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Model-Based Loss Minimization in High-Speed Motors

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***Abstract*— High-speed drives are becoming increasingly important as the need of higher power densities has been driving the trend towards higher speeds in electrical drives. This trend, however, possesses several challenges, one of which is the thermal constraints due to the higher loss densities in the machines. For example, rotor losses are critical in applications where the rotor runs in vacuum, whereas the total drive efficiency including the converter and the motor is critical in applications such as blowers. In order to find a loss-optimal design, it is important not only to limit the amount of losses but also to predict and influence where they occur. In this paper, loss models developed in a previous work are used to evaluate different converter modulation schemes as well as changes in the machine construction, in order to find a loss-optimal drive system. Typical modulation schemes such as Pulse-Amplitude-Modulation (PAM) and Pulse-Width-Modulation (PWM) as well as Pulse-Width-Amplitude-Modulation (PWAM) are compared for two off-the-shelf high-speed machines. On the machine side, different options such as using different retaining sleeve or permanent magnet materials as well as the segmentation of the permanent magnets are analyzed to evaluate their effects on different loss components of the drive system.**

***Index Terms* — High-speed drives, losses, modeling, optimization.**

I. Introduction

RECENTLY, the need of higher power density in emerging applications such as in micro gas turbines, turbocompressor systems, drills for medical applications, micromachining and optical spindles has been driving the trend for high-speed electrical drives [1], [2]. This trend towards high speeds and power densities possesses several challenges. Besides increased mechanical stresses in the rotor and rotordynamic constraints, thermal considerations become more important due to the higher loss densities resulting from a smaller volume. Therefore, modeling the losses of a high-speed drive is a crucial step for designing an optimum drive system.

Fig. 1 shows two typical Permanent-Magnet-Synchronous-Machine (PMSM) topologies (not drawn to scale) that are widely used for high-speed drive applications: the slotless (Fig. 1(a)) and the slotted (Fig. 1(b)) machine. In both cases, the permanent magnets are contained in a retaining sleeve, typically made of titanium or non-magnetic steel, for its mechanical strength.

Pulse-Width-Modulation (PWM) is a well-known modulation strategy for three-phase inverters and it is commonly applied in PMSM drives with speeds up to 50 krpm [3]. However, with increasing speeds, the increasing inverter switching frequency and current control bandwidth requirements along with the lower stator inductance of especially the slotless machines make PWM unfeasible. Therefore in literature, Pulse-Amplitude-Modulation (PAM) has been proposed for speeds above 200 krpm [1]. In a PAM converter, an additional DC/DC converter is used to adjust the DC link voltage (and/or control the DC link current) whereas the three-phase inverter switches with the fundamental frequency of the machine, limiting the switching losses at the expense of an additional DC/DC converter consisting of two semiconductor devices, and a DC link inductor which are not required in a PWM inverter.

For speeds between 50 – 200 krpm, there is no consensus on which motor topology or modulation scheme to select – a decision that would ideally be made based on the losses of the drive system [3]. This is, however, not a straightforward decision as the importance of the overall drive efficiency and distribution of the losses in the drive system might have different significance in different applications. For example, the compactness (hence efficiency) of the machine is the main

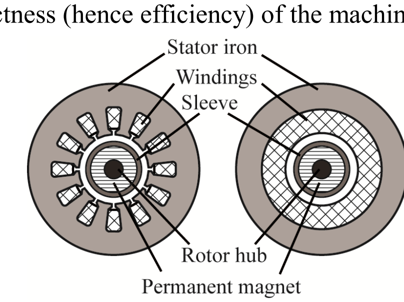

Fig. 1. Conceptual cross sections of typical slotted (a) and slotless (b) high-speed motors. The rotor hub is optional, it exists in the slotted machine investigated in this work, and not in the slotless one.

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priority in machining spindles, whereas an oversized, lossy converter is not a major drawback. On the other hand, the overall drive efficiency is crucial in turbo compressors in heat pumps or gas turbines. Furthermore, the rotor losses are generally considered to be more problematic due to the limited rotor cooling whereas converter cooling is usually less of a challenge. In the case of applications running in vacuum, such as optical systems, it is crucial to limit the rotor losses and a lower overall efficiency can be tolerated.

Therefore, the ideal modulation strategy and the ideal motor topology have to be identified according to the application. For that reason, in [3], individual models for calculating the rotor, copper, core and inverter losses in a high-speed drive are given. These models take the influence of the modulation scheme on the individual loss components in motor and the converter into account. The models are applied to the off-the-shelf slotted and the slotless high-speed motors as well as a converter which operates with both PWM and PAM. The overall efficiency and the loss distribution in the drive system are evaluated for speeds between 50 – 200 krpm. Finally, it is shown that harmonics of the armature field are responsible for a considerable amount of losses. Furthermore, the converter modulation scheme can be changed to shift the losses from the machine to the converter or vice versa. This is an important result as the challenge in high-speed drives is not only to limit the amount of losses but also to calculate, or even to influence where they occur.

In this paper, the models presented in [3] are further used for evaluating a number of modifications both on the converter and the machine side in order to decrease the losses. Firstly, modifications on the converter modulation are investigated. Here the goal is to minimize the armature field harmonics while the switching losses are kept within feasible limits. Secondly, modifications on the machine such as modifications of the geometry or the materials are analyzed. Experimental results are given to show the validity of the described evaluation.

