Influence of the magnet shape on the rotor eddy-current losses in the outer rotor permanent magnet synchronous motor

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Abstract—This paper is focused on the comparison of the permanent magnet’s shape and magnetization direction influence on the rotor eddy-current losses in the 3 kW 30 000 rpm high-speed outer rotor permanent magnet synchronous motor. The analysis uses the results of the finite element simulations. The harmonic analysis of the air-gap flux density was done to better understand the difference between the studied magnet shapes.

Keywords—PMSM, eddy-current losses, rotor shape, fast Fourier transform

1. INTRODUCTION

The improvements in the quality of materials used in electrical machines and the development in power electronics have brought an increase in the utilization of high-speed electrical machines. Their main advantage is the high power density and the possibility to directly connect the load with the machine without the need for a gearbox. This leads to less complex drives and more miniaturized systems. [1]

The high-speed permanent magnet machines with an inner rotor need to consider the effects of the centrifugal forces on the magnets. The magnets are therefore usually placed inside a metal or carbon fiber sleeve. This complicates the manufacturability and the thermal state of the rotor. The permanent magnet machines with an outer rotor utilize the fact that the permanent magnets have high compressive strength and the rotor yoke act as the holding sleeve. The cooling of the outer rotor is also better. [2]

The high frequency of the high-speed machines brings not only a high power density but also a high loss density. The stator steel needs to be as thin as possible to reduce the eddy-current core losses. The eddy-currents also affect the stator winding and could cause a substantial increase of losses in comparison with lower frequency machines. The stator winding wire therefore needs to have a small diameter or to consist of more parallel conductors of a small diameter [3]. The permanent magnets and the rotor yoke are also subjects of the eddy-current losses. These are generated by the high-order harmonics in the air-gap. These losses increase the temperature of the magnets, which decreases their strength and could, in the worst case, cause their demagnetization.

2. ANALYZED MACHINE

The studied machine is an outer rotor permanent magnet synchronous motor. It’s main parameters are in Table I.

Table I: Main parameters of the motor

Name	Unit	Value
Rated speed	min^{-1}	30 000
Rated power	W	3 000
Number of stator slots	-	18
Number of poles	-	10
Rotor outer diameter	mm	52
Active length of the motor	mm	44
Radial air-gap length	mm	0.5

The stator steel is made from NO-20 steel to mitigate the effects of the high rated frequency on the core losses. The stator winding is made of copper wire made of parallel strands of a small diameter, therefore the eddy effects in the winding are not calculated. The rotor material is high tensile steel with good mechanical and electromagnetic properties. The neodymium surface permanent magnets are used to provide a high magnetic coercivity and a high remanent flux density.

The electromagnetic properties of the motor were calculated using the transient finite element method with the step of 1/400 of the period, which should be enough to properly calculate the eddy-current losses [4]. The model with rectangular magnets is shown in Figure 1. The model includes the air on the outer side of the rotor to properly calculate the leakage flux in that area. To produce the required power, the motor was supplied by the three-phase sine current in the most torque per ampere mode. The temperature of the magnets was set to 120 °C.

