EFFECT OF STATOR SLOT OPENINGS IN AXIAL FLUX PERMANENT MAGNET MACHINES

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Abstract - The width of the stator slot openings near the air gap has a large influence on the power loss in the stator core and in the permanent magnets of axial flux permanent magnet synchronous machines. On the one hand, the increase in stator slot openings results in lower power loss in the stator iron. On the other hand, it also results in increased loss in the permanent magnets. Also the torque is reduced for large but also for very small slot openings. This paper deals with axial flux machines of the YASA type: yokeless and segmented armature. It is shown that the slot openings contribute to an unequal flux density level over the different laminations in the stator core. The effect on the power loss and the flux distribution is shown.

Keyword - axial flux, permanent magnet machine, losses

1 INTRODUCTION

The authors of [1] very recently investigated the influence of stator slotting on the performance of a radial flux permanent magnet machine (PMSM) with concentrated windings. As shown in [1], the stator slot opening width has a major influence on the stator core loss and the eddy current loss in the permanent magnets. The influence of the stator slot openings width on both loss mechanisms is contrary; widening of the stator slot openings will result in lower stator core loss, but will increase the eddy current loss in the permanent magnets and *vice versa*. In [2], soft magnetic wedges were introduced in the stator slot openings to modify the no load performance.

Recently, the yokeless and segmented armature (YASA) axial flux PMSM is studied by many research groups [3] because of its high efficiency and torque density. For an axial flux PMSM, the effect of this slot opening width is investigated in the following paragraphs. In contrast with radial machines, this parameter has also an effect on the distribution of the flux density over the different laminations in the stack. To investigate the influence of the stator slot openings width on the losses, the multislice 2D model using finite element analysis, introduced in [4, 5], is used to calculate the stator core loss. The eddy current losses in the permanent magnets are evaluated using the multislice 2D - 2D model, introduced in [6]. Next to the slot opening width, other geometrical parameters have an influence on the losses and the torque. For the same YASA machine, an optimization process regarding a limited set of parameters was performed in [4]. In this optimization, it was already noticed that some parameters have a contrary effect on the different losses in the machine. For example, a high axial length of the stator cores combined with large slot openings is beneficial with respect to the copper loss, but it results in higher stator core loss.

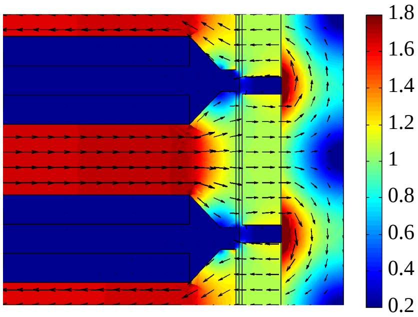
In the simulations in the following paragraphs, the stator slot openings width is varied from nearly closed slots (1 mm) to nearly open slots (9 mm) using a domain scan. A variation of the stator slot openings width has also a minor impact on the electromagnetic torque. Therefore, a final comparison is made in which the total losses in the machine are placed against its output power. The geometrical details of the machine can be found in [6].

2 STATOR CORE LOSS

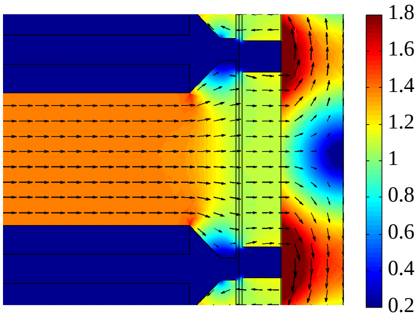
The stator slot openings width b_0 has a direct impact on the magnetic flux density pattern in the stator core elements. As the magnetic flux density can be subdivided into a component by the permanent magnets and by the armature reaction, both contributions are first being examined separately before considering the total flux. Two values are chosen in all further examples: rather closed slots with b_0 = 3 mm and rather open slots with b_0 = 9 mm.