II. Characterization of Loss Types

A. Machine Losses

The drive system considered in this paper consists of a PMSM and a converter. Different loss components of the PMSM, that are considered in this paper are the rotor losses that are caused by the armature field harmonics due to the time harmonics in the phase currents and space harmonics caused by the winding geometry or stator slotting; the copper losses in the windings of the machine that can be divided into DC, skin and proximity effect losses; and the core losses that make up only a small fraction of the losses due to the high quality of the iron sheets used in the machines under investigation. Detailed information on the individual models for those machine loss components as well as information about the slotted and the slotless machines (both rated at 200 krpm and 30 mNm) under investigation can be found in [3].

B. Converter Losses

In this work, the off-the-shelf converter CC-75-500 (rated power 500 W, maximum DC link voltage 75 V, rated output current 6.2 A) from Celeroton is investigated. The switching and the conduction losses of the semiconductor devices as well as the iron losses of the inductor (applicable in PAM) are calculated based on datasheet values. For the switching loss calculation, the method presented in [4], which is a *worst-case* linear approximation of the semiconductor switching process, is adopted. The conduction losses are calculated based on the RMS values of the currents through the semiconductor devices and their forward voltage drops or resistances. The core losses in the inductor are calculated using the Steinmetz equation and the datasheet values. The copper losses of the inductor are not considered as they are negligible in the converter under investigation.

This modeling approach is simple, fast and does not require an actual converter for time consuming reference measurements as described in [3], therefore it can easily be used at the design stage of a converter. However, especially the switching losses depend on the actual board layout, and the core loss calculation is based on sinusoidal currents, limiting the accuracy of this modeling method.

C. Minimization of losses

The investigated concepts to minimize the losses that are evaluated in this work are grouped in two categories: motor design and converter modulation as shown in Table 1.

TABLE I
INVESTIGATED CONCEPTS FOR OPTIMIZATION

Motor design	**Converter Modulation**
Sleeve material	Pulse-amplitude-modulation (PAM)
Magnet material	Pulse-width-modulation (PWM)
Magnet segmentation	Pulse-width-amplitude-modulation (PWAM)
Conductive coating on rotor	Selective-harmonic-elimination (SHE)
Winding permeability (slotless motor only)	Energy-optimal-control (EOC)

III. Modifications on the Converter Side

It is mentioned above that PAM is preferred to PWM in high-speed drives due to its lower losses and easier control implementation. PAM, however, results in higher low-order harmonics that are responsible for additional eddy-current losses in the rotor [3]. Selective-harmonic-elimination (SHE) [6] makes it possible to eliminate certain lower order harmonics, however the higher order harmonics are amplified, making this method useless for minimization of rotor losses. Energy-optimal-control (EOC) is presented in [7] for minimizing the total-harmonic-distortion; however, as in SHE, the switching frequency remains high in this method. Therefore, SHE and EOC are not considered further.

A system similar to a PAM converter, with a boost type DC/DC converter is presented in [8]. The three-phase inverter operates with conventional PWM whereas the DC link voltage is set to an optimum value depending on the operating point of the motor, to minimize the losses. In [9] the same system is investigated, but with a new modulation scheme called the pulse-width-amplitude-modulation (PWAM) for the inverter.

Space-vector-modulation is a well-known PWM technique, where each one of the three bridge legs of a three-phase inverter is either connected to the positive or the negative rail of the constant voltage DC link. The six of the eight possible switching states are shown as the voltage vectors in Fig. 2 and the remaining two are zero voltage vectors where all the inverter outputs are short circuited. Any output voltage vector $\underline{u}_r$ that lies within the circle can be composed as a combination of two neighboring voltage vectors and the zero voltage vectors within one switching cycle. In PWAM, as described in detail in [9], within each of the six sectors, one upper and one lower switch in two different bridge legs are turned on. The third bridge leg is switched, connecting the third inverter output to the upper and lower rails of the DC link, meaning that the output voltage vector $\underline{u}_r$ is composed only by the two neighboring voltage vectors, and the use of zero vectors is not anymore possible. This leads $\underline{u}_r$ being able to move on the borders of the hexagon, but not anywhere inside. However, using the DC/DC converter the DC link voltage can be varied, changing the amplitude of the voltage vectors and making it possible to compose $\underline{u}_r$ vectors lying inside the circle.

The disadvantage of PWAM is the need to adjust the DC link voltage to have a ripple of six times the fundamental frequency of the machine, in order to create a rotating output voltage vector with a constant magnitude. The practical implementation of this in high-speed drives is demanding due to the high control bandwidth requirement. For this reason, in this work this approach is simplified by using a constant DC link voltage and called the approximated-PWAM (aPWAM) scheme, where a rotating voltage vector $\underline{u}_r$ with varying amplitude is created, following a hexagonal trace unlike the circular trace of PWM or the original PWAM.

In order to evaluate the performance of PAM, PWM, PWAM and aPWAM, first an operating point is set for the motors at 100 krpm and 30 mNm. Then, the current waveforms having the same fundamental component are calculated for each modulation scheme. Finally, the calculated current waveforms are input to the converter loss model described in II.B as well as the machine loss models described in [3].