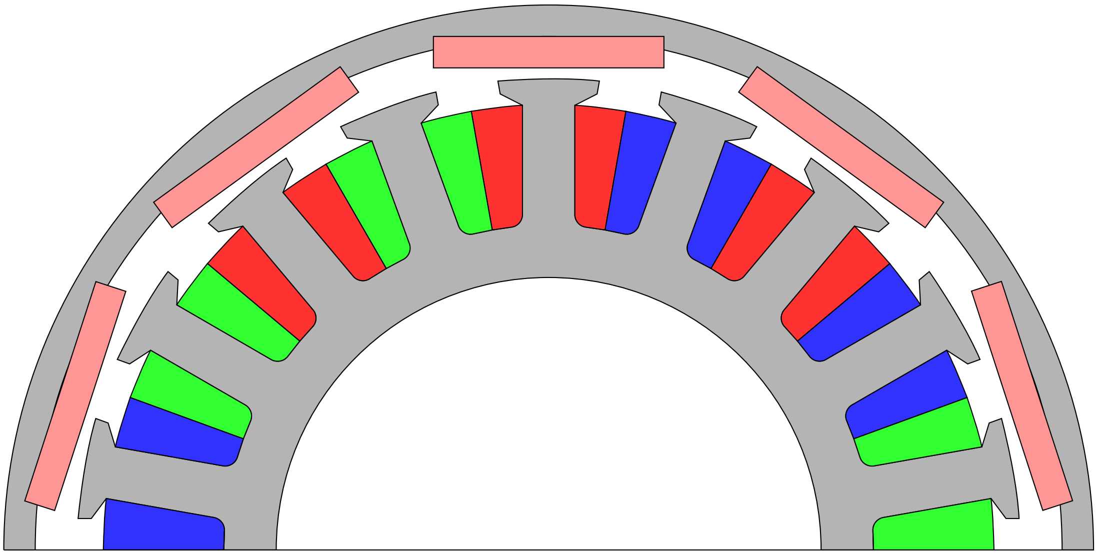


Figure 1: 2D motor model used in finite element method analysis.

The studied shapes and magnetization directions of the magnets are shown in Figure 2. The motor dimensions and other parameters were kept the same for the different magnet shapes. The change in the radial air-gap length (δ) was done by keeping the rotor dimensions the same while decreasing the outer diameter of the stator and the stator slot cross-section.

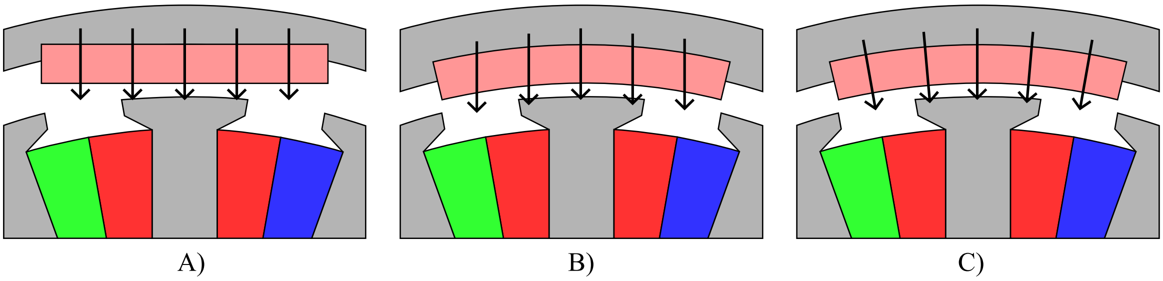


Figure 2: Analysed shapes and magnetization directions of the magnets. A) rectangular magnets with vertical magnetization, B) radial magnets with vertical magnetization and C) radial magnets with radial magnetization.

3. SIMULATION RESULTS

The value of the effective current was set for the motor to produce the 3 000 W, while the rotation speed of the rotor was kept at a constant 30 000 rpm. $\delta = 0.5$ mm and $\delta = 1.0$ mm was studied to compensate the increased losses for the radial magnets. But the increase of δ decreases the stator outer diameter and the copper slot area, which causes higher current density and losses in the winding.

