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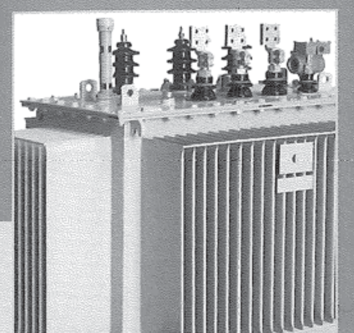

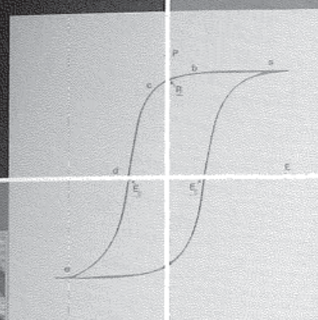

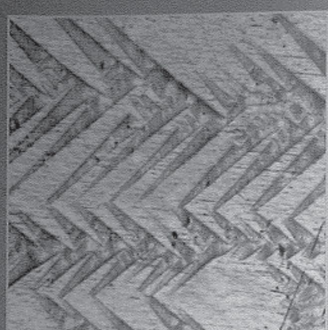

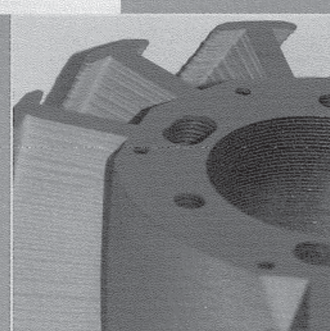

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Soft magnetic material modelling – The key to high power density electrical drives

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Summary

High power density electrical drives require high utilization of the soft magnetic materials. Modeling of properties such as magnetizability, iron losses and mechanical strength is indispensable in the design stage of electrical drives. Of particular interest is the estimation of losses in order to ensure high efficiencies in the required operational points.
The design of a traction drive for an electric sports vehicle with limited installation space is studied as an example. Specific material modeling is found to be one key aspect to solve the conflict of objectives with efficiency, installation space and costs.

I. Introduction

The majority of electric motors are speed variable drives. In these, the material utilization is strongly depending on the drive cycle of the machines' application. Optimizing the drive for a specific working point is not sufficient.

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. The rigorous 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 electric 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 formulae to the particular material operated at defined frequency and polarization. In highly utilized and speed variable drives, this approach is rather inaccurate and therefore inappropriate [5].

To further enhance the properties of electric motors the accurate determination by idealized model assumptions of the locally distributed iron losses alone is not sufficient [5, 6]. Other loss generating effects have to be considered and it must be possible to distinguish between the causes of particular loss components.

In fact, parasitic loss mechanisms which additionally contribute to the total losses are originating next to the fundamental frequency, from field harmonics, from the ferromagnetic material's non-linearity, from rotational magnetizations and from effects caused by the machines' manufacturing process or from temperature. Such losses are not explicitly determined in the common iron-loss models, probably even not specifically contained in the mentioned calibration factors.

Effects which are manufacturing or process dependent can, e.g., roughly be allocated to the cutting, respectively punching process, to imposed mechanical strain or stress to the material or can be temperature dependent.

Following the afore-mentioned reasoning, an improved estimation of iron losses is indispensable, which is applicable in a wide range of frequency and flux density [5]. In addition, parasitic loss inducing effects, particularly occurring in electrical machines, such as higher harmonics, dc-biased magnetizations and rotational fields need to be taken into account [6, 8].

Depending on the operating point in electrical machines, copper losses and iron losses make a different share in the overall loss. For high torques the ohmic losses are dominant. For high speeds the iron losses dominate.

The local loss distribution within the machine is important in permanent magnet excited machines. For instance, the rotor iron losses make a small portion of the overall losses, but they have to be analyzed in particular because of the influence on the temperature of the magnets. Depending on the operating point, the rotor hysteresis losses make a significant share in the rotor iron losses [8].

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 motor. The design of a traction drive for an electric sports vehicle with limited installation space is studied as an example. Specific material modeling is found to be one key aspect to solve the conflict of objectives with efficiency, installation space and costs.