Fig. 3 shows a comparison of different modulation schemes with respect to the total (machine and converter) losses, for the machine operating at 100 krpm and 30 mNm. For all of the cases, the aPWAM and PWAM give similar results, eliminating the need of a high-bandwidth control of the DC link voltage. It can be seen that PAM is the best modulation scheme for the slotless motor for this operating point, when total losses are considered. For this machine and operating point, PAM also gives lower machine losses compared to other modulations unless the inverter switching frequency is increased above 180 kHz. The fact that PAM results in lower machine losses might be considered counter intuitive as smoother currents may be expected for PWM. However, the

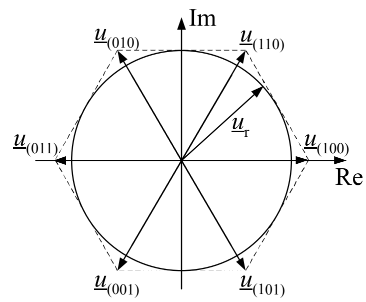

Fig. 2. The six nonzero voltage vectors and the output voltage vector $\underline{u}_r$ on the complex plane. Three subscripts denote the switching state of individual bridge legs of the three-phase inverter, where 1 means upper switch on and 0 means lower switch on. The zero voltage vectors are not shown, and they are called $\underline{u}_{(000)}$ and $\underline{u}_{(111)}$.

low machine inductance and the adjustable DC link voltage property of PAM actually lead to lower losses, also in the machine. The lower machine losses of PWAM and aPWAM compared to PWM can be explained the same way.

For the slotted machine, aPWAM with an inverter switching frequency above 40 kHz gives minimum overall losses. Furthermore, above 100 kHz both PWM and aPWAM approach the *ideal machine losses*, which occur in the hypothetical case of pure sinusoidal currents (leading to zero rotor losses), and cannot be further minimized for a given operating point.

IV. Modifications on the Machine Side

In literature, several concepts for the low-loss design of PMSMs can be found, some of which consider especially high-speed drives. Besides reducing the eddy-current losses in the copper wires by reducing the wire diameter and using high-frequency iron core materials, several methods also try to reduce the eddy-current losses induced in the rotor due to the flux harmonics. A conductive sleeve on the rotor surface may be used to shield the field harmonics and reduce the eddy currents in the rotor [10], [11]. The use of low-conductive sleeve and magnet materials [12] as well as segmentation of the permanent magnets [13] are also proposed for decreasing the eddy currents induced in the rotor. In this paper, along with modifications on the geometries and materials of the sleeve and permanent magnets, the altering of the winding permeability, which is only applicable to the slotless motor topology, is also analyzed.

Only PAM is considered at this stage as it results in the lowest total losses in most of the cases as shown before. The current waveform is calculated and input to the loss models derived in [3] to evaluate the loss reduction potentials of each modification. The machine inductance is calculated for each modification on the machine, and taken into account when calculating the phase currents. The air-friction losses are not considered for the sake of simplicity, as the main goal is to have insight on the behavior of the electromagnetic losses under various modifications.