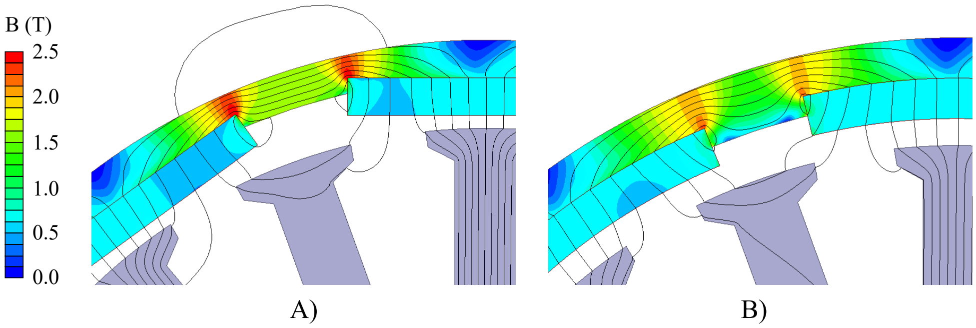
3.1. Motor losses and rotor state

The resulting losses are shown in Table II. The results show bigger rotor eddy-current losses for the radial magnets with both magnetization directions with $\delta = 0.5$ mm. The main reason for this is a bigger magnetic flux resulting from lowering the rotor saturation near the end of rectangular magnets. The radial magnets don't have the rotor yoke bottleneck which is one of their geometrical advantages.

Table II: Current and losses in the motor for different magnet shapes, magnetization directions and δ, output power 3 kW at 30 000 rpm

Magnet	Magnetization	Air-Gap	Current	Losses			Electromagnetic
Shape	Direction	Length		Rotor Eddy	Core	Copper	Efficiency
-	-	mm	A	W	W	W	%
Rectangular	Vertical	0.5	8.85	90.3	77.4	108.1	91.6
		1.0	10.10	40.3	56.3	156.1	92.2
Radial	Vertical	0.5	7.79	142.2	102.8	83.7	90.1
		1.0	8.71	58.6	73.8	114.9	92.4
	Radial	0.5	7.55	157.7	110.2	78.7	89.6
		1.0	8.33	62.2	80.1	105.1	92.4

This phenomenon can be seen in Figure 3. $\delta = 1.0$ mm was used to effectively lower the rotor eddy-current losses, but this is done at the cost of increasing the stator copper losses. This is the case mainly because of a slightly smaller stator copper cross-section and a higher leakage flux.

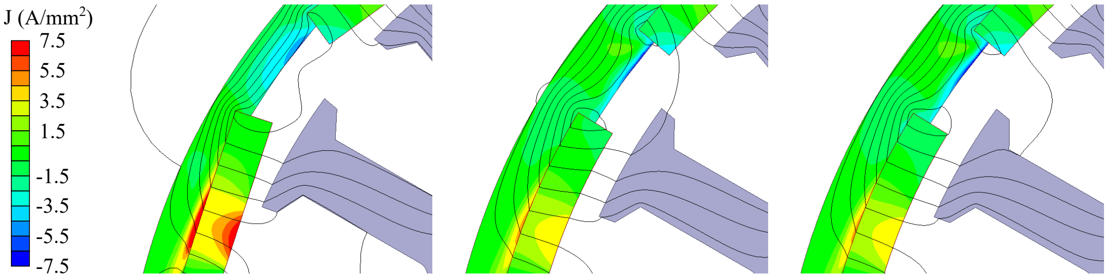


A)

B)

Figure 3: Flux density distribution for A) rectangular magnets with $\delta = 0.5$ mm and B) radial magnets with vertical magnetization with $\delta = 1.0$ mm.

Figure 4 shows the current density in the permanent magnets and the rotor yoke. The amplitude of the eddy-currents for the rectangular magnets with $\delta = 0.5$ mm reaches up to 7.5 A/mm^2. The lower eddy-current values are clearly visible for the radial magnets with $\delta = 1.0$ mm, especially in the magnets.



A)

B)

C)

Figure 4: Eddy currents in the rotor for A) rectangular magnets with $\delta = 0.5$ mm, B) radial magnets with vertical magnetization with $\delta = 1.0$ mm and C) radial magnets with radial magnetization with $\delta = 1.0$ mm.

3.2. Harmonic analysis of air-gap flux density

To better understand the influence of the magnet shape and magnetization on the motor, the analysis of the air-gap flux density was done. In Figure 5 the radial flux density in the air-gap 0.25 mm from the rotor at the rated operation can be seen. The 0.25 mm distance from the rotor (middle of the air-gap for δ = 0.5 mm) was chosen to properly evaluate the effect of the harmonics on the rotor losses for the different air-gap lengths.