2.1 PERMANENT MAGNETS

In Fig. 1 the magnetic flux density pattern in the stator core element is illustrated in case only permanent magnets were present and aligned with the stator core element in case of 3 mm slot opening width. In case



(a) Inner diameter region



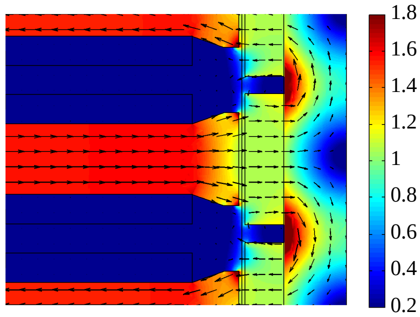
(b) Outer diameter region

Fig. 1. Magnetic flux density in Tesla in the stator core when the permanent magnet is aligned with the stator core for the 3 mm stator slot openings width.

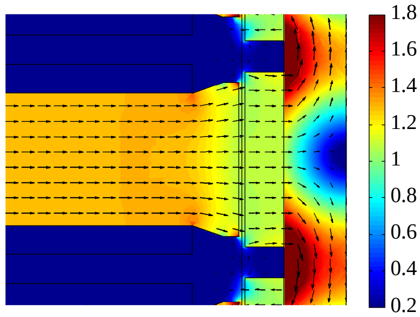
of alignment of the permanent magnets with the stator core, the overall maximal values of the magnetic flux density are found in the stator core material. Due to the shape of the permanent magnets[1], the magnetic flux density in the laminations near the inner radius is found to be higher than the one at the outer radius. This is caused by the variable tooth pitch as a function of the diameter combined with a constant slot width. Flux leveling over the laminations by radial magnetic flux components, is limited due to the very poor permeability of the stator cores in the direction perpendicular to the lamination planes. Consequently, radial flux components remain limited.

The influence of increasing the slot opening width from 3 to 9 mm is illustrated in Fig. 2. At the inner diameter lamination regions, the magnetic flux density in case of b_0 = 9 mm has decreased with an average value of 0.3 T compared to the case of b_0 = 3 mm as the smaller tooth tips catch less magnetic flux. In the laminations at the outer diameter region, this effect is less visible due to the relatively larger tooth tip width, having only an average decrease with less than 0.1 T. As a result, the magnetic flux density is better levelled

[1] The permanent magnet span is generally chosen to have a constant value, for example a span of 0.8 τ_p



(a) Inner diameter region



(b) Outer diameter region

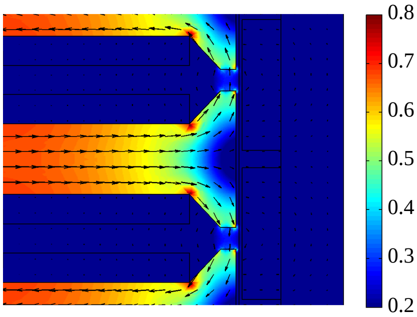
Fig. 2. Magnetic flux density in Tesla in the stator core when the permanent magnet is aligned with the stator core for the 9 mm stator slot openings width.

over the different lamination layers and possible saturation of the inner diameter laminations is avoided. Nevertheless, the total magnetic flux in the stator core element reduces.

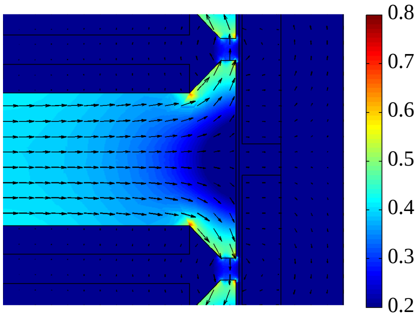
2.2 Armature Reaction

In this paragraph, only the armature reaction is considered. The remanent flux density of the permanent magnets in the multislice 2D FEM is set to zero.