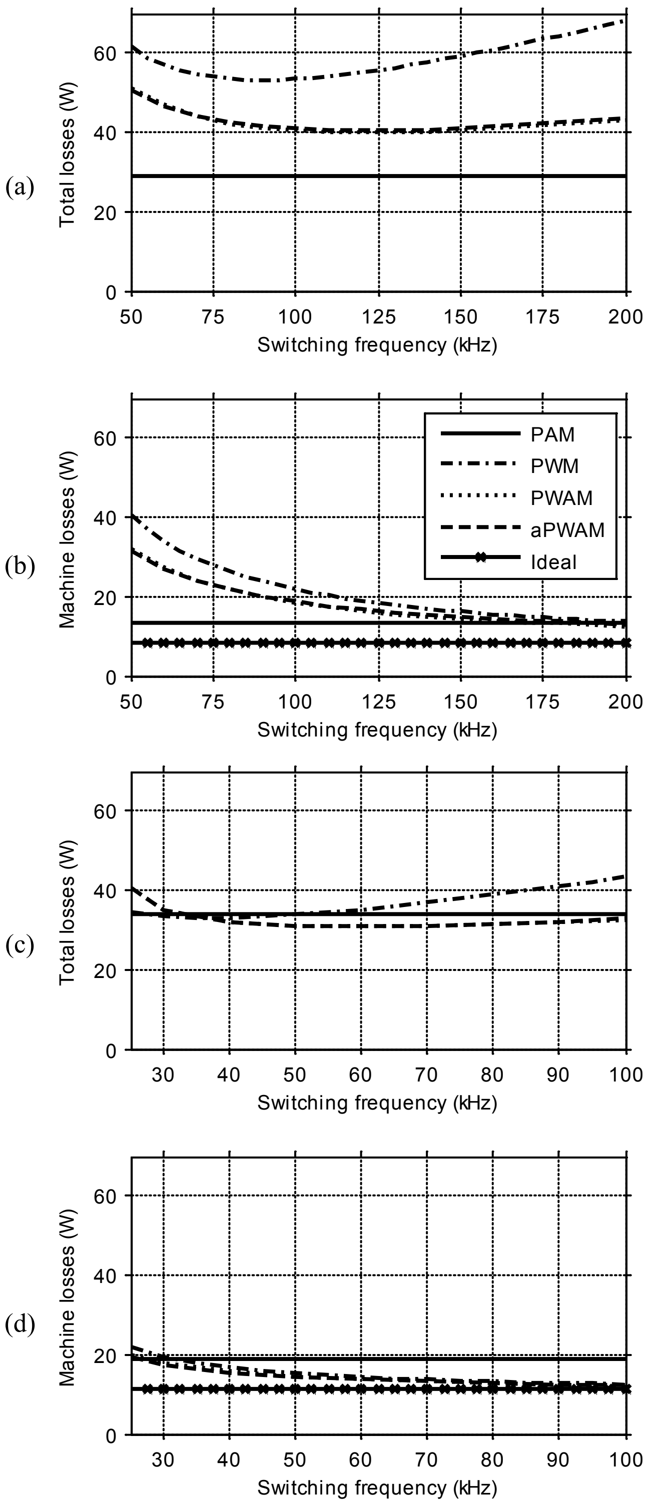

Fig. 3. Total (converter and machine) losses (a, c) and machine losses (b, d) over the switching frequency for the modulation schemes PAM, PWM, PWAM and aPWAM, for the slotless machine (a, b) and the slotted machine (c, d). The losses for PAM are constant because the inverter is switched with the fundamental frequency of the machine. For PWAM and aPWAM, the DC/DC converter switches with the same switching frequency as the inverter. The machines are operating at 100 krpm and 30 mNm. Ideal means pure sinusoidal currents with no harmonics – which is the minimum amount of losses generated for driving the machine at the specified operating point.

A. Sleeve material

In the high-speed motor topologies of Fig. 1, a sleeve is used in the rotor mainly in order to ensure mechanical stability. Titanium is widely used for its mechanical strength and low density, and the sleeve thickness is generally determined by mechanical constraints. However, the sleeve material and thickness can be optimized for minimizing the rotor losses. In this work, two different grades of copper (DHP and ETP), titanium and carbon fiber sleeves are considered; whose conductivities are 43, 59.2, 0.585 and 0.049 S/µm respectively. As before, the operating point for the machine is 100 krpm and 30 mNm.

Fig. 4 shows the rotor losses for different sleeve materials and thicknesses. For mechanical reason, the sleeve must have a minimum thickness, which is not considered at this stage. The stator inner diameter is kept at the same value, i.e. the air gap is decreasing if the sleeve thickness is increasing. Rotor losses with a carbon fiber sleeve do not depend on the sleeve thickness due to its low conductivity, as eddy currents are induced only in the magnet and the rotor hub if there is one. Titanium and the permanent magnet have conductivities in the same range, therefore the losses increase slightly with increasing sleeve thickness due to the closer proximity of the conductive material to the stator and therefore to higher field harmonic amplitudes. With copper, the high conductivity results in a thin skin depth, which helps shielding the permanent magnet and decreasing the rotor losses. Segregation of the rotor losses for a copper sleeve thicker than 200 µm showed that almost all the losses are induced in the sleeve and

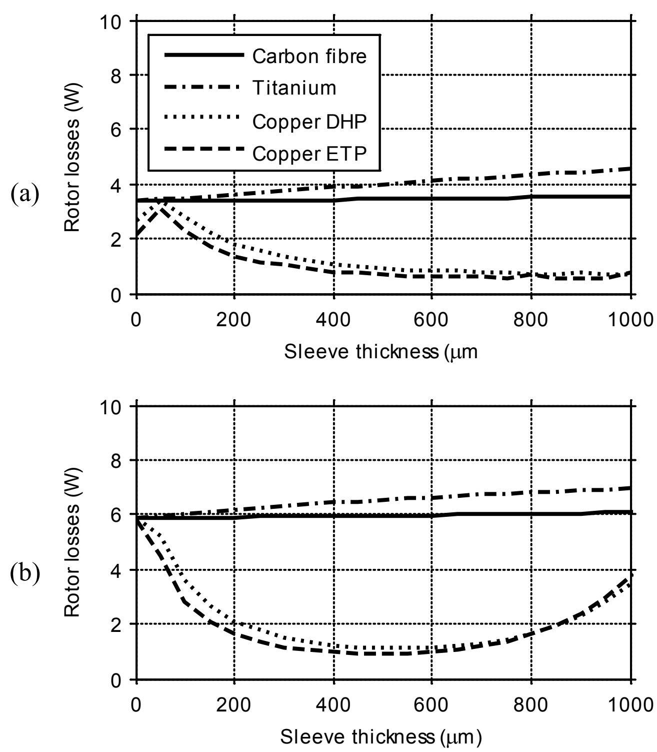

Fig. 4. Rotor losses over sleeve thickness for different sleeve materials for the slotless (a) and the slotted (b) machine. ETP and DHP are different grades of copper. It can be seen that a conductive sleeve with an optimum thickness can shield the eddy currents and reduce the total rotor losses.

not in the permanent magnet anymore. An interesting result is the increasing rotor losses in the slotted machine for sleeve thicknesses above 600 µm. The reason for this is the much smaller magnetic air gap of this machine, compared to the slotless one. If the distance between sleeve and inner stator bore gets smaller, the armature field harmonic amplitudes and therefore rotor losses increase.