Based on the *IEM-Formula* the local loss distribution and the overall losses occurring in different operational points are simulated. Subsequently the influence of material selection is studied. The differentiated loss separation allows a specific material selection according to the operational demands of the vehicle. The results show a beneficial application of different materials in rotor and stator. Furthermore it can be shown that the most expensive material yields not in any case best results when considering the described constraints.

This paper is structured as follows. Section II introduces the main demands on a traction drive, leading to a design-triangle representing the major driving forces when designing a traction drive. This will be detailed in section III. In line with this the loss-modeling methods are presented in section IV. Section V applies the proposed methodology to a permanent magnet synchronous machine simulation. Further on, the importance of iron losses is discussed.

II. General Demands on Traction Drive

Extensive demands are made on the traction machine of an electric powertrain. In order to reach a high operating range of the vehicle, the electric motor must be light and have compact dimensions.

In addition, the available space in the vehicle is limited. All in all, this leads to large demand for a high power density. However, the power density of an electric machine cannot be increased arbitrarily because increasing power density also increases the power losses. Thus, the maximum power dissipation leads to a thermal design limit.

For the purpose of reducing power loss and efficient use of electrical energy stored in the batteries, the electrical machine needs a very high efficiency. Matters are complicated further due to the fact that electrical machines in traction drives operate in comparison to many industrial operations not only in one operating point.

Therefore, not the maximum achievable efficiency is decisive, but the average efficiency over a typical drive cycle for the traction drives.

Currently, from the customer's perspective, electric vehicles are still significantly more expensive than conventionally powered vehicles, which is another aspect hindering the breakthrough of electric mobility.

The overall share of the electric traction drive to the total costs of an electric powertrain, including battery, is 5 % to 20 %. Thus, the reduction of the costs of the machine is a worthwhile approach on the way to reduce the overall costs of the powertrain [9]. Both material costs and manufacturing costs need to be considered.

III. The Design-Triangle

Figure 1 shows the essential requirements applying to the entire drive train and its individual components. These are considered in detail by the example of an electrical machine for a sports car.

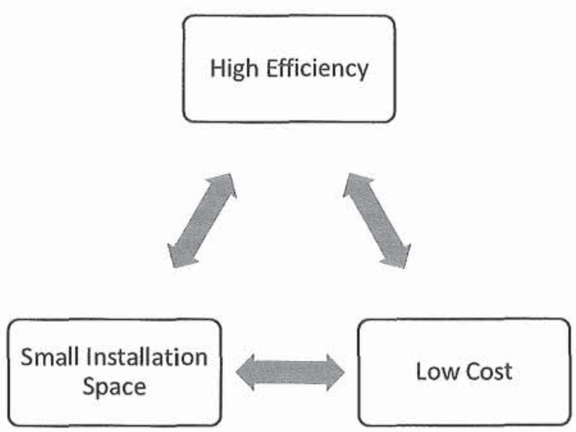

Fig. 1. The Design-Triangle

The goal in the design of an electrical machine for a traction drive is to develop a machine which achieves the intended performance requirement in accordance with the requirements of the three aspects of the design triangle (Fig. 1). The basic relationships of these three aspects are explained below using the example of a permanent magnet synchronous machine. As a starting point, the target is chosen to achieve the highest possible efficiency of the machine. To increase the efficiency, the losses must be reduced. Ohmic losses in the stator winding, iron losses in the stator and rotor lamination and eddy current losses in the permanent magnets of the rotor are considered.

i. Ohmic Losses

The Ohmic losses in the stator winding increase with the winding resistance as well as with the square of the phase current. Thus, current and resistance form starting points to reduce the copper losses. Both points will be tackled briefly in the following paragraph.

There are various ways of influencing the power demand of the machine. For one thing, the magnitude of the current is dependent on the selected voltage level. Here the design of the stator winding is important. For torque generation mainly the fundamental wave generated by the winding is beneficial. Therefore, the winding should produce a high fundamental component, while minimizing harmonics.

In order to produce the required torque for a given fundamental wave of the flux with the lowest possible power and loss, a coil with a high winding factor of the fundamental wave must be selected.

A limitation in the choice of the winding is given by an already fixed pole pair number. On the other hand, only a certain maximum number of stator teeth can be implemented meaningful in a certain stator diameter due to geometrical reasons. This leads to an additional restriction of the available range of combinations of pole pairs and number of slots.

