Electromagnetic and Mechanical Analysis of High Speed SPM Rotor with Copper Shield

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***Abstract*— For high-speed applications, the surface-mounted permanent magnet (SPM) machine is preferred due to its high torque density and efficiency. However, induced eddy currents in the rotor conductive parts result in a loss of efficiency and rotor heating. Therefore, several methods to reduce such losses have been proposed in the literature including copper shielding. In this paper, a high-speed SPM machine rotor with a copper shield is designed and investigated both electromagnetically and mechanically. Several quantitative investigations including placing the copper sheet around the retaining sleeve or magnets, different copper sheet and airgap thicknesses, different retaining sleeve materials, different harmonic contents in the current waveform, i.e. pulse amplitude modulation (PAM) and pulse width modulation (PWM) generated waveforms, and different frequencies and current levels are reported. Additionally, a mechanical analysis investigating possible failure modes of the rotor with the copper sheet is reported.**

Keywords—Copper shield, conductive shield, SPM, surface-mounted, loss reduction, eddy current loss

I. INTRODUCTION

Surface-mounted permanent magnet (SPM) machines are considered suitable candidates for high-speed applications due to their high torque density and efficiency [1]. Conventionally, a high-speed SPM machine rotor is made of a shaft, back-iron (rotor yoke), PMs and retaining sleeve, the last is required to maintain the mechanical integrity of the rotor. However, the high electrical conductivity of the permanent magnets (PMs) and the retaining sleeve and the presence of space- and time-harmonics in the electromagnetic field cause eddy currents to be induced in the rotor. The heating due to the eddy currents can cause an irreversible demagnetization of the magnets, mechanical degradation of the rotor and therefore a machine failure. Therefore, in the literature, several methods have been proposed to reduce the space-harmonics, e.g. slot-less machine and closed slot stators [2-3], and the time-harmonics, e.g. high switching frequency and external inductance [4-5]. Moreover, radial segmentation of the PMs [6], and axial segmentation of the PMs and/or sleeve are proposed to reduce the eddy currents [7]. In addition, a copper shield to reduce such loss by shielding rotor components from the harmonic content of the magnetic field has been reported.

A copper shield for SPM rotors was firstly introduced in [8], where the authors concluded that using a copper shield around the rotor together with subdividing the phase winding can reduce the rotor losses to an acceptable level of the rated power. Further work on copper shielding was reported in [9-10]. These papers stated that the copper shield reduces the rotor loss at high-speeds, whereas magnet segmentation is preferred for low speeds. In [11], space-harmonic analyses of several SPM machine topologies were used to assist the design of high-speed rotors with copper shielding and/or magnet segmentation, and in [12], time-harmonic analyses of a SPM machine to assist the design is used.

In this paper, using finite element analysis (FEA), a wider investigation of the design aspects associated with copper shielding has been carried out through several quantitative studies. These include placing the copper shield around the sleeve or between the sleeve and magnets, different copper shield and airgap thicknesses, different sleeve materials and current waveforms with different harmonics, frequencies and levels. Moreover, mechanical FEA of the rotor with the copper shield placed in between the sleeve and magnets sheet and placed around the sleeve has been undertaken to determine possible mechanical failure modes.

II. HIGH-SPEED SPM MACHINE

The SPM machine used in this study is designed for a speed range of 100 to 200krpm. The rotor consists of a shaft, yoke (made of the same material as the sleeve), PMs and outer retaining sleeve.

III. ELECTROMAGENTIC ANALYSIS

The thickness of the copper shield is selected based on the skin depth of either the current time-harmonics [13] assuming that the space-harmonic has little effect, or based on the space-harmonics assuming that the current is purely sinusoidal [14]. However, if the machine operates at variable frequencies and current modulations, the harmonics and their skin depths will also vary. While having the copper shield outside the rotor can supress the harmonics in the whole rotor, i.e. sleeve and magnet, the loss in the copper shield might increase the overall rotor loss. This highly depends on the stator harmonics, i.e. stator poles and winding, and airgap thickness, i.e. the effectiveness of the stator-harmonics. Alternatively, having the copper shield between the sleeve and magnets can still supress the harmonics, especially low order high amplitude time-harmonics, and therefore reduce the overall losses in the rotor. It is worth noting the graphs presenting the rotor loss in this section are with logarithmic vertical axis/rotor loss axis).

The work described here has been funded by BorgWarner and the Regional Growth Fund Award 01.09.07.01/1789C

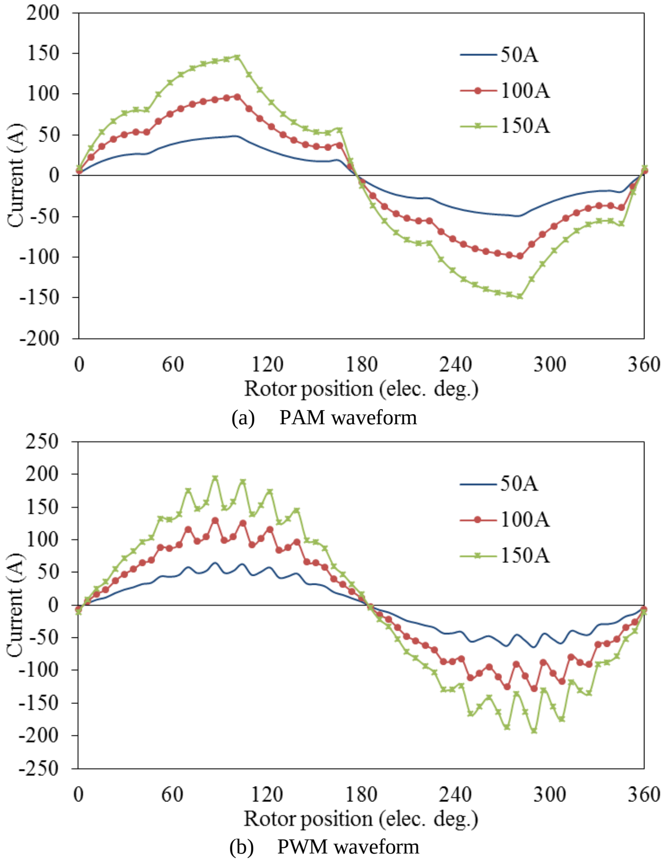


Fig. 1. PAM and PWM generated current waveforms.