B. Conductive coating

It is shown above that using a copper sleeve instead of a titanium sleeve may decrease the rotor losses sacrificing the mechanical strength of the rotor, which may limit the maximum possible speed. An alternative way of shielding the rotor is to use a highly conductive sheet such as a thin copper layer in addition to the titanium sleeve. This additional sheet may be placed on the outer face of the titanium sleeve, or in between the titanium sleeve and permanent magnet. The first method is advantageous in the sense that the existing rotors might be coated with a layer of copper whereas a new rotor construction would be necessary otherwise. However, coating copper on titanium is not an easy process due to the chemical properties of titanium whereas permanent magnets are commonly coated with different materials in order to prevent oxidation.

In order to evaluate the conductive coating method, the machine model in [3] has been extended to have an additional layer (similar to that of the titanium sleeve) accounting for the coated copper layer. Fig. 5 shows simulation results for different thicknesses of copper coating for both the slotted and slotless machines, where the coating is on the titanium sleeve, and Fig. 6 shows the same where the coating is between permanent magnet and the titanium sleeve (titanium sleeve thickness is kept constant). It can be seen that most of the losses occur in the conductive layer, regardless of its position. The difference Fig. 5(b) and Fig. 6(b) can again be explained by the difference in proximity of the shielding layer and the stator bore. The amplitudes of the field harmonics and therefore the losses are higher if the conductive coating is closer to the stator bore. In the slotted machine this is much more significant than in the slotless machine where the magnetic air gap is much bigger.

C. Magnet material

Rare earth magnets such as sintered NdFeB or SmCo offer high energy densities which results in high power densities in PMSMs. However, high electrical conductivities (0.56 S/µm) of those materials lead to high eddy currents in the rotors of PMSM due to the field harmonics. Replacing these materials with plastic bonded permanent magnets would essentially solve this problem, as their electrical conductivities are much lower (0.0039 S/µm). However, using plastic bonded magnets means reduced flux linkage due to their lower remanent flux densities (0.68 T compared to 1.35 T of sintered rare earth magnets) and therefore higher currents for a given torque. Therefore, in order to make a fair comparison first a new bonded magnet slotless machine that fits in the same volume as the sintered magnet slotless machine is designed by optimizing the machine geometry for minimum losses according to [14]. A titanium sleeve is assumed for its mechanical strength.

The optimization results in a machine with the same winding area, but a larger magnet and a thinner stator iron compared to the sintered magnet slotless machine. As it can be

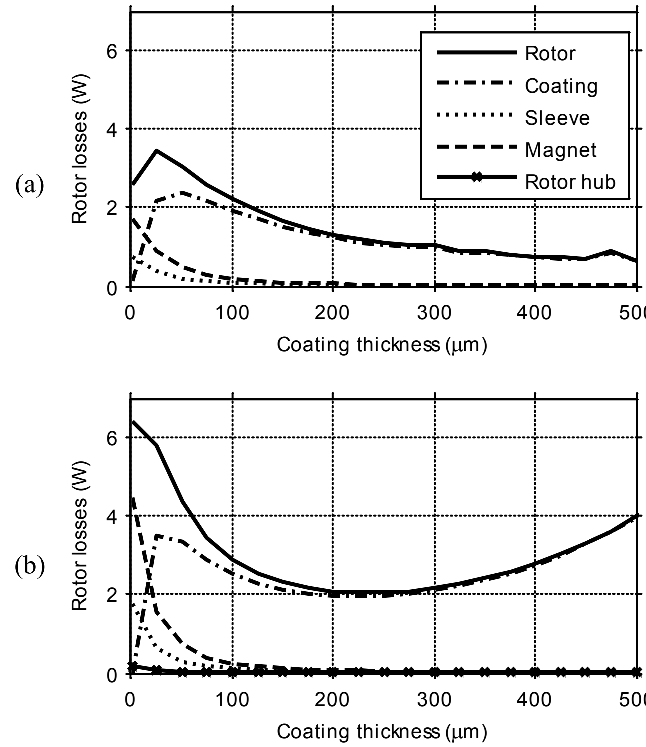

Fig. 5. Rotor losses over coating thickness for copper ETP coating around a titanium sleeve for the slotless (a) and the slotted (b) machine.

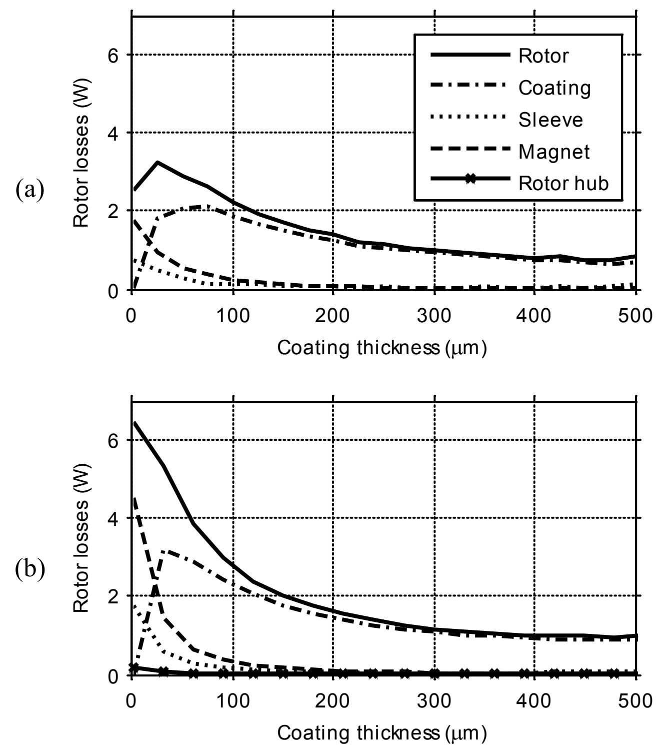

Fig. 6. Rotor losses over coating thickness for copper ETP coating on the permanent magnet inside the titanium sleeve for the slotless (a) and the slotted (b) machine.

