Core Loss Reduction in Axial Flux Permanent Magnet Motors Using Tooth Shaping

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Abstract — **The performance of axial flux permanent magnet (AFPM) motors can be adversely affected by magnetic saturation. The flux density distribution and the magnetic saturation can be affected by the tooth shape. In this paper, a tooth shaping technique is used to reduce the core loss and the optimal results are then compared with those obtained from the basic model. The results show that the trapezoidal form of stator teeth is effective in reducing the core loss. In addition to the core loss reduction, the use of tooth shaping technique leads simultaneously to an increase in the output torque and a reduction in armature reaction effect on permanent magnets.**

Keywords - Axial flux permanent magnet (AFPM) motor*; *Magnetic saturation*; *Core loss*; *Finite element method (FEM)

I. INTRODUCTION

One of the main goals in electrical machine design is having the maximum possible amount of specific magnetic loading (air gap flux density) while considering the magnetic saturation and the core loss. The maximum flux density should be placed in the knee region of B-H curve under rated condition. It usually happens in tooth tips and tooth body, where cross section of the core is lower. The using of narrower teeth leads to the increase in the ratio of tooth flux density to specific magnetic loading. In this case, the lower specific magnetic loading permits the lower saturation effect in the teeth. However, the corner tips of triangular teeth may have higher flux density. This leads to the higher saturation degree and consequently the higher core loss.

In high speed motors, such as AFPM motors, the mechanical and core losses are not negligible. The core loss calculations based on the assumption that only the fundamental component of the flux density exists is not valid [1-2]. For good estimation of core losses the effects of harmonics have to be taken into account. For this reason, FEM is usually used to calculate the core loss [3]. The non-salient AFPM motors may have different structures, such as multi-disk, slotted or slotless, and the coreless structures. Nowadays, AFPM motors are widely used in marine and military industries due to their high efficiency and power density [4-6].

Marignetti et al in [7] investigated the effect of core material on the core loss for one typical AFPM motor with triangular teeth. The optimization of stator teeth for one typical AFPM motor was performed in [8] with the aim of reduction the amount of copper used in the stator winding. However, the shaping of stator teeth with the aim of core loss reduction has not been studied in previous publications. In this paper, the influence of stator tooth shaping on the core loss, output torque and torque ripple is studied.

II. THE AFPM MOTOR

The analyzed motor is a single-sided AFPM motor, i.e. it has a single PM rotor disk opposite to a single stator unit consisting a three phase winding and ferromagnetic core (See Fig. 1). The rotor PMs are surface mounted and the stator teeth have triangular form. Table. I shows the main parameters of this AFPM motor.

TABLE I. THE STUDIED AFPM MOTOR PARAMETERS

Parameter	Value and Unit
Rated Power	2200 (Watt)
Rated Speed	1285 (rpm)
Winding type	Δ , 3φ
Number of pole pairs	14
Number of slots	24
Magnet remanence	1 T
Rated frequency	300 Hz
Stator outer diameter	200 mm
Stator inner diameter	116 mm
Rotor diameter	206 mm
Stator yoke thickness	10.5 mm
Rotor yoke thickness	10 mm
Air gap length	1.2 mm
Magnet thickness	3 mm
Magnet type	NdFeb
Core type	50JN400
Winding turns per coil, N_c	130
No-load voltage	210 (V)

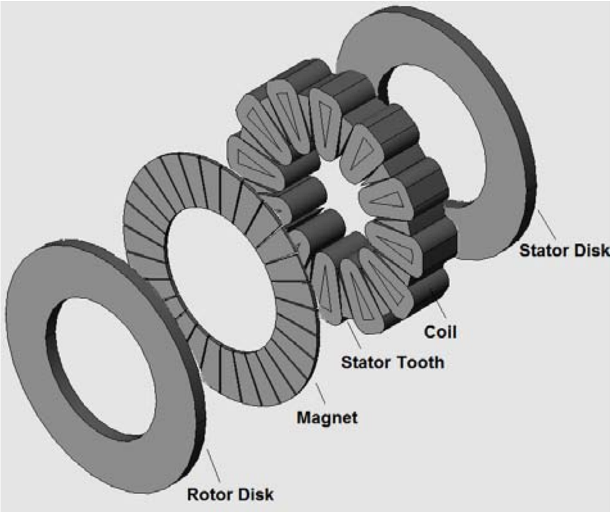

Figure 1. The analyzed AFPM motor.