To make full use of the machines' capability it needs to be ensured that the later operation in the base speed range is done by a maximum torque per ampere control [10]. That is, the requested torque is provided with the minimum current at which this torque can be achieved. Otherwise, unnecessary winding losses would be generated or the machine would have to be oversized, subject to a maximum current limit. This would lead to an increased space and a reduced power density.

Measures taken to reduce the winding resistance can also contribute to the reduction of the Ohmic losses. The coil resistance is dependent on the resistivity of the conductor material, the mean length of turn, as well as the cross-sectional area of the conductor.

The electrical resistivity results from a specific choice of material. The selection of a suitable material is a compromise in terms of specific resistance, density and commodity price.

Another approach is to reduce the mean length of the winding. For instance, end-windings of a single-tooth winding are smaller than that of a distributed winding. Thus, when using a single-tooth winding, the total length of the machine is smaller at a constant active length and the Ohmic losses are reduced. Keeping the total length of the machine constant a greater active length can be installed at the same volume.

In both cases, the power density of the machine is increased. Due to high numbers of pole pairs higher torques can be achieved, however, iron and magnet losses are increased disproportionately with the number of pole pairs.

ii. Iron losses

The iron losses form depending on the operating point a significant portion of the total losses. They are composed of hysteresis losses, marcoscopic and microscopic eddy current losses [2, 6, 8, 11, 12]. These are strongly influenced by occurring electrical frequencies [5, 12], material properties of the selected electrical steel as well as the geometric design of the magnetic circuit [13].

Iron losses increase disproportionately with the electrical frequency and thus the product of speed and number of pole pairs: $f_{el} = np$.

The machine speed has a significant influence on the installation space of the machine. When the required power is obtained by means of high speed, the required torque decreases accordingly and thus the volume of the machine.

Thus, the space requirement increases at low machine speeds, where the required power needs to be achieved through a high torque.

With decreasing number of pole pairs disadvantages in the rotor and stator arise. When decreasing the number of pole pairs, the dimensions of the individual magnets have to grow at unchanged pole coverage. The increase of the associated magnetic mass increases the centrifugal load and resultantly the iron bridges in the rotor, keeping the permanent magnets in position, have to be thicker in order to further ensure the mechanical strength. However, the thicker iron bridges increase the leakage flux of the magnets and decreases the air-gap flux required for torque production.

The utilization of the introduced magnetic material in the rotor is reduced and the power density of the machine is reduced. To cope with this and to increase the utilized flux again, more permanent magnetic material would have to be installed in the machine, which would mean an increase in material costs. In the stator a smaller and smaller number of pole pairs lead to larger end-windings and higher Ohmic losses in the stator winding.

Through a careful selection of soft magnetic materials for stator and rotor the occurring iron losses can be significantly influenced. With different alloy compositions, different material grades can be produced, which differ in the level of specific iron losses and magnetization behavior in different frequency ranges.

Apart from the composition of the alloy the sheet thickness (due to its beneficial effect on macroscopic eddy current losses) and the sheet metal processing (due to related degradation effects) are of great importance. With low-loss sheets of small thickness, such as NO10, the efficiency of electrical machines can be significantly increased. Furthermore, the small thickness requires a significantly higher number of individual sheets in order to achieve an identical stack length. In the example given, a four-fold number of individual sheets would be necessary when using NO10. The more sensitive handling of the plates leads to a more expensive manufacturing process. The increased production effort in the packaging of the active parts suggests an additional negative impact on the costs.

The geometry of the magnetic circuit affects the iron losses as well. In order to reduce the magnetic resistance, the magnetic path length should be as short as possible. One possible measure to reduce the magnetic path length in the stator would be a reduction in the height of the stator teeth. This would lead to a smaller outer stator diameter and a smaller cross-sectional area of the stator slots. The current density in the slots and hence in conductors would rise accordingly.

As a result, the winding resistance would grow and thus the Ohmic losses. This would shift the losses from the stator iron to the winding. The thermal load of the slots would increase, since in addition to greater losses a smaller contact area between the slots and the stator to dissipate the heat losses would be available.

