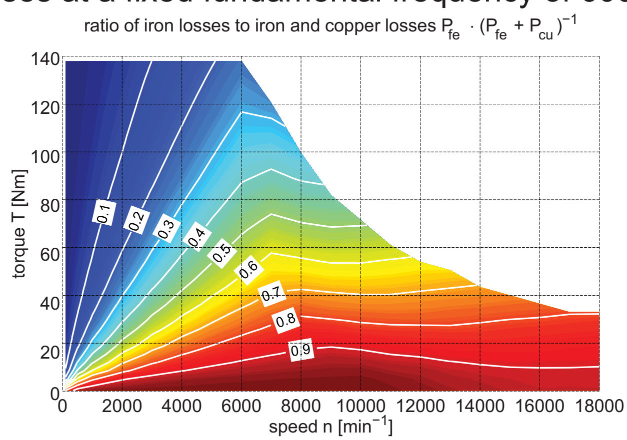

Figure 6: Ratio of iron losses and the sum of iron and copper losses in the entire torque-speed range of the studied machine.

Fig. 5 depicts the iron losses at a fixed rotating speed of 12,000 rpm, i.e., in field weakening operation. An increase in current and thus also an increase in flux density results in an increase of iron losses. It is shown that the influence of quadrature current and direct current on the iron losses is different. Fig. 5

shows the influence of direct and quadrature axis current on iron losses is highly depending on the working point of the machine.
Since the increased currents lead to an increase in copper losses, it is necessary to consider the distribution between iron and copper losses and their percentage distribution.
The importance of a detailed examination of the iron losses is emphasized by Fig. 6. Initially the proportion of the iron losses rises significantly in the base speed range. Reaching the field-weakening range the rise is despite increasing rotational speed less significant due to higher stator currents and reduced stator flux linkage values and therefore lower flux density values.

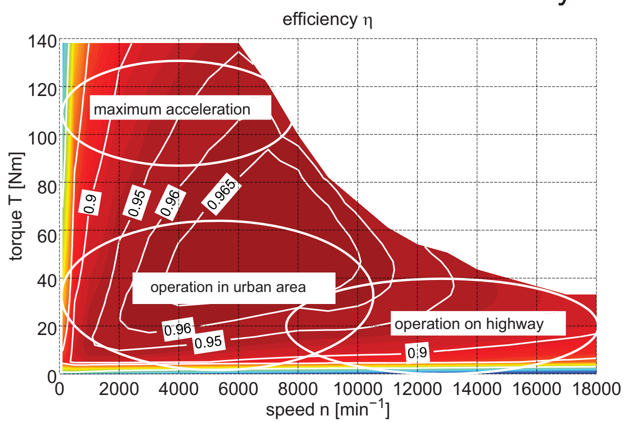

Figure 7: Torque-speed efficiency map of the studied synchronous machine. Ellipses indicate operation modes.

Fig. 7 depicts the total efficiency distribution across the whole torque-speed map of the studied synchronus machine. In addition characteristic working areas are indicated by ellipses. In the area of high torque and low frequencies a high acceleration is achieved. The operating area of the machine for a city drive is located at low frequencies and medium torque, while the area for a highway drive is located at high frequencies and low to medium torque.
For high torque, higher levels of magnetic flux are needed [16]. Therefore, the hysteresis losses (2) and the non-linear losses (5) are the most dominant part of the iron losses in the maximum acceleration mode.
In the highway operation, less magnetic flux is possible (field weakening) [16]. In combination with high operating frequencies at high machine speeds, the Foucault and excess eddy current losses (3,4) dominate the iron losses.
The afore-mentioned analysis underlines the importance of a differentiated consideration of the iron-loss distribution across the whole torque-speed map, when aiming at an improvement of the electrical machines properties. A consideration of the locally distributed iron losses alone is not sufficient. It is indispensable being able to distinguish between the causes of particular loss components.