The magnetic flux density pattern is plotted in Fig. 3 for the 3 mm slot width opening and the nominal 7 A current. Apparently the magnetic flux is hardly crossing the air gap, but is transferred through the tooth tips to the adjacent teeth where the flux is in the opposite direction. This is a general observation in surface mounted PM machines where the air gap is generally significantly bigger than the slot opening width. As this flux is not crossing the air gap, it can be considered as leakage flux. Due to the relatively low reluctance for this leakage flux through the tooth tips, the level of the magnetic flux density in the stator core is not negligible. Moreover, similar to the magnetic flux by the permanent magnets, higher magnetic flux densities are found at the inner diameter regions compared to the outer diameter regions. For machines with a high electric loading, saturation of the inner di-

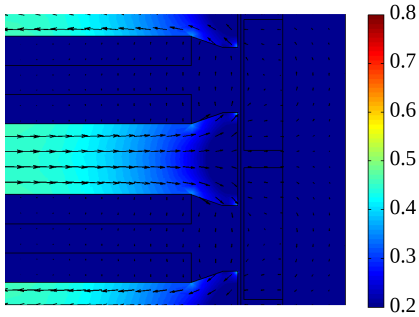


(a) Inner diameter region

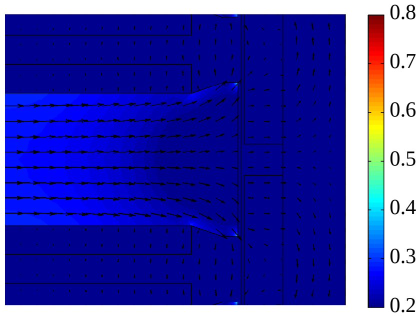


(b) Outer diameter region

Fig. 3. Magnetic flux density in Tesla in the stator core taking only armature reaction into account for the 3 mm stator slot openings width.



(a) Inner diameter region



(b) Outer diameter region

Fig. 4. Magnetic flux density in Tesla in the stator core taking only armature reaction into account for the 9 mm stator slot openings width.

ameter lamination might take place while the upper laminations are still unsaturated.

Increasing the slot openings width to 9 mm results in the magnetic flux density pattern in Fig. 4. Due to the increase of the slot openings, the reluctance path for the leakage flux through the tooth tips increases. Therefore, the magnetic flux density levels in the stator core elements are strongly reduced for the same stator current. The reduction of the magnetic flux density is higher at the inner diameter regions compared to the outer diameter regions. For the same current density, the risk of saturation of the stator cores is hence less in case of wide slot openings.

2.3 Combination

The previous flux density patterns, both taken at the maximum value of the magnetic flux, showed lower magnetic flux density levels for the machine with the wider slot openings. As the peak values of the magnetic flux density are strongly related to the stator core loss, a lower stator core loss is expected for the machine with the wide slot openings. In contrary, the flux linkage with the tooth coils will be influenced as well, which will result in a variation of the electromagnetic torque.

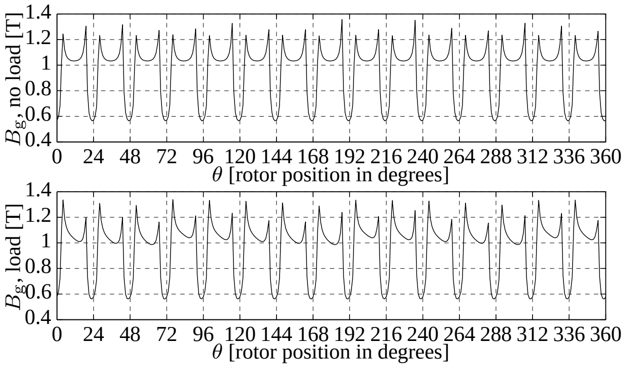
3 Analysis of the Air Gap Magnetic Flux Density

Next to the effect of b_0 on the magnetic flux density pattern in the stator cores, the stator slot openings have also a major influence on the air gap magnetic field. The analytical expression for the permeance function, introduced in [7], can be used to explain the influence of an increase in b_0 on the air gap magnetic flux density.

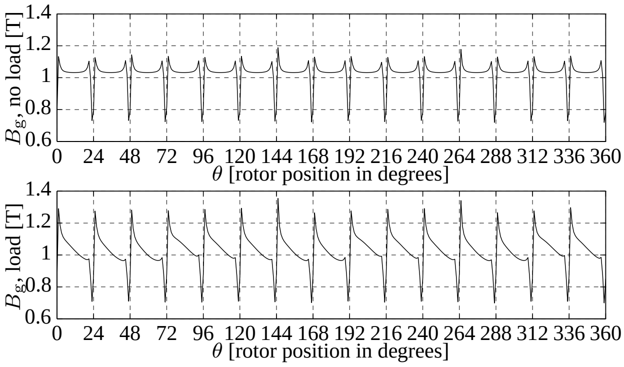
As will be illustrated in the next paragraphs, an increase of b_0 results in a bigger variation of the air gap magnetic flux density. This increase in the variation of the air gap magnetic field induces higher eddy currents in the permanent magnets, and hence, causes additional losses. Moreover, the increasing slot openings result in a higher reluctance difference over the circumference of the machine which will result in a higher cogging.