Next to the length of the magnetic path the cross section in which the magnetic flux is passed has an effect on the amount of generated iron losses. Since in a smaller cross section, the flux density increases and ensures higher iron losses, because they depend disproportionately on the flow density. In the literature, guidelines for maximum flux densities in the various areas can be found [14].

iii. Permanent Magnet Eddy Current Losses

The eddy current losses in the permanent magnets are caused by flux density variations within the magnets. Causes are the reaction of the stator field and periodic reluctance variations due to the stator teeth during rotation. The losses increase with the load current of the machine and the square of the frequency of change of the magnetic flux density.

To hinder the propagation of eddy currents and reduce the losses the magnets are divided into mutually insulated magnet pieces. The segmentation can be done in this case both in the tangential and in the radial direction. Figure 2 shows an example of the distribution of eddy current density as a function of the number of segments in the axial direction.

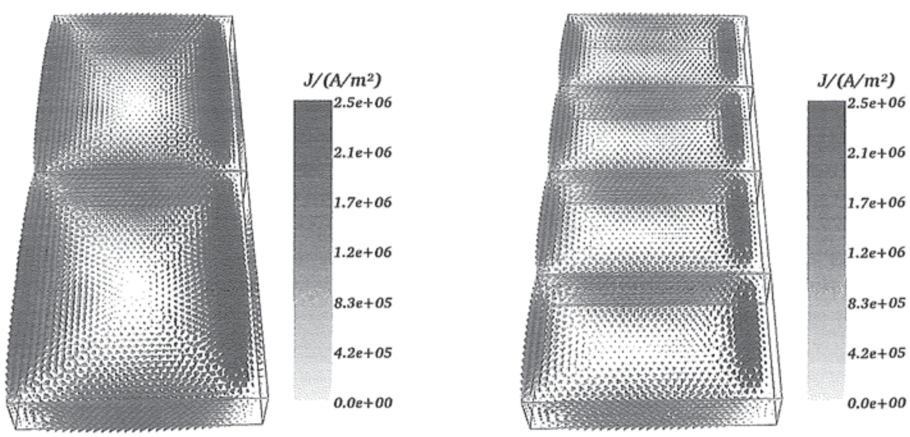

Fig. 2 Influence of permanent magnet segmentation. Left: 2 segments. Right: 4 Segments.

It should however be noted that the increased number of individual magnets due to the segmentation is accompanied by an increased manufacturing effort and thus increased production costs.

Furthermore, the rotor topology has an impact on the amount of eddy current losses in the permanent magnets. It has been shown that rotor topologies with magnets on the surface lead to much higher magnetic losses than topologies where the magnets are disposed buried in the rotor. The reason for this lies in the better shielding of the magnets from the repercussions of the stator when the magnets are buried in the rotor iron.

The selection of the winding has an impact on the amount of eddy current losses in the magnets. The periodic change in the flux density of the magnet is highly dependent on the number of stator slots. An increasing number of slots increase the frequency of the flux density fluctuations, but their amplitude decreases.

This means the effect of shielding the magnets outweighs and eddy current losses are reduced. Therefore distributed winding causes, due to their higher number of stator teeth, lower eddy current losses in the magnets compared to a single tooth winding.

When increasing the number of pole pairs the number of stator teeth increases. Rising eddy current losses in the magnets would be the result. Contrary to this expectation, however, the influence on the magnet losses with increasing number of pole pairs is not clearly recognized. The reason for this lies in the fact that with increasing number of pole pairs, the individual poles and hence the installed magnets are smaller. This acts as a further segmentation of the magnets and contributes to the reduction of losses.

IV. Iron-loss Modeling

In order to predict the efficiency of the desired machine already during the design process a reliable loss modeling is indispensable. Mechanical losses due to air friction and bearing friction, Ohmic losses in the stator windings, eddy current losses inside the permanent magnets and iron losses in stator and rotor cores need to be accounted for. Due to high rotational speeds and corresponding high electrical frequencies the overall share of iron losses to the total losses becomes significant. Using the IEM-Formula the iron losses can be accurately calculated under these special conditions. The iron-loss calculation will be detailed later.

The selection of soft magnetic materials is an important aspect to fulfill the requirement of high vehicle efficiency. Due to the operation at high speeds connected with high centrifugal loads of the rotor the mechanical material properties are of importance in addition to the electromagnetic ones.