seen in Fig. 7(a), for the same torque, more current is needed for the bonded magnet machine, resulting in more copper and hence more total losses. Fig. 7(b) shows that the rotor losses have shifted from the magnet to the sleeve; however the overall rotor losses stay the same.

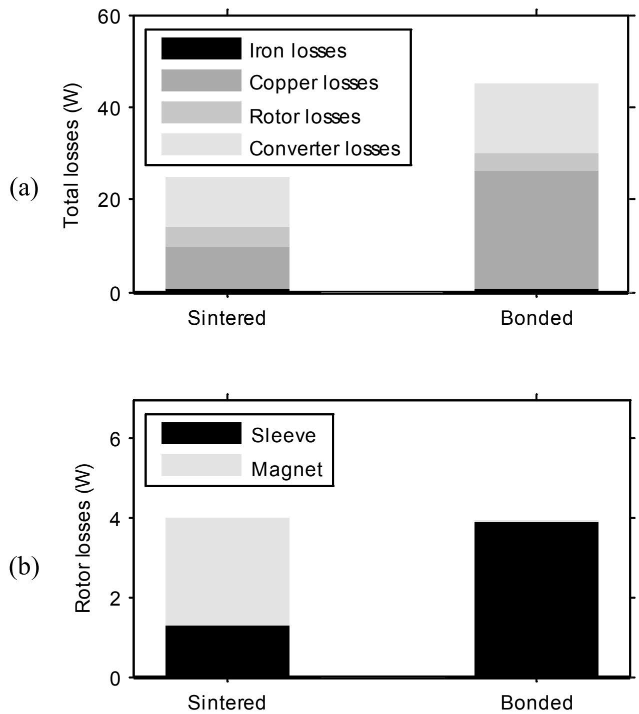

Fig. 7. Total (a) and rotor (b) losses of two slotless machines with different magnets, with the same outer dimensions, both optimized for minimum losses for the same operating point.

D. Magnet segmentation

Axial segmentation of the permanent magnets is a commonly used method in order to reduce the eddy-current losses in the rotors of PMSMs. The end effects in each segment, introduced by the axial segmentation cannot be modeled using 2D models such as the ones in [3]. However, there are 2D models which take segmentation into account by introducing a correction factor that adjusts the conductivity of the magnet material based on geometrical dimensions of the single segments [15]. Unfortunately, the assumptions that these models are based on, such as the magnet dimensions being smaller than the skin depth, or homogeneous flux density on the magnet are not satisfied in the high-speed motors investigated in this work. Therefore, 3D time-transient FEM is used for calculating the effect of magnet segmentation on rotor losses. A titanium sleeve and sintered rare earth magnets are assumed.

Fig. 8 shows the results of this analysis, both for the slotted and the slotless machines. It can be seen that in both the cases the rotor losses can be decreased, but not significantly. The reason is the increasing sleeve losses for increasing number of magnet segments, which is similar to the case where the plastic bonded magnets are used instead of sintered rare earth magnets. These results may point the use of segmented magnets with a carbon fiber sleeve; however it is not analyzed here due to the increased complexity and decreased mechanical strength of the rotor.

E. Winding permeability

The slotless machine is usually preferred for high-speed applications due to the low armature reaction and the lack of field harmonics caused by the stator slotting. However, the

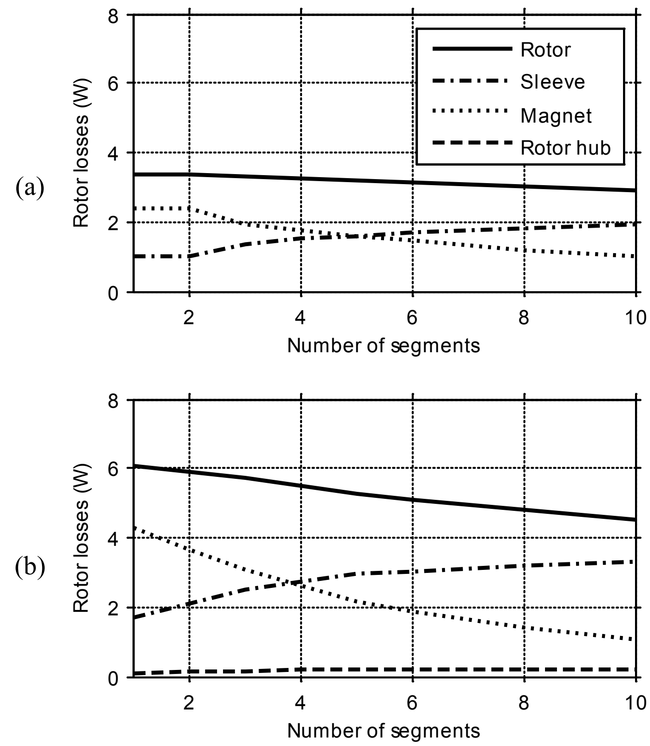

Fig. 8. Different components of rotor losses as well the total rotor losses for the slotless (a) and the slotted (b) machine. The rotor hub exists only in the slotted machine.