Therefore, a quantitative analysis of the rotor eddy current loss and torque has been conducted at different design conditions. These design conditions were: 1) copper shield location, between the sleeve and magnets (Internal) or outside the sleeve (External), 2) copper shield thickness, 3) airgap thickness, 4) sleeve material, high and low conductive sleeves, 5) current waveform with different harmonic content, sinusoidal, and pulse amplitude modulation (PAM) and pulse width modulation (PWM) generated waveforms, 6) frequency, and 7) current level. Fig. 1 presents the PAM and PWM current waveforms used in the analysis.

A. Copper Shield Location

Internal and external copper shields with different thickness were investigated. The copper shield thickness was subtracted from the sleeve thickness. This caused small reduction in the mechanical retaining capability of the sleeve. The investigation is conducted using pure sinusoidal current waveform with different amplitudes (50, 100 and 150A), speeds (100, 150 and 200krpm), airgap thicknesses (1, 2 and 3mm), and copper shield thicknesses (0, 0.1, 0.2 and 0.3mm).

Figs. 2 and 3 show the total rotor loss of SPM machine with internal and external copper shield, respectively. It can be seen that the internal copper shield reduces the total rotor loss, except at the lowest speed where the space-harmonics have large skin depth. On the other hand, using the external copper shield leads to a significant increase in the total rotor loss since the copper shield is located near the airgap. Therefore, the influence of the stator space-harmonics (slotting effect) is large. However, at high speeds with a thick copper shield (thicker than the skin depth of lowest space-harmonic order), the total rotor loss can be reduced.

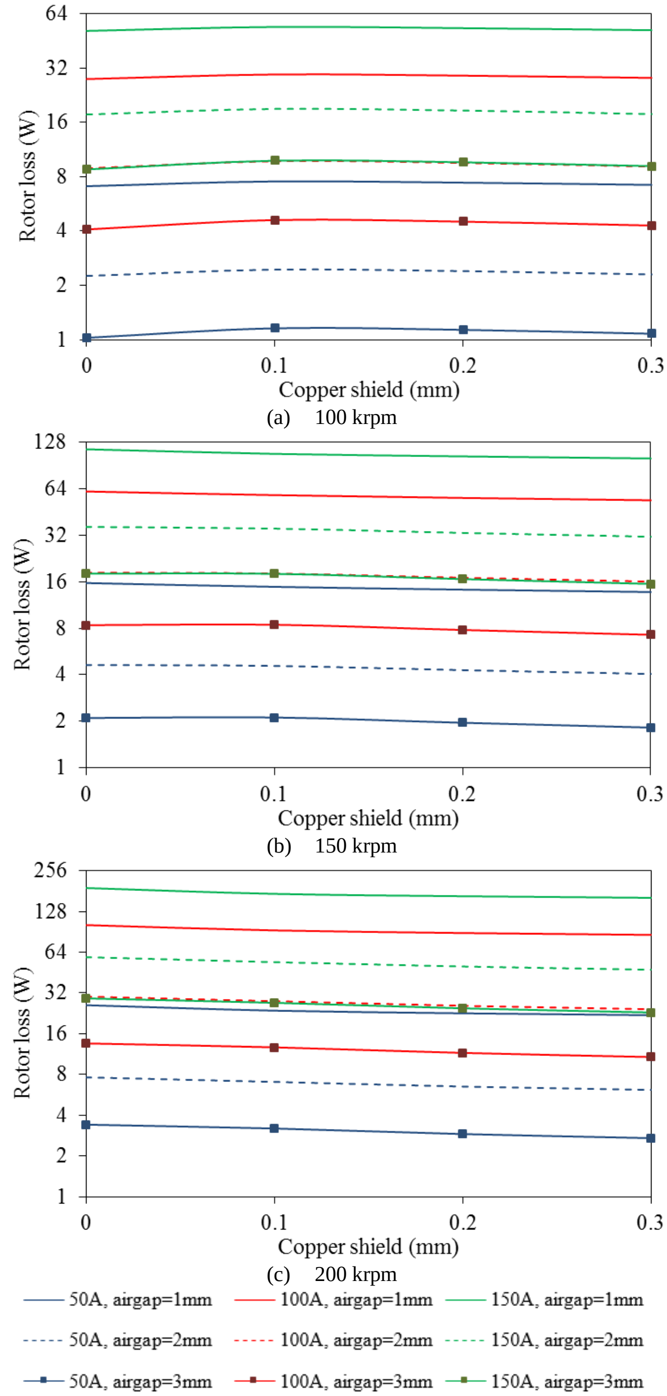


Fig. 2. Rotor loss with different internal copper shield thicknesses, current levels and frequencies.