5 Appropriate choice of soft magnetic materials

The soft magnetic material with its high magnetizability is the main component for conducting and guiding the magnetic flux through the magnetic circuit of electrical machines. If the material allows for higher magnetic flux

densities in stator and rotor core, the maximum magnetic flux that the magnetic circuit can guide is increased. Fig. 8 shows magnetization curves of five different soft magnetic materials commonly used for high-quality electrical machines. It can be seen that the material *M470-50HP* has a better magnetizability (i.e. higher magnetic flux density is reached at lower magnetic field strength) when compared to the other materials at high magnetic field strength values (more than 200 A/m).
Since this maximum flux is only required for high torque operation in the base speed region of the machine, the material M470-50HP is expected to lead to higher torque density and less power losses in the base speed region when compared to the other materials. Materials which generate less iron losses (here exemplarily M250-50A with the same thickness is considered) should yield less total power losses in the machine, when operated at high frequencies (i.e. high operating speeds). In the following the two materials M250-50A and M470-50HP are compared by the machine simulation of an induction machine.

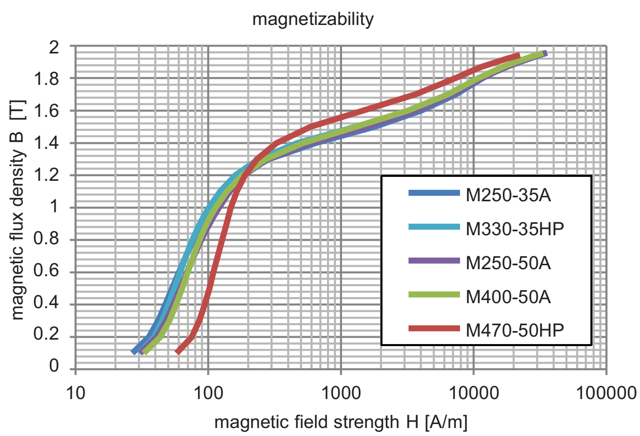

Figure 8: Magnetizability of commonly used soft magnetic materials for high-quality electrical machines (50 Hz).

The overall power losses of an induction machine are simulated for two different soft magnetic materials (Fig. 9). To model the differences of the materials, different magnetization curves are used in non-linear FEM simulations and the iron losses are calculated in the post-processing. It is apparent, that with M470-50HP lower losses are generated in the base speed region. Whereas in the field weakening region (where lower flux densities in the soft magnetic material and higher magnetization frequencies are present), M250-50A leads to lower power losses.
In Fig. 10 the difference of the anticipated power losses for the two compared materials is shown. It becomes clear that at low operating frequencies and highest torque the advantage of M470-50HP is the highest. At a torque of 130 Nm, the overall power losses are 365 W lower compared to M250-50A. The maximum advantage of M250-50A is 600 W lower power losses at the power limit at speeds higher than 3,500 rpm.

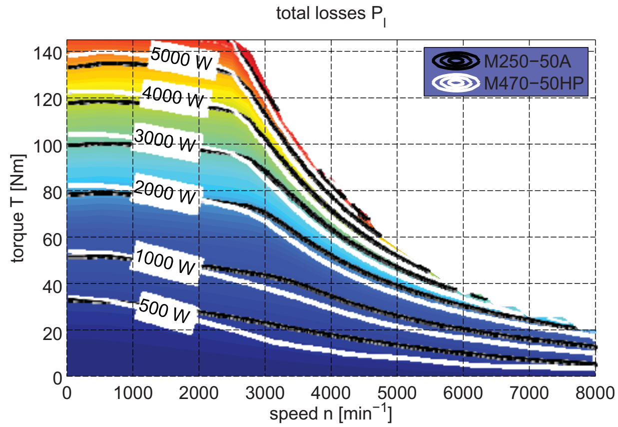

Figure 9: Total power losses for an induction machine with two different soft magnetic materials.