resulting large magnetic air gap decreases the flux linkage, limiting the utilization of the permanent-magnets. In [16] compound wires of copper and iron have been examined for a use in slotless PMSMs. These wires consist of a copper core cladded by an iron sheet. Due to the high permeability of iron, the flux linkage of the permanent magnet can be increased compared to PMSMs with standard litz wires. A further characteristic of this configuration is that the copper wire is shielded from the magnetic flux because of the iron around it, meaning that the proximity losses in the copper should not increase by the increase in flux linkage. However, to the best of the authors' knowledge, those wires are not manufactured in large quantities today. Therefore, in this work, a simpler and cheaper approach is analyzed to have a similar effect.

The copper filling factor in high-speed slotless machines is around 30-40%. The rest of the winding volume consists of insulation of the litz wire and epoxy filling the voids. The equivalent permeability of the winding area can be improved by adding iron powder into the epoxy.

For evaluating the influence of the winding permeability on the machine losses, the models of [3] cannot be used as there the windings are modeled as thin current sheets in the stator bore as a boundary condition rather than current densities on the actual winding area. Therefore, for the calculation of the field and the losses in the machine, the models given in [17] are adopted, where individual winding areas are modeled separately. Equivalent relative winding permeabilities between 1 and 30 are simulated. The results are shown in Fig. 9. The rotor losses are decreasing as the flux linkage increases, as lower currents are needed to generate the same torque. However, after the flux linkage stops increasing, the continuously increasing inductance means increased armature reaction, hence increasing rotor losses. According to those results, the rotor losses may be decreased by increasing the equivalent winding permeability. However, the amount of iron to be added into the epoxy to reach the desired permeability as well as its effects on the electrical stresses in the winding insulation need to be analyzed further.

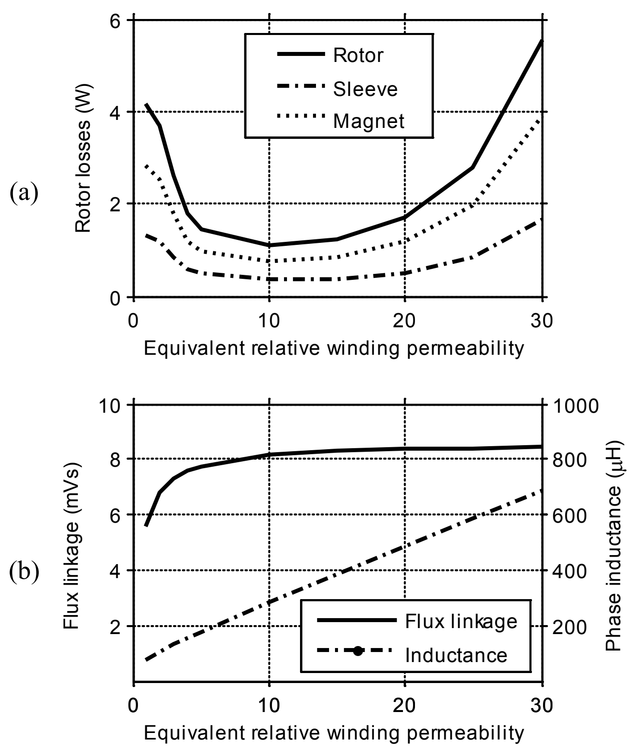

Fig. 9. (a) Rotor losses over equivalent winding permeability for the slotless machine. (b) Phase inductance 1.67 kHz and flux linkage over equivalent winding permeability for the slotless machine.

V. Evaluation of the Model Results

The simulations described above showed that aPWAM method has a potential for decreasing the rotor losses compared to PAM, especially for the slotted machine. Therefore this method is implemented in hardware and tested.

The effects of the modifications on the machine side (considering PAM operation) are shown in Table II.

As described above, coating of titanium with copper is not an easy task because of the relatively strong dioxide layer on titanium's surface, which prevents any material to be deposited. Sintered permanent magnets are easily coated with different materials; however the thickness of this coating is usually only several micrometers, which is not enough for an effective shielding performance. Mounting a hollow copper cylinder in the rotor can be considered instead of coating, but the mechanical stability remains an open point due to the different thermal expansion coefficients of titanium and copper. Therefore, a sleeve made of copper is chosen and manufactured as a first verification step.

TABLE II
Rotor Loss Reduction in Percent for the Slotted and the Slotless Machines

Modification	Slotless machine	Slotted machine
Copper (ETP) sleeve	86%	86%
Copper (ETP) coating on titanium sleeve	84%	85%
Copper (ETP) coating on the permanent magnet	82%	69%
Winding permeability	72%	N/A
Magnet segmentation (10 axial segments)	27%	27%
Plastic bonded magnet	1%	N/A

The rotor losses for the original machines (without any modifications) are 3.99 W (slotless) and 6.53 W (Slotted).