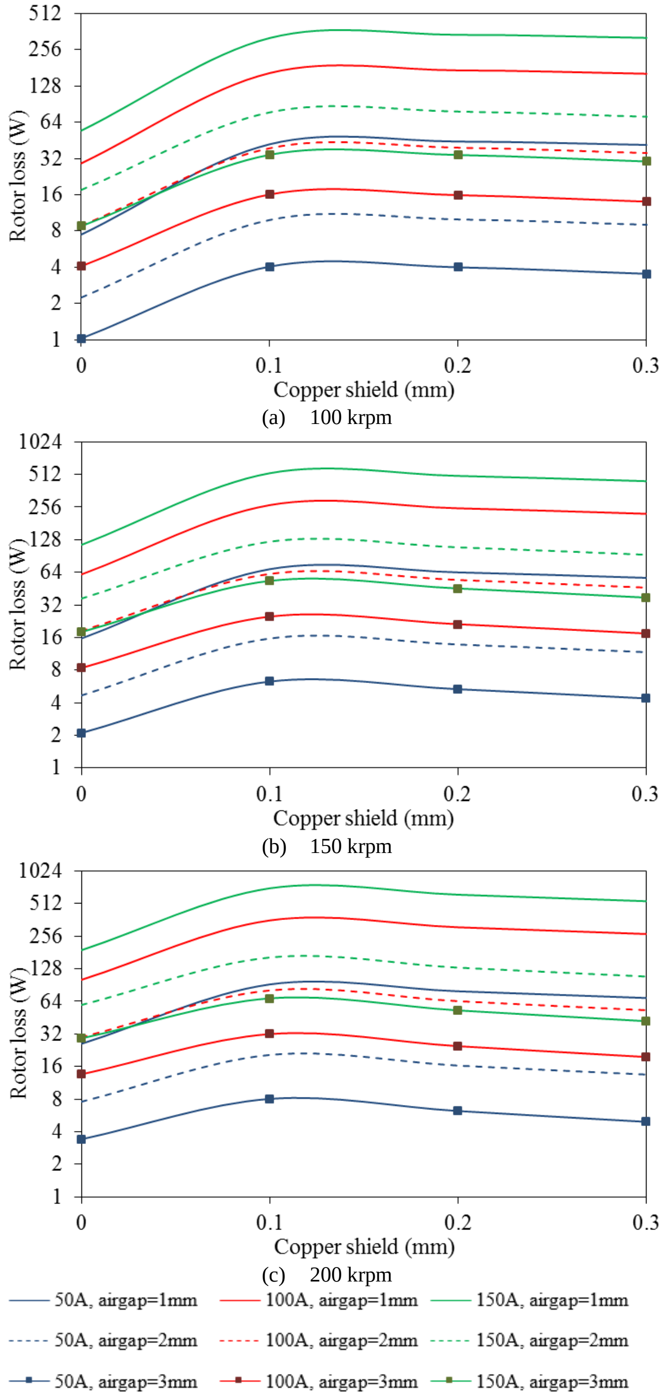


Fig. 3. Rotor loss with different external copper shield thicknesses, current levels and frequencies.

B. *Current Wavefrom Harmonics (Sine, PAM, and PWM)*

The influence of the time-harmonics on the SPM machine with copper shielding was investigated using a purely sinusoidal current waveform and current waveforms generated by PAM and PWM inverter strategies, shown in Fig. 1. The investigation included different current amplitudes (50, 100 and 150A), airgap thicknesses (1, 2 and 3mm), and copper shield thicknesses (0, 0.1, 0.2 and 0.3mm). The investigation was conducted at a speed of 100krpm.

Figs. 4 and 5 show the influence of different current waveforms on the total rotor loss of the SPM machine with internal and external copper shields, respectively. The internal copper shield reduced the total rotor loss in both PAM and PWM cases. A greater reduction in losses was observed with the PAM compared to PWM, i.e. percentage difference with the original. This was due to the high amplitude, low order harmonic content. The external copper shield reduced the total rotor loss at high current levels, large airgap and thick copper shield. Similarly, more reduction was found with the PAM compared to the PWM.

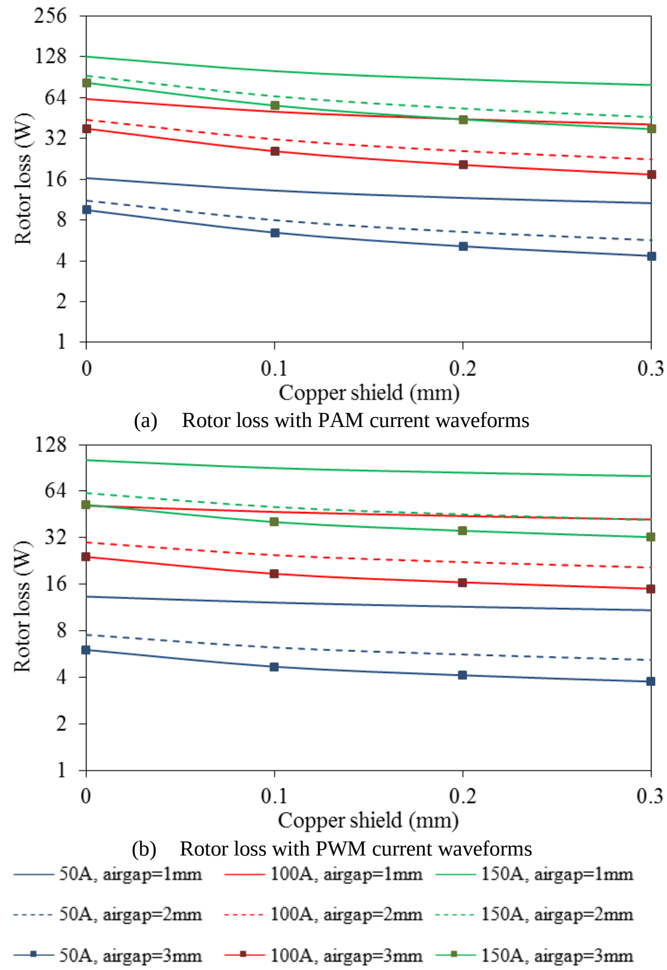


Fig. 4. Rotor loss with different internal copper shield thicknesses, current harmonics and current levels.

