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Influence of stator slot openings on losses and torque in axial flux permanent magnet machines

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Abstract

Among the different geometrical parameters to be chosen during design of axial flux permanent magnet synchronous machines, the width of the stator slot openings near the air gap is an important parameter: it has a major influence on the power loss in the stator core and in the permanent magnets on the two rotors of the studied type of axial flux machines. Moreover, the stator slot openings parameter has a converse impact on both power losses. On the one hand, the increase in stator slot openings results in a reduction of the power losses in the stator core elements. 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. Insight in the impact of the slot openings variation on both power losses (in stator iron and in permanent magnets) is provided, and an illustrative case is discussed in which the impact of the slot openings variation on both power losses is examined quantitatively.

Keywords: Axial flux; Permanent magnet machine; Losses

1. Introduction

In design of permanent magnet electrical machines, many geometric parameters have to be chosen, each of them varying in a wide range. Finite Element Models (FEM) can be used if the number of parameters to optimize is limited. In the pre-design stage, often much faster analytical models are used for coarse optimization [17]. The width of the stator slot opening is a parameter that is not always considered in the design. Nevertheless, it has a major influence on the stator core losses and eddy current losses in the permanent magnets of a permanent magnet machine. This was shown by the authors of [21], who investigated the influence of stator slotting on the performance of a radial flux permanent magnet machine (PMSM) with concentrated windings. As shown in [21], 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

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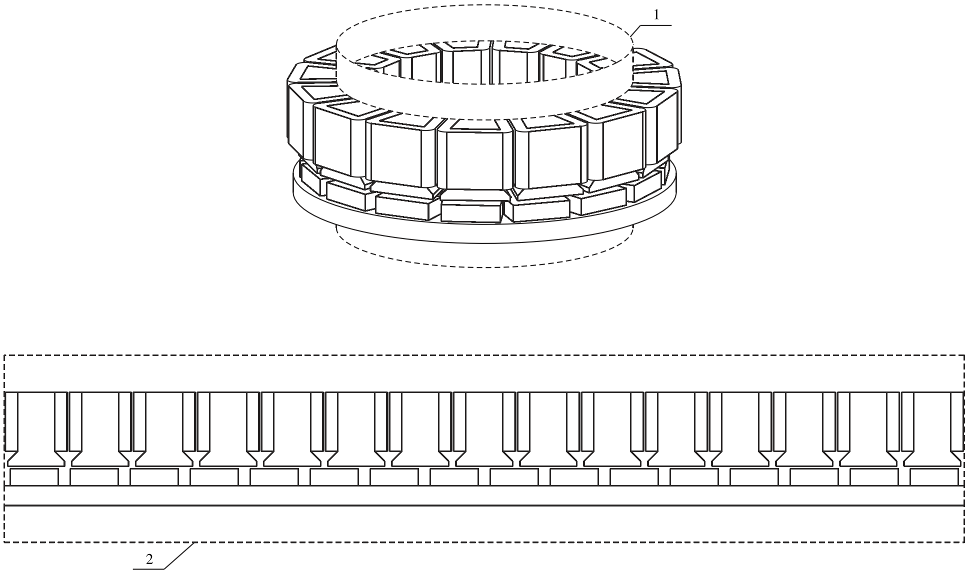

Fig. 1. Principle of the transformation of the 3D geometry of an axial flux PM machine to a 2D geometry, which can be used in multislice 2D computation. At different radii (only one radius depicted), cylindrical surfaces (1) are defined. The analytical modelling uses a cylindrical coordinate system for these surfaces (1), while the 2D finite element computations use an unrolled variant (2) which can be treated like a common planar 2D geometry in Cartesian coordinates as used in most finite element packages.

core loss, but will increase the eddy current loss in the permanent magnets and *vice versa*. In [7,8], 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 [9] 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 [16,18], is used to calculate the stator core loss. This multislice 2D modelling technique is explained in Fig. 1. The eddy current losses in the permanent magnets are evaluated using the multislice 2D–2D model, introduced in [19]. 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 [18]. 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 (11 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 [19]. Although the losses in the stator core elements strongly depend on the grade of the considered laminated silicon steel, and the eddy current losses in the permanent magnets on the segmentation grade, always the same material and segmentation grade is used in the evaluation of the losses. Consequently, the aim of the work is to point out the important effect of the stator slot openings width on the losses in the design stage of the machine, focusing on the acting loss phenomena rather than aiming an extensive quantitative analysis.

2. Stator core loss

Accurate computation of iron loss in the machine is crucial when studying the effect of a parameter on the losses, or when doing optimization of a machine [15]. The stator slot openings width b_0 has a direct impact on the magnetic flux density pattern in the stator core elements, and by consequence on the stator core loss. As the magnetic flux density