3.1 Eddy current loss in the permanent magnets

In Fig. 5a the air gap magnetic field in the rotor reference frame is plotted for the 9 mm slot opening for both no load and rated load. Comparison of this figure with Fig. 5b, which differs only from Fig. 5a by the 3 mm slot opening, reveals that the local drops in the air gap magnetic flux density near the stator slots are wider and deeper, from 0.8 T for the 3 mm slot openings to 0.6 T for the 9 mm slot openings. Due to the wide and deep drops in the air gap magnetic flux density, the average value of the air gap magnetic field will be lower.



(a) Slot opening is 9 mm



(b) Slot opening is 3 mm

Fig. 5. Air gap magnetic flux density for (a) b_0 = 9 mm and (b) b_0 = 3 mm, taking into account stator slotting effect only (upper), and both the stator slotting effect and armature reaction (lower) as a function of the rotor position. Data are expressed in the rotor reference frame.

In Fig. 5b, corresponding to the 3 mm slot opening, there is a significant difference of the no load and rated load air gap magnetic field due to the armature reaction. In Fig. 5a, the difference is smaller. Consequently, this observation is expected to have its consequences with respect to the eddy current loss in the permanent magnets. For the 3 mm slot openings, the difference between no load eddy currents loss in the permanent magnets and eddy current losses at load are relatively high, *cfr.* Table 1. With increasing slot openings, the relative difference between the eddy current losses in the permanent magnets at no load and load is expected to decrease.

I. Effect of segmentation on the eddy-current loss in the magnets for 3 mm slot opening

	magnet eddy current loss	
# segments	**no-load**	**rated load**
1	8.144	15.415
2	6.610	11.756
4	5.877	10.145
14	2.888	4.090

4 Evaluation and Comparison

Whereas the previous sections were introduced to acquire some understanding on the mechanisms causing the different losses qualitatively, a quantitative analysis is performed in this section.

For the material in the stator core elements, a laminated steel with M600-50A grade is chosen and the permanent magnets are assumed to consist of four electrically isolated segments. Table 1 shows the loss in the magnet for other segmentations in case of b_0 = 3 mm. The stator slot openings are varied between 1 mm and 9 mm.

To evaluate the electromagnetic torque, stator core loss and eddy current loss in the permanent magnets, the multislice 2D model is used and coupled with the 2D model for the eddy currents in the permanent magnets [6]. Simulations were performed for both no load and the rated load current of the machine. All relevant data are presented in Table 2.

4.1 Stator core loss

Analysis of Table 2 indicates that the stator core loss for both no load and load working conditions decreases as the stator slot openings become wider. It should be noticed that the effect at no load is less significant as for working at rated load. Indeed, the analysis of the magnetic flux density patterns showed minor change for the flux density caused by the permanent magnets compared to those by the armature reaction. The effect of the increased reluctance path in the tooth tips by increasing stator slot openings has a dominant position in the decrease of the magnetic flux density in the stator core and the corresponding stator core loss. The difference between the core losses with closed slots and open slots is large; a decrease of about 30% is achieved. At the same time the flux density levels in the stator core elements are reduced, possibly resulting in less saturation of the lamination profiles at the inner diameter region.

II. Influence of the stator slot openings width on the machine's performance, at rated speed (2500 rpm), rated load current (7 A) and with 4 segments per magnet. The copper losses in the windings are estimated at 60.8 W.