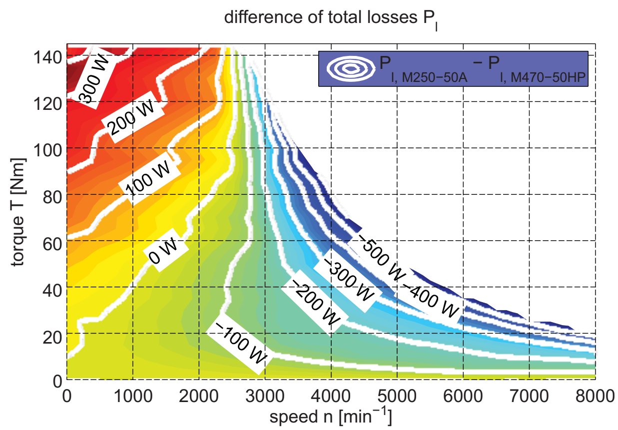

Figure 10: Difference of total power losses for two different ferro magnetic materials.

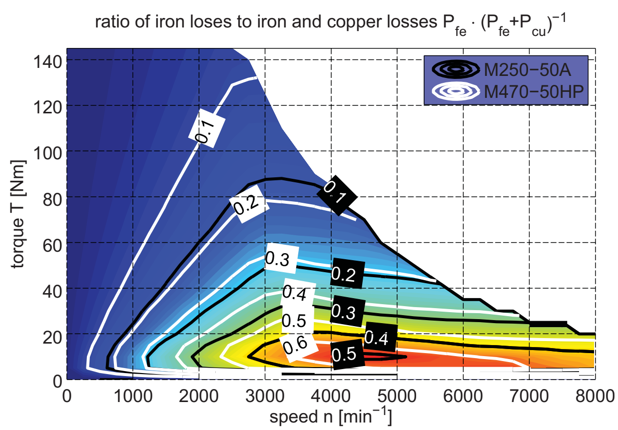

Figure 11: Ratio of iron losses and the sum of iron and copper losses in the entire torque-speed range of the studied induction machine.

To verify the reasons for the loss advantages of the two materials in different operating ranges, the ratio of iron losses to copper and iron losses is analyzed (Fig. 11). It is clearly visible, that M250-50A has a lower ratio of iron losses to copper losses. The loss advantage of M470-50HP over M250-50A in the high torque region is possible through higher magnetic flux densities. Through the

higher magnetic flux densities a lower stator current is needed and less copper losses are dissipated.
The previously shown loss simulation method is applied to different ferromagnetic steels. The losses in different operating regions of the exemplary induction machine (maximum acceleration, higway operation, and operation in urban area) are analyzed. From this methodology, the suitability of different steel grades for specific operation regions is concluded (Table I).

Table I: Steel grades and their suitability for different operating regions of the studied induction machine.

Material	High torque (max. acceleration)	High speed (highway)	Operation in urban area
M250-50 A	-	-	o
270-50 PP	+	+	+
M330-35 A	o	+	o
330-50 PP	+	o	+
390-50 PP	+	-	+
M400-50 A	-	-	-
M400-50 AP	+	-	o
440-35 AP	+	o	o
M470-50 HP	+	-	-

6 Conclusions

This work presents a general approach for rigorous understanding of material characteristics in electrical machines. In particular, the iron losses have to be analyzed regarding their loss mechanism and their local distribution. This enables to increase power density and custom-designed drive characteristics. The local loss distribution allows the development of tailor-made soft-magnetic materials. The approach being able to distinguish between different loss mechanisms enables to individually consider particular loss mechanisms in the model of the electric motor particular. In torque applications a soft magnetic material with higher saturation and magnetizability is advantageous. Whereas in speed (high frequency) applications a material with lower iron losses is favorable.
With the deep understanding of the loss dissipating effects, the electric steel could be chosen specifically for the target application. It can be concluded, that thinner steels and steels with less iron losses are better suitable for high speed operation (e.g. driving on highway), whereas high permeability steel grades are most suited for maximum torque applications in the base speed region of electrical machines, e.g., maximum acceleration. The investigated links between steel grade and suitability for different applications gives the designer of electrical machines as well as the producer of electrical steel the possibility to choose the best material for the application. Further the production and research of new electric steel grades can be aimed at to enhance the operation points (region of operation) the steel will be used in.

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