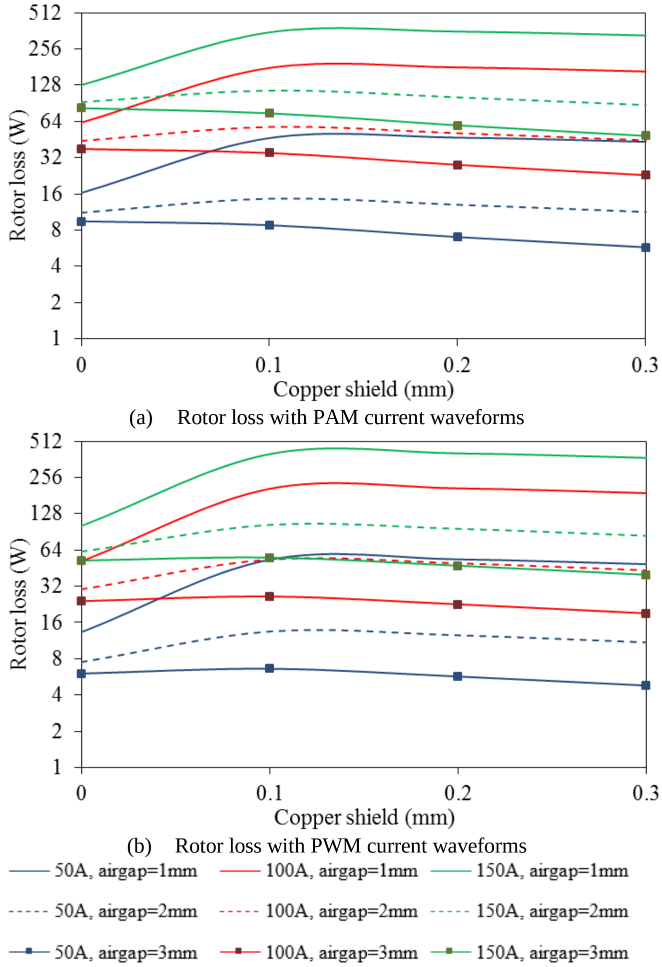


Fig. 5. Rotor loss with different external copper shield thicknesses, current harmonics and current levels.

C. *Sleeve Material*

An investigation of the impact of sleeve electrical resistivity on the total rotor loss when a copper shield is used was conducted. The analyses presented in sections A and B are conducted using a high electrical resistivity carbon fibre sleeve. The analyses was repeated with a low electrical resistivity Inconel sleeve giving the results shown in Figs. 6 and 7.

Compared with the high resistivity sleeve presented in sections A and B, the internal copper shield with a low resistivity sleeve leads to slightly lower rotor losses at 100krpm compared with the original, i.e. without the copper shield. When PAM and PWM current are used with an internal copper shield, the percentage of rotor loss reduction is less than the high resistivity sleeve machine. This is due to the high induced loss in the sleeve. With an external copper shield, the same total rotor loss is found in the low and high resistivity sleeve machines, since the copper shields the losses in the rest of the rotor components and the rotor loss occurs mainly in the copper shield.