VI. Experimental Results

The test setup and measurement approach described in [3] is used for comparing the losses of the rotors with the copper and titanium sleeves for PAM, as well as comparing the machine and converter losses of aPWAM, PWM and PAM for a rotor with titanium sleeve.

Fig. 10 shows that for PAM, the machine losses are lower for the copper sleeve compared to the titanium sleeve, as the simulations predicted. It can also be seen that the 2D analytical models are able to predict the losses accurately for both the slotless and the slotted machines.

Fig. 11 shows the difference of the machine and converter losses of PWM and aPWAM compared to PAM for the slotted machine. It can be concluded that PWM and aPWAM produce lower machine losses than PAM, as predicted by the simulations. For PWM and aPWAM, converter losses are approximately equal over the whole frequency range, contradicting the simulations especially for high frequencies. For PWM, the simulated losses have a steeper slope than measured. For aPWAM, both simulation and measurement shows the same slope, but there is an offset error of about 2 W. Over the whole frequency range, PWM and PWAM produce lower converter losses than PAM, also in contradiction to the simulation results. Although the explanation of this mismatch is the subject of undergoing research, a possible reason is the *worst case* approach adopted for modeling the switching losses, which may lead to results in favor of PAM compared to PWM at increased switching frequencies. On the machine side in general, the neglected end effects are considered to be limiting the accuracy of the models. Furthermore, the measurement accuracy is challenging, as loss differences in the Watt range have to be detected while absolute powers measured are in the 100-Watt range, and as high frequency components in currents and voltages also contribute to the power and have to be measured.

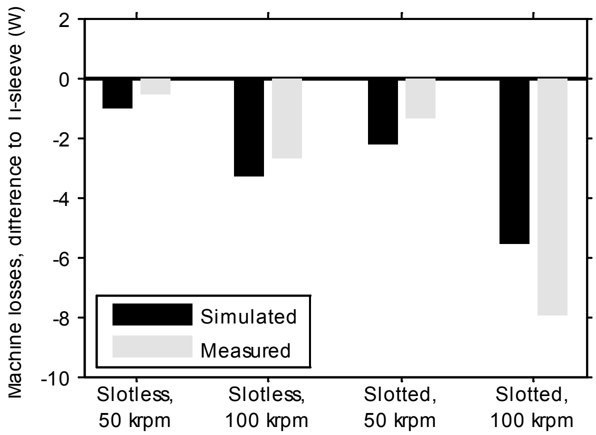

Fig. 10. Difference of machine losses for the copper sleeve rotor compared to the titanium sleeve rotor. The speeds of the machines are 50 krpm and 100 krpm, the nominal torque is 30mNm and the modulation scheme is PAM.

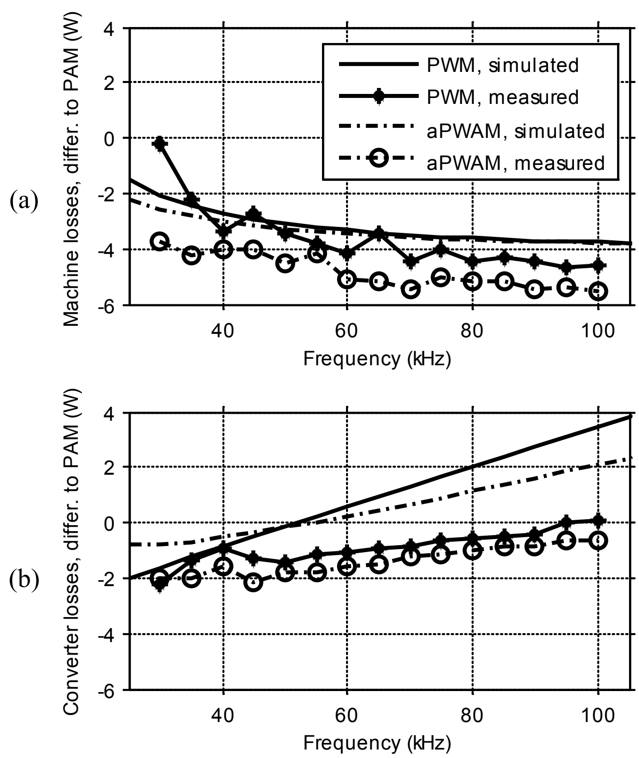

Fig. 11. Difference of machine losses (a) and converter losses (b) for the slotted machine for PWM and aPWAM to PAM over inverter switching frequency. The operating point is 50 krpm, 30 mNm. A titanium sleeve is used. The DC/DC converter switching frequency is set to 80 kHz for PAM, and for aPWAM the DC/DC converter and the inverter switching frequencies are equal for each measurement point.

VII. Conclusion

In this paper, analytical loss models derived for high-speed drives are used for evaluating different modifications on the converter modulation and the machine construction, analyzing their influence on different loss components, in order to find a loss-optimal design for a given application. After a comprehensive evaluation of different modulation schemes and machine constructions, the aPWAM scheme and a copper sleeve are implemented in hardware and the models are verified with experimental results. Future work includes evaluation of combination of the analyzed methods, e.g., a copper sleeve with aPWAM.

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