Measurements of the iron loss and magnetizability at different frequencies on Epstein frames form the basis for the choice of material, since the parameters of the iron-loss formulae are determined from these measurements.

In [15], the measurement results of the grades M250-35A and 280-30 AP were exemplary presented. The 0.2 % yield point Rp0.2 of 280-30 AP is about 30 % to 40 % higher than standard electrical sheets and is therefore particularly suitable for use in rotors of high speed machines of interest.

Using sheets with increased strength the thickness of the bridges can be reduced selectively in order to reduce leakage flux and to increase the utilization of the introduced permanent magnetic material.

In the stator, however, the focus is on the selection of a low-loss sheet grade, as in the stator the majority of the iron losses is generated.

Prediction of Iron Losses

Soft magnetic materials are classified by international standards [16, 17] using only one value for frequency and magnetic flux density. Materials with a sheet thickness from 1.0mm to 0.35mm are classified by a loss measurement for a frequency of 50Hz and a magnetic polarization of 1.5T [16]. Thicknesses from 0.2mm to 0.05mm are characterized at 400Hz and 1.0T [17].

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

The more physically based approach of loss-separation divides the total amount of iron losses in different components representing different space-time scales. Therewith, the components could be attributed to different loss mechanisms.

Based on these assumptions, the state-of-art model (SoA) is developed by Bertotti [2, 11]. This model contains a loss contribution of hysteresis losses for quasi-static magnetization behavior, classical eddy current losses in line with the change of the magnetic flux over time for linear material behavior and excess losses, that describes local eddy currents occurring in the region of the domain walls, or correlated active regions, of the soft magnetic material.

From the physical background the SoA-Model is valid for linear material behavior, i.e., the material is not in saturation so that permeability can be considered to be constant near this operation point. With respect to this, an iron-loss formula has been developed to improve the accuracy in this higher frequency range [5].

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

with the material specific parameter a1 to a5 and α.

Parameter identification is done in line with the physically interpretation of the phenomena. Parameters describing pure hysteresis losses α, a1 are identified by quasi static measurements [18] using an Epstein frame with 1200 windings. The specimen under test is a set of mixed strips (half of the number cut along rolling direction as well as in transverse direction).

The classical eddy current parameter a2 could be calculated using material characteristics d, ρ, ρe, which are identified by a standardized process.

The excess loss parameter a5 is determined from measurements for low frequencies, i.e., at frequencies where the influence of disturbing induced eddy currents is negligible (dependent on the material characteristics) and magnetic flux densities using the same configuration as described for the quasi-static measurements.

The material behavior in this range of frequency and magnetic flux density is almost constant and the eddy current losses are not dominant, so the excess loss term is easily separated.

The identification of parameters a3 and a4 describing the non-linear material behavior is based on the identification of the non-linear loss contribution.

With regard to the operating conditions of electrical machines, other loss generating effects have to be considered. Epstein measurements are performed under uniaxial (spatial) and sinusoidal (temporal) magnetic flux density. Thus, magnetic flux density in Epstein frame measurements is completely represented by its fundamental wave.

However, in rotating electrical machines this is not the case: higher harmonics (in time) due to iron saturation, skin effect, stator yoke slots and the use of a 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 have to be considered [6].

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 suffer from rotational magnetization as well as from higher harmonics. For this the loss contributions of (1) can be written as:

$$P_{\mathrm{hyst}} = a_1 \cdot \left(1 + \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}} \cdot \left(r_{\mathrm{hyst}}(B_{\mathrm{max}}) - 1\right)\right) \cdot B_{\mathrm{max}}^{\alpha} \cdot f \tag{2}$$

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

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

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

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, α, $a_1 - a_5$ the material specific parameters and the rotational loss factors r_{hyst} and r_{exc}.

i. Machine Simulation

In order to understand the influence of machine design of a traction drive it is not sufficient to consider one operating point. Therefore, the entire operating area of the machine needs to be 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 flux vector is defined by the fixed 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.

Based on the magnetic flux density distribution the iron-losses are calculated according to (2-5). Finally, combining the occurring iron losses with additional losses (copper, air friction, bearing, ...), the operation point of the machine can be calculated in line with the used control strategy, i.e., maximum-torque-per-ampere (MTPA) or maximum-torque-per-voltage (MTPV).