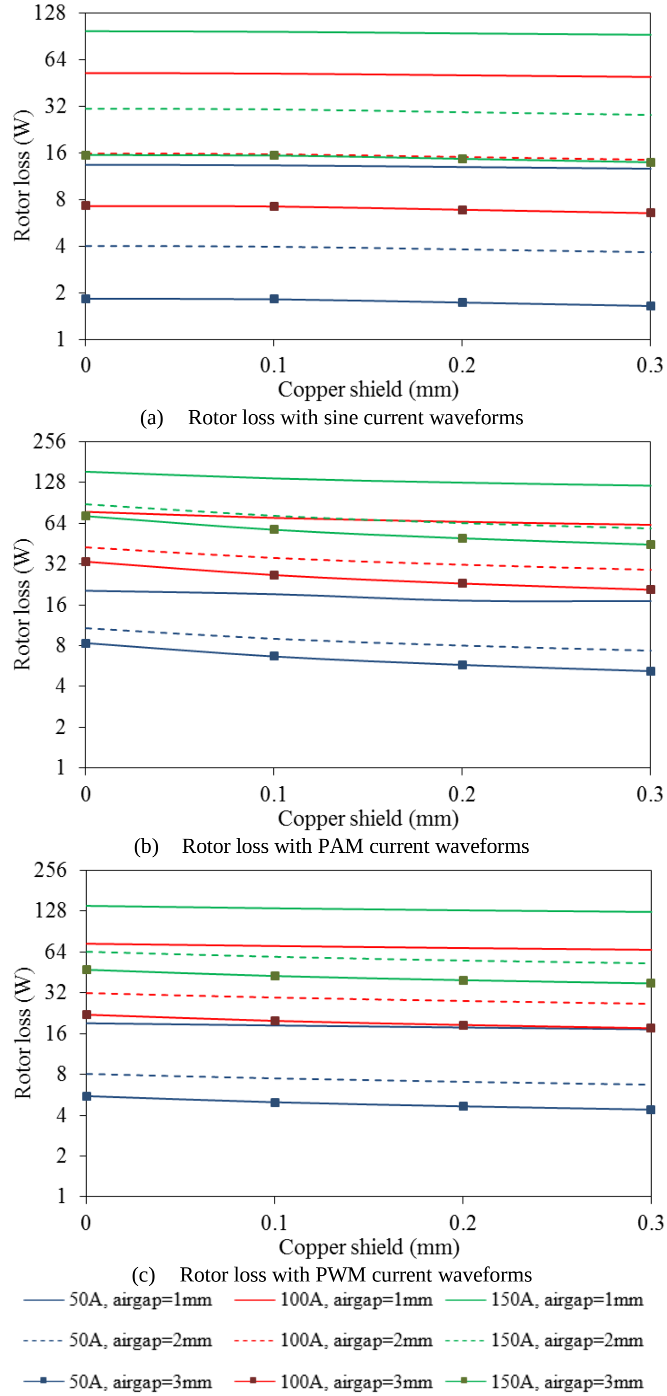
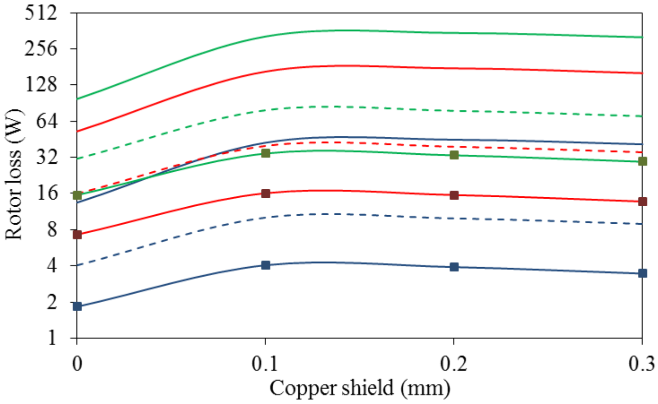
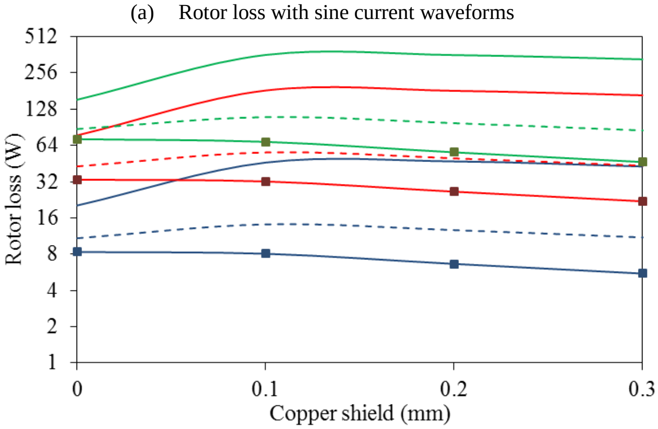


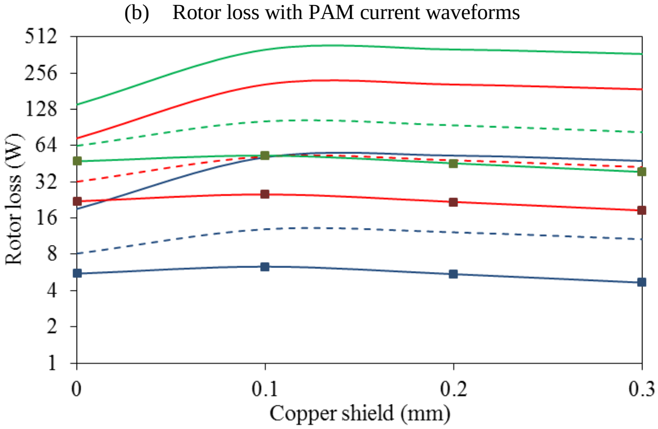
Fig. 6. Rotor loss with different internal copper shield thicknesses, current harmonics and current levels.



(a) Rotor loss with sine current waveforms



(b) Rotor loss with PAM current waveforms



(c) Rotor loss with PWM current waveforms

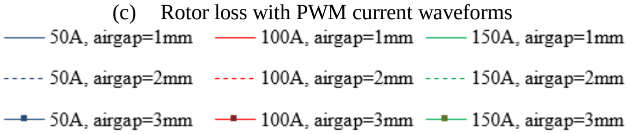
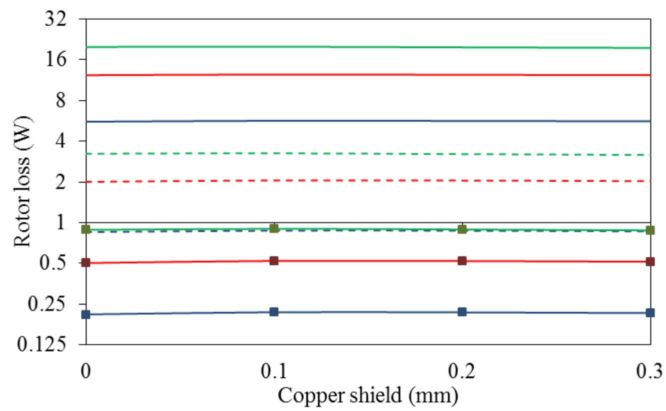


Fig. 7. Rotor loss with different external copper shield thicknesses, current harmonics and current levels.