Stator slot openings width [mm]	**Average torque [Nm]**	**Average power [kW]**	**Load losses**			**No load losses**		
			Core [W]	**PM [W]**	**Total [W]**	**Core [W]**	**PM [W]**	**Total [W]**
1	18.22	4.769	148.0	5.446	214.3	124.4	0.1691	124.6
3	18.50	4.844	135.1	10.15	206.1	124.5	5.877	130.4
5	18.38	4.811	127.3	21.91	210.0	120.3	18.42	138.7
9	17.65	4.622	109.2	40.52	210.5	104.8	37.55	142.4

4.2 Eddy current loss in the permanent magnets

Although the losses in the stator cores decrease, Table 2 indicates that the losses in the permanent magnets due to eddy currents increase seriously. Increasing eddy current losses in the permanent magnets as a function of increasing stator slot openings are found at no load as well as at rated load. For the nearly closed slots, the no load eddy current loss almost vanishes as the small slot openings hardly influence the air gap magnetic field. For these small stator slot openings, the effect of the armature reaction is dominating the loss. This is in agreement with the relative big differences in the air gap magnetic field at no load and load that were presented in Fig. 5b, having the 3 mm stator slot openings. As the stator slot openings become wider, the effect of stator slotting dominates the armature reaction resulting in a lower variation of the loss at load compared to the loss at no load.

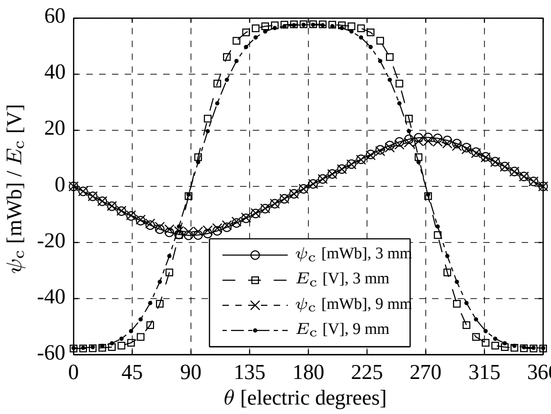


Fig. 6. Comparison of the coil flux linkage and coil electromotive force for the stator slot openings width set to 3 mm and 9 mm.

4.3 Electromagnetic Torque and Power

In Fig. 1 and Fig. 2 it was illustrated that the stator slot openings influence the magnetic flux density in the stator core elements. Comparison showed that the total flux in the stator core elements decreases with increasing b_0. Moreover it can be expected that a variation of the stator slot openings has an impact on the harmonic content of the coil flux linkage and coil electromotive force. Indeed, Fig. 6 presents the coil flux linkage and coil electromotive force for b_0 set to 3 mm and 9 mm respectively. The figure illustrates a non-negligible reduction of the peak value of the coil flux linkage for larger stator slot openings, while comparison of the coil electromotive force clearly indicates the change in the harmonic content. The electromotive force corresponding to the 9 mm stator slot openings has less harmonic content and is a better approximation to the pure fundamental sinusoidal component.

Consequently, the stator slot openings have also an effect on the average electromagnetic torque and torque ripple. In Fig. 7 the electromagnetic torque is plotted for the 3 mm and 9 mm stator slot openings.

Although the electromagnetic torque has decreased for the 9 mm with respect to the 3 mm width of the stator slot openings, it is wrong to conclude that the maximum electromagnetic torque is obtained for fully closed slots. Table 2 indicates that the maximum of the electromagnetic torque for the 7 A load current is reached for the 3 mm stator slot opening. The reason is that for very small b_0, the leakage flux passing through the tooth tips increases. Although this flux crosses the air gap, it is not linked to the stator coils. A similar conclusion in [1] confirms this observation.

Although large slot openings are likely to decrease the electromagnetic torque, Fig. 7 indicates a reduction of the torque ripple for the wide stator slot openings. It should be mentioned that the cogging torque in the prototype machine has almost vanished due to the choice of the 15-slot-16-magnet configuration and the T-shaped permanent magnets.