Using this detailed information it is possible to calculate and analyze the iron-loss distribution in each working point across the torque-speed map of the machine. In the following section this scheme will be exemplarily applied to a permanent-magnet synchronous machine, which works as a traction drive.

V. Permanent Magnet Synchronous Machine

The *IEM-Formula* in combination with the simulation scheme is exemplarily employed to a permanent magnetic synchronous machine for automotive application. The studied machine with V-shaped permanent-magnets inside the rotor has a maximum rotational speed of $n_{\max}$ = 18.000 rpm, a maximum torque of $M_{\max}$ = 165 Nm, a maximum current of $I_{\max}$ = 450 A and operates with an intermediate circuit voltage of U_{dc} = 400 V.

In particular, in these high efficient electrical machines operating as traction drives, iron losses are important, as will be detailed in this section. Depending on the torque, rotational speed and frequency the dominating loss terms change.

Single-valued magnetization curves have been used 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 in the laminated stator and rotor cores are estimated a posteriori.

The rotor material was selected with respect to the mechanical properties (yield strength) in combination with best magnetic properties (magnetizability and iron losses). Due to limited amount of materials with such optimized properties for permanent magnet rotors the rotor material was kept fixed and not varied.

Centrifugal forces, which are generated during rotation of the rotor, increase with the square of speed. Therefore the rotor material is subjected to very high loads especially at high speeds.

The highest stresses occur in the outer bridges of the V-shaped magnet arrangement, and the middle bridge between the two magnets in one V-configuration. Hence, the bridges must be of sufficient size in order to ensure the mechanical strength at any time, but in contrast to this they should be as thin as possible to avoid leakage fluxes in the rotor.

Accordingly for each parameter variation, in which the rotor geometry is changed, an adaptation of the bridges is necessary. Here 280-30AP is used as a rotor material because of its increased mechanical strength.

Next to this, enabling the aforementioned simulation scheme different materials for the stator iron are compared (Figs. 3, 5, 6-8). These are M270-35A, M235-35A and NO20. Changing the stator electric steel grade greatly influences the iron losses. This allows significantly reducing the overall losses and increasing the efficiency in operating points where the iron losses are dominant. These operating ranges are at high speeds (>10000 1/min), where the copper losses are small compared to the iron losses (Fig. 3, 4).

At operation points with high torque (>100 Nm) and lower speeds (< 8000 1/min) the copper losses are dominant and a reduction in iron-losses does only lead to a minor loss reduction.

The efficiency maps of the machines are simulated with the different stator steel grades (Fig. 7-9). It becomes apparent, that the highest efficiency increase of approx.

1 % is reached at the maximum speed and the region of highest efficiencies can be enlarged. With a given cooling capacity of the machine, higher power outputs at high speeds become possible for both short (i.e. boost mode) and long term operation modes.

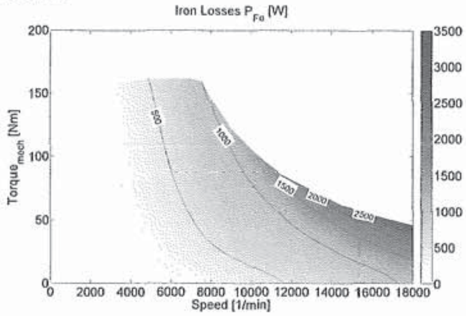

Fig. 3 Iron-loss map of M235-35A.

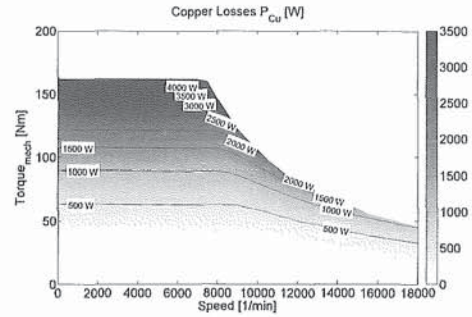

Fig. 4 Copper-loss map of M235-35A.