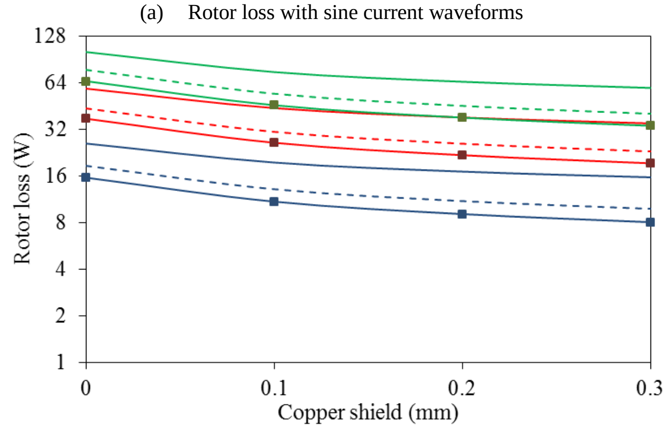
D. *Stator Pole Number*

To investigate the influence of the space-harmonic on the total rotor loss in the SPM machine with copper shielding, a 24/4 stator/rotor pole machine with the same main dimensions as the original 18/2 stator/rotor pole machine and carbon fibre sleeve was analysed and compared with the original 18/2 machine. Different current amplitudes (90, 140 and 190A), airgap thicknesses (1, 2 and 3mm), copper shield thicknesses (0, 0.1, 0.2 and 0.3mm), and rotor speed of a 100krpm were included in the investigation. The results of the 24/4 machine are shown in Figs 8 and 9. It is worth noting the current in the 24/4 machine was selected to provide the same current density as in 18/2 machine. Additionally, the PAM and PWM current waveforms used in the 24/4 machine were scaled from the current waveforms shown in Fig. 2.

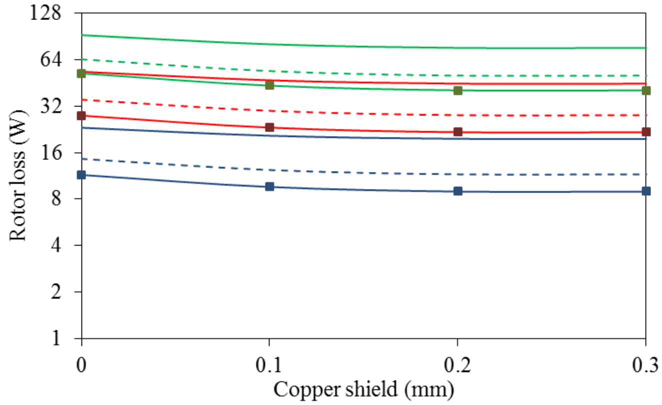
Comparing Figs. 8 and 9 with Figs. 2-5, it can be seen that using a higher number of stator poles reduces the influence of the slotting effect (space-harmonics) and therefore, lower rotor loss can be seen in the 24/4 machine compared to the 18/2 machine. When a PAM or PWM current is used, the reduction in the rotor loss in the 24/4 machine is more than the 18/2 machine. However, when a large airgap thickness is used, the influence of the slotting effect becomes smaller and therefore the percentage reduction of the rotor loss in 18/2 and 24/4 machines is similar. On the other hand, using an external copper shield with PAM or PWM waveforms leads to higher rotor losses when the airgap thickness is small and lower rotor losses when the airgap is large. The same effect is found in the 18/2 machine however the magnitude of the effect is lower in the 24/4 machine.



(a) Rotor loss with sine current waveforms

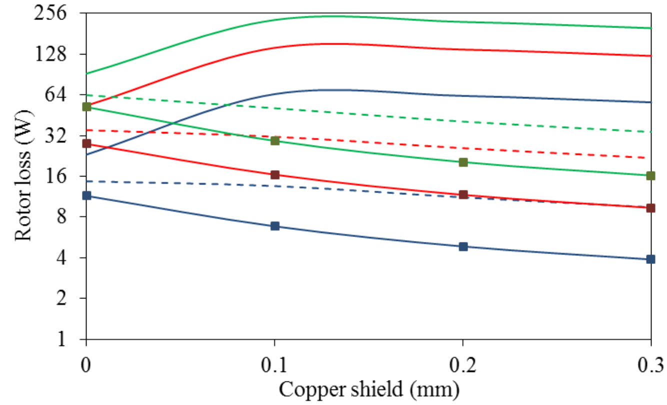


(b) Rotor loss with PAM current waveforms



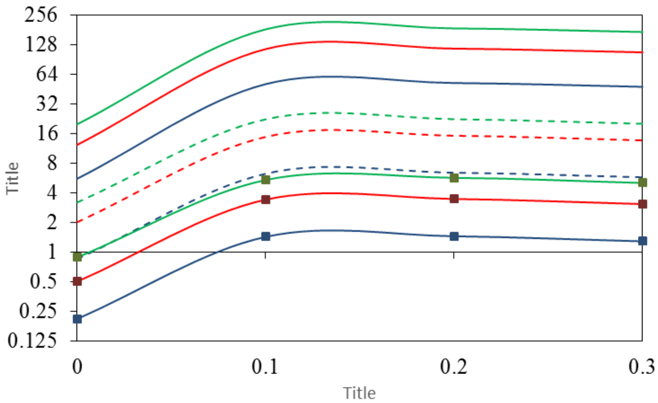
(c) Rotor loss with PWM current waveforms

Fig. 8. Rotor loss with different internal copper shield thicknesses, current harmonics and current levels, 24/4 machine.

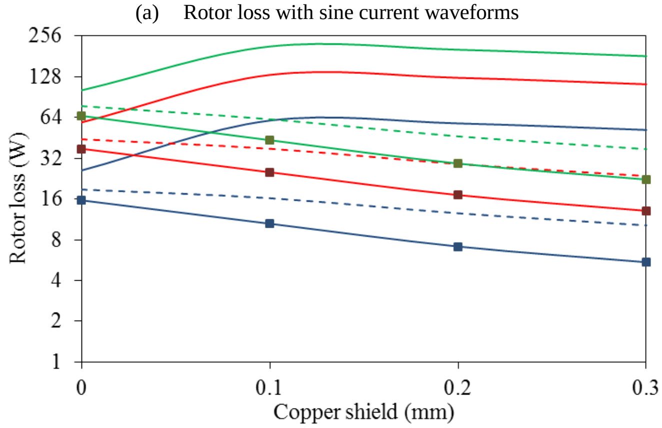


(c) Rotor loss with PWM current waveforms

Fig. 9. Rotor loss with different external copper shield thicknesses, current harmonics and current levels, 24/4 machine.