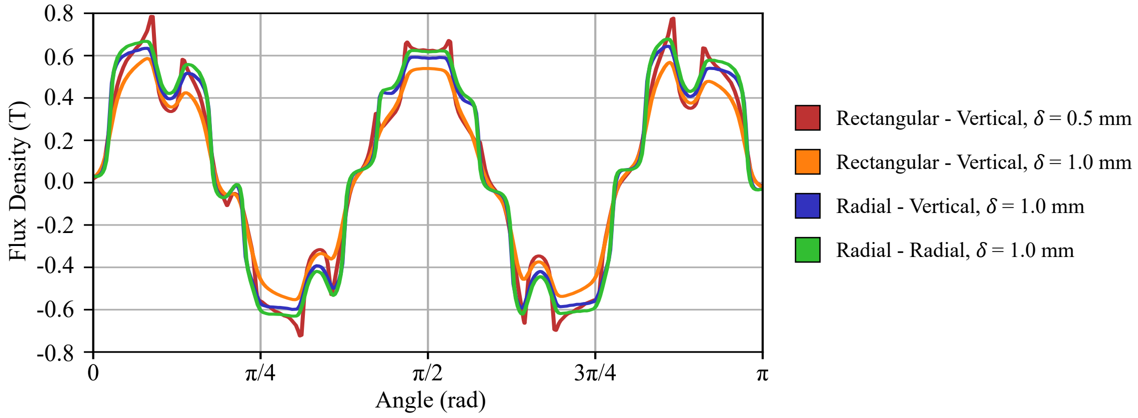


Figure 5: Flux density in the air-gap 0.25 mm from the rotor different magnet shapes and magnetization directions.

The 2D Fast Fourier Transformation presented in [5] was done to properly separate the source of the flux density harmonics. Figure 6 shows the space and frequency harmonics from the stator point of view. The harmonics are separated by their color according to their main source. The first order stator slot space harmonics 23rd and -13th are also generated by the stator winding but their main source is the stator slots. The fundamental 5th space harmonic amplitude is 606 mT and is not shown to the full extent to preserve the readability of the figure. Only the harmonics with an amplitude higher than 1 mT are shown.