4.4 Overview

The selection of the appropriate stator slot opening is a trade-off between average power output, stator core

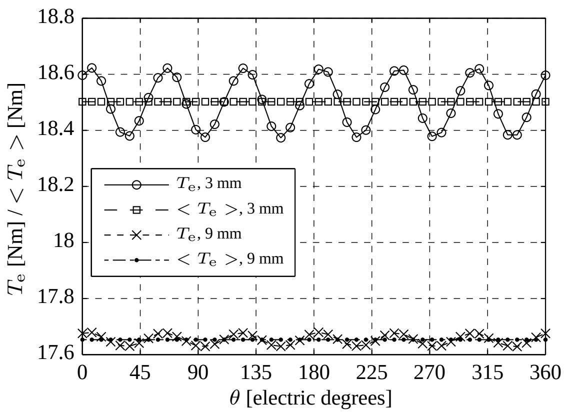


Fig. 7. Comparison of the electromagnetic torque for the stator slot openings width set to 3 mm and 9 mm.

loss and eddy current loss in the permanent magnets. Within the focus on this work, it is obvious to choose for the configuration with the best energy efficiency. The highest energy efficiency is obtained for the 3 mm stator slot openings. Nevertheless other requirement in the design such as thermal behaviour of the machine can be decisive in the selection of the stator slot openings. If the stator cannot be cooled efficiently it might be a good choice to move the losses to the rotor where the power losses are removed by convection.

On the other hand it should be mentioned that these comparisons used only one grade for the stator core material and one segmentation grade for the permanent magnets. Moreover the electric loading of the machine will have a major influence on the selection of the stator slot openings. The selection of the appropriate stator slot openings by quantitative analysis is left for the machine designer and will not be elaborated in this work.

5 Conclusion

This paper investigated the influence of the stator slot openings on the power losses in the stator cores and in the permanent magnets. On the one hand, an increase of the stator slot openings results in a reduction of the leakage flux, which results in an overall decrease of the magnetic flux density in the stator core elements. Therefore, the core loss decreases with increasing stator slot openings. On the other hand, larger stator slot openings increase the variation of the magnetic flux density in the air gap near the stator slot openings. Hence, the eddy current loss in the permanent magnets increases.

To illustrate the effect of a variation of the stator slot openings on both loss terms quantitatively, a domain scan on the geometry of the test case machine is performed. Here, the stator slot openings are varied from nearly closed slots to nearly open slots and the power losses are calculated for each case. It was observed that although the variation of both losses is significant, the sum of both losses is less varying. On the other hand, for very wide stator slot openings, a decrease of the electromagnetic torque output is found. For the test case machine, the optimal slot opening with respect to the total losses and the torque output was found to be a semi closed slot opening of 3 mm.

Acknowledgements

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References

[1] H. Vu Xuan, D. Lahaye, H. Polinder, and J. Ferreira, Influence of stator slotting on the performance of permanent-magnet machines with concentrated windings, IEEE Trans. Magn., vol. 49, no. 2, pp. 929-938, 2013.

[2] G. De Donato, F. G. Capponi, and F. Caricchi, No-load performance of axial flux permanent magnet machines mounting magnetic wedges, IEEE Trans. Industrial Electronics, vol. 59, no. 10, pp. 3768-3779, 2012.

[3] A. Di Gerlando, G. Foglia, M. Iacchetti, and R. Perini, Evaluation of manufacturing dissymmetry effects in axial flux permanent-magnet machines: Analysis method based on field functions, IEEE Trans. Magn., vol. 48, pp. 1995-2008, 2012.

[4] H. Vansompel, P. Sergeant, and L. Dupré, Optimized design considering the mass influence of an Axial Flux Permanent-Magnet Synchronous Generator with Concentrated Pole Windings, IEEE Trans. Magn., Vol. 46, pp. 4101-4107, Dec. 2010.

[5] A. Parviainen, M. Niemelä, and J. Pyrhönen, Modeling of axial permanent-magnet machines, IEEE Trans. Ind. Appl., vol. 40, no. 5, pp. 1333-1340, Sep./Oct. 2004.

[6] H. Vansompel, P. Sergeant and L. Dupré, A Multilayer 2D-2D Coupled Model for Eddy Current Calculation in the Rotor of an Axial-Flux PM Machine, IEEE Trans. Energy Conv., Vol. 27, No. 3, pp. 784-791, Sep. 2012.

[7] Z. Zhu and D. Howe, Instantaneous magnetic field distribution in brushless permanent magnet dc motors. Part III. effect of stator slotting, IEEE Trans. Magn., vol. 29, no. 1, pp. 143-151, 1993.