(a) Rotor loss with sine current waveforms



(b) Rotor loss with PAM current waveforms

E. Torque

Fig. 10 presents the average torque of the 18/2 and 24/4 machines at different airgap thickness and currents. It can be seen that the reduction in the 18/2 machine torque is 8% and 15% when the airgap thickness changed from 1mm to 2mm and 3mm, respectively. The 24/4 machine suffers from a higher reduction due to the rotor leakage, i.e. 13% and 23%.

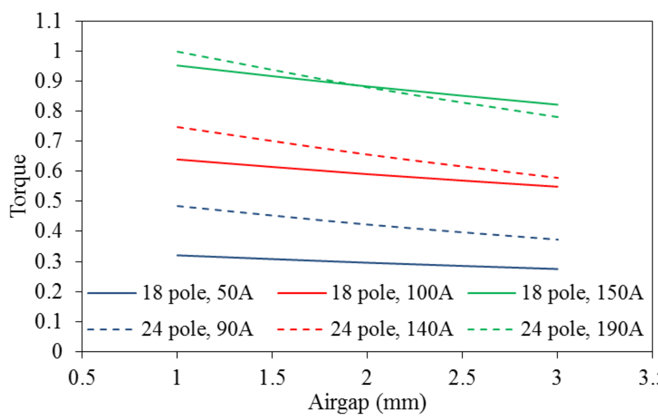


Fig. 10. Normailized average torque at different airgap thicknesses, stator pole number and current levels.

IV. Mechanical Analysis

In a conventional high-speed SPM rotor, i.e. without a copper shield, there are three main modes of mechanical failure:

1- At standstill, the circumferential stress in the PM (internal radius) exceeds the compressive strength of the PM. Cracking occurs and the magnet becomes fragmented.

2- At maximum speed, the von-Mises equivalent stress in the sleeve (internal radius) exceeds the yield stress of the material and sleeve deforms plastically, i.e. irreversible deformation. This reduces the interference between the sleeve and magnet.

3- At maximum speed, the circumferential stress in the PM (internal radius) exceeds tensile strength of the material. Cracking occurs and the magnet becomes fragmented

With the copper shield placed between the magnet and sleeve, the rotor failure conditions are unchanged. The copper shield can withstand much larger tensile circumferential stresses due to centripetal loading than the magnet and the stiffer sleeve will carry the stresses due to interference.

On the other hand, placing the copper around the sleeve without any bonding will allow it to expand freely due to centripetal loading. Since copper is less stiff than the sleeve material, even at low rotor speed it will lose contact with the sleeve and the rotor assembly will fail. Bonding of the copper sheet to the sleeve by means of adhesive or electroplating is therefore required. In this case, mechanical failure would occur if:

1- The equivalent stress in the copper exceeds the yield stress and the subsequent plastic strain exceeds the strain at rupture.

2- The radial stress in the copper to sleeve interface exceeds the cohesive strength of the electroplated copper or the adhesive used.

It is worth noting that electroplating of the copper leads to a degradation of its mechanical properties. This degradation depends on the electroplating process and time, the thickness of the electroplated copper and the properties of the sleeve material [15]. Therefore, obtaining the mechanical properties of electroplated copper is a complex experimental process. In this paper, the mechanical properties of bulk copper are used. Table I lists the mechanical properties of the rotor components of the SPM machine.

To illustrate the possibility of mechanical failure of the external copper shield, an axisymmetric FEA analysis of the SPM rotor with copper shield outside the sleeve was conducted, Fig. 11. An interference fit of 0.054mm between the sleeve and magnet was used. The model was constrained in the axial direction on both the top and bottom surfaces. This simulated a rotor where growth in the axial direction was restricted by other components

The distribution of equivalent stress in the full rotor, and equivalent plastic strain and radial stress in the copper shield of rotors with Inconel and Carbon Fibre sleeve and a copper shield of, 0.1, 0.2 and 0.3mm operating at the rated speed of 100krpm are presented in Fig. 12.

It can be seen in all the cases studied cases that although the equivalent stress in the copper shield is higher than the yield stress, the equivalent plastic strain does not exceed the rupture strain of the copper, and the radial stress is relatively low at the shield to sleeve interface.

The application of an internal copper shield has been investigated, again using an axisymmetric FEA. An interference fit of 0.054mm between the sleeve and the copper shield was specified. Table II presents the equivalent stress in the copper shield at standstill and at the rated speed of 100krpm. In all the investigated cases, the equivalent stress is lower than the yield stress of the copper.

It is worth noting that when an internal copper shield is used with a high interference fit, i.e. higher rated speed or larger rotor diameter, the equivalent stress of the copper may exceed the yield stress. Plastic deformation of the shield would then be expected. However, since the shield is radially restricted some axial extrusion of the copper shield might occur.