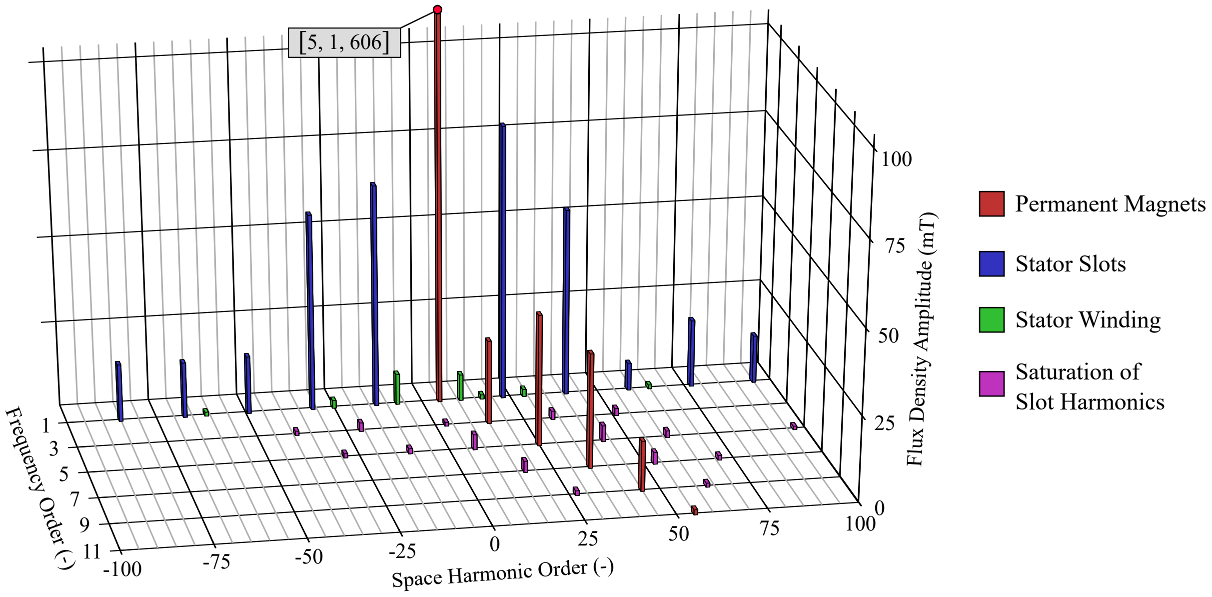


Figure 6: Space and frequency harmonics of the flux density in the air-gap 0.25 mm from the rotor for the rectangular magnets at rated operation with highlighted sources. The fundamental 5th harmonic is not shown in its full extent.

From the rotor point of view, only the 1st frequency order harmonics are the source of the eddy-current losses and are further studied. The saturation harmonics are predominantly caused by the rotor and should therefore not contribute to the rotor losses [5]. Figure 7 shows the chosen air-gap harmonics comparison for different shapes and δ. The fundamental 5th harmonic for the rectangular magnets with δ = 0.5 mm reaches 606 mT, for δ = 1.0 mm 529 mT, for radial magnets with vertical magnetization and δ = 1.0 mm 619 mT and for radial magnets with radial magnetization and δ = 1.0 mm 650 mT. The model with longer air-gap benefits from lower high-order harmonics. The rectangular magnets have slightly lower slot harmonics than the radial magnets. The radial magnets with radial magnetization have slightly higher slot harmonics than the radial magnets with vertical magnetization.

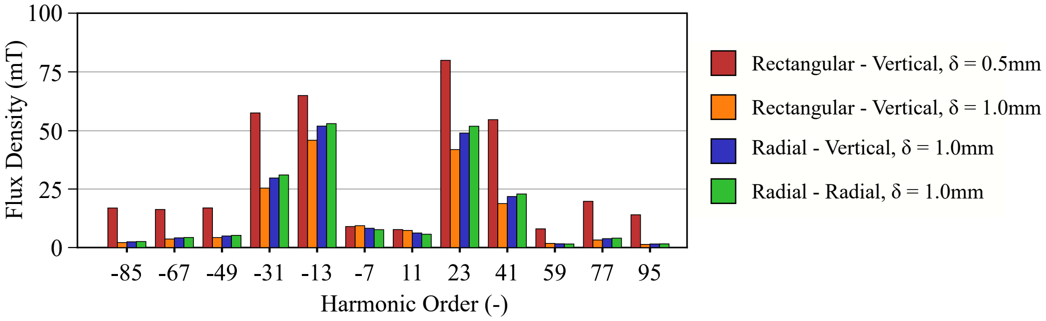


Figure 7: High-order space harmonics of the 1st frequency order of the flux density in the air-gap 0.25 mm from the rotor for different magnet shapes and δ.

4. CONCLUSION

According to the results, the main advantage of the radial magnets in comparison to the rectangular magnets is an elimination of the bottleneck in the rotor yoke. This increases the magnetic flux for this shape of magnets which allows an increase in the air-gap length from 0.5 mm to 1.0 mm while keeping the supplied stator current nearly the same. The harmonic content of the flux density in the air-gap is mainly influenced by the length of the air-gap while the shape of the magnets has not shown a strong influence on it.

The radial magnets should be used when possible. In the analyzed machine, they reduced the rotor eddy-current losses from 90.3 W for the rectangular magnets to 58.6 W and 62.2 W for the vertical and radial magnetization respectively. The efficiency increased from 91.6 % to 92.4 % while the needed supply current was slightly lowered. The difference between the vertical and radial magnetization is marginal.

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