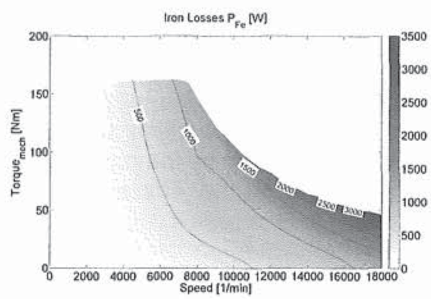

Fig. 5 Iron-loss map of M270-35A.

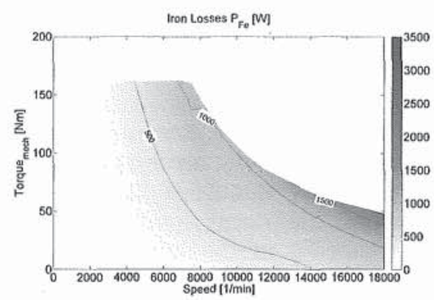

Fig. 6 Iron-loss map of NO20.

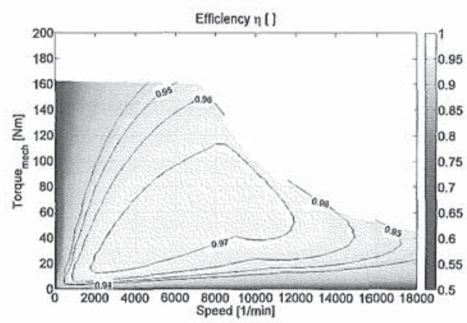

Fig. 7 Efficiency map of M270-35A

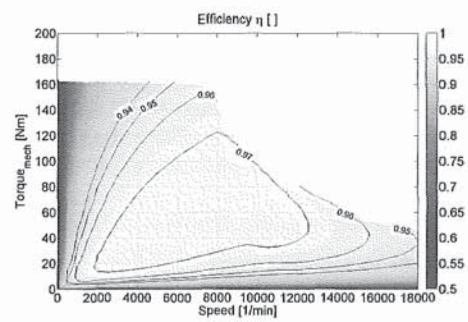

Fig. 8 Efficiency map of M235-35A

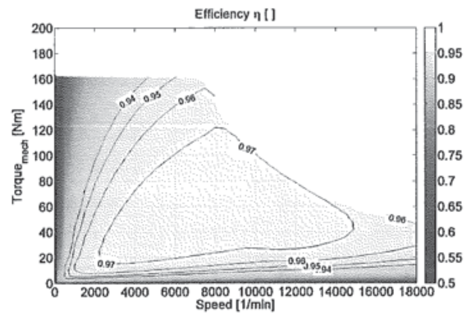

Fig. 9 Efficiency map of NO20.

VI. Conclusion

This work presents a general approach in order to analyze the influence of various material characteristics in electrical machines, in particular on the efficiency.

This enables to increase power density and custom-designed drive characteristics. The approach being able to distinguish between different loss mechanisms enables to individually consider particular loss mechanisms in the model of the electric motor.

With this, a sensibility analysis of the model parameter can be performed in such a way, that we obtain information about which loss origin for which working point has to be manipulated by the electromagnetic design of the machine or by the control of the motor's electric quantities to enhance the properties, e.g. the efficiency of the machine.

The flexibility of the iron-loss model allows for consideration of parasitic loss mechanisms additionally contributing to the total losses, such as the manufacturing process.

Enabling this approach the design conflict between installation space, efficiency and overall costs could be tackled. In this regard the soft magnetic material plays an important role. It is shown that high strength material with sufficient magnetic properties enables small bridges in the rotor to avoid leakage-flux and to increase the permanent magnets' utilization. The stator material needs to be chosen in line with the desired application of the machine.

High speed applications (high frequencies) lead to strong demands on the mechanical properties of the rotor material. Further on, induced eddy current losses are dominating necessitating thin gauge materials to increase the power density and efficiency.

However, electric traction drives for electric vehicles operate in various points of the torque-speed map. Hence, it needs to be differentiated between low iron loss grades reducing the iron losses at high rotational speeds (lower eddy current losses) and high torque grades, which lead to a reduction of the excitation current (compare Fig. 3 and 4). Therefore the material selection process is always application-specific.

The presented approach enables to analyze the material influence on the properties of the machine with respect to the real application and operating points. Therewith an application-specific material selection process as well as an improved design is possible.

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