TABLE I. MECHANICAL PROPERTIES OF THE ROTOR COMPONENTS

Mat-erial	Young's Modulus (GPa)	Poisson's Ratio	Mass Density (Kg/m^3)	Yield Stress (MPa)	Tensile Stress (MPa)	Ture Strain
Shaft	210	0.3	7850	950	-	-
SmCo	150	0.24	8400	-	41	-
Inconel	200	0.29	8220	1200	-	-
Carbon Fiber	135	0.3	1600	2100	-	-
Copper	110	0.34	8300	60	250	0.33

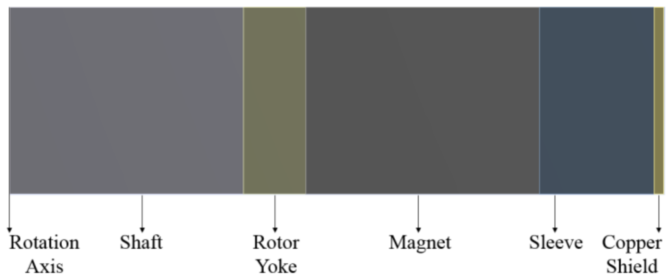
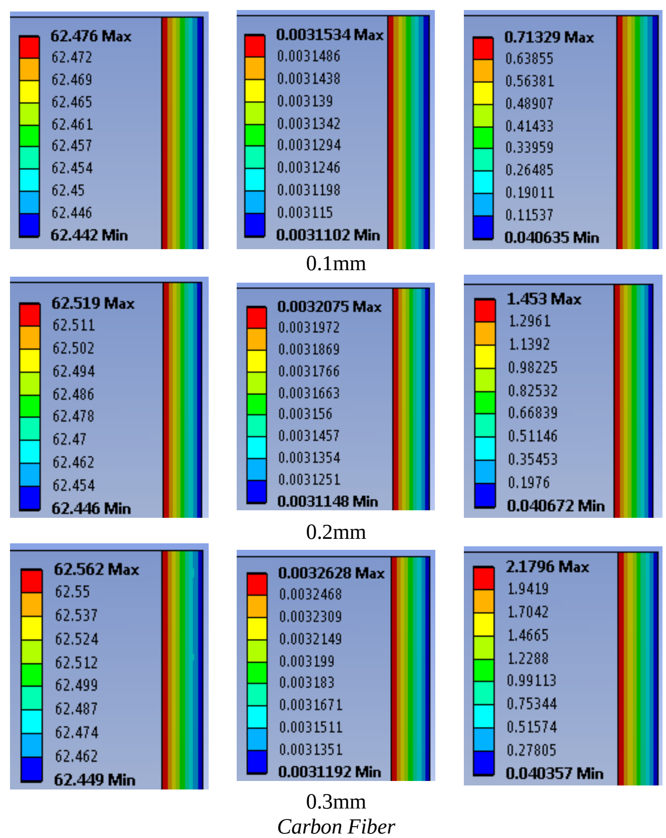


Fig. 11. Axisymmetric mechanical FEA layout.



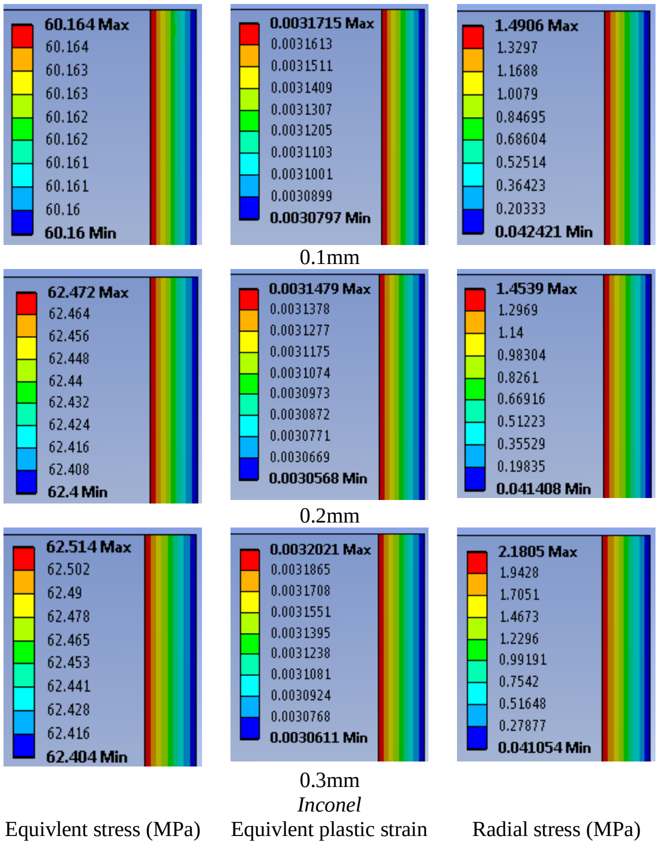


Fig. 12. Mechanical analysis of the SPM rotor with different copper shield thickesses.

TABLE II. EQUIVALENT STRESS IN INTERNAL COPPER SHIELD

Copper shield	Inconel		Carbon Fiber	
	Standstill	100krpm	Standstill	100krpm
0.1	53.34	44.8	38.24	36
0.2	51.38	43.15	36.55	34.31
0.3	49.13	41.06	34.88	32.72

V. CONCLUSION

Quantitative comparison of the total rotor loss of SPM machine with copper shield using FEA has been conducted in this paper. The comparison included different copper shield locations and thicknesses, airgap thicknesses, sleeve materials, and current waveform with different harmonic contents, frequencies, and levels. Moreover, mechanical FEA analysis of the SPM rotor with copper shield has been completed. In addition to the mechanical advantages, locating the copper shield between the magnets and sleeve can reduce the total rotor loss under many operation conditions, i.e. current harmonics and frequencies. On the other hand, locating the copper shield outside the rotor will increase the potential for mechanical failure and large thickness is required to reduce the overall rotor loss. When the switching frequency is low, i.e. high harmonic content in the current waveform, the copper shield is a good solution to reduce the loss and increasing the airgap can help to further reduce the losses, however, this comes at the expense of the torque.

VI. REFERENCE

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