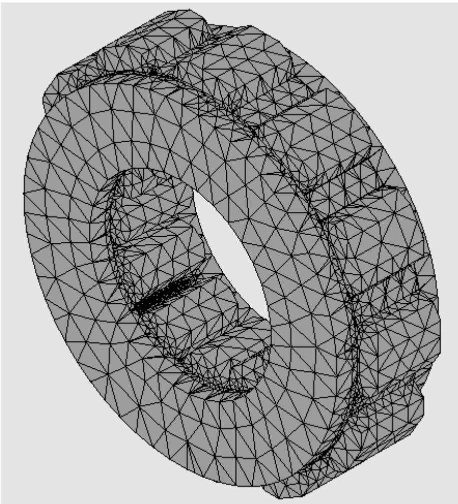
Figure 2. Finite-element mesh of the AFPM motor model.

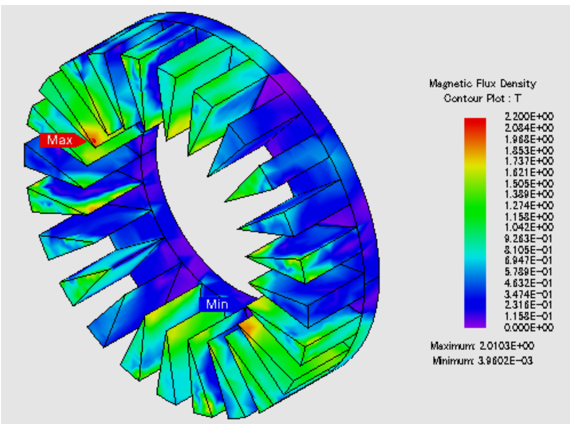

Figure 3. The flux density distribution in stator core of basic model in t=0.00316 (s).

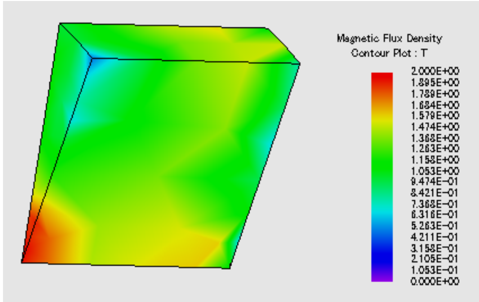

Figure 4. The flux density distribution in one stator tooth.

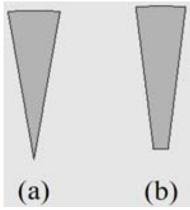

Figure 5. The stator teeth in (a) basic model, (b) proposed model.

III. Performance Analysis Using FEM

The dynamic modeling of AFPM motor under rated condition is necessary to calculate the core loss. These calculations include the instantaneous values of stator currents and rotor position. These instantaneous values are applied to the FE model of AFPM motor in a specified period of time. The needed outputs are then obtained from FE model.

A mesh with 29343 elements is used in finite element analysis (FEA). The meshed FE model is shown in Fig. 2.

Fig. 3 shows the flux density distribution in the stator core. As shown in Fig. 3, the higher flux density happens in the tooth corners.

The high saturation is clearly seen in taper corner of the tooth (See Fig. 4).

IV. Tooth Shaping

Tooth shaping is used to reduce the saturation effect on stator teeth and the core loss. The rectangular slots and the trapezoidal teeth are used in the proposed model (See Fig. 5).

Fig. 6 shows the flux density distribution in stator core with trapezoidal teeth. As seen, the flux density is significantly reduced in stator teeth.

Fig. 7 shows the core loss reduction in rotor disk and stator core by using the tooth shaping. Overall, the core loss is reduced by 72.76 percent using this proposed model. Table. II shows the reduction in maximum flux density in stator core about 3.63 percent.

Fig. 8 compares the output torque obtained through the basic and optimal models. As shown, the average torque is increased by using the tooth shaping. However, the torque ripple is not almost affected by this technique.

Fig. 9 shows the reduction in the ripple of air gap flux density obtained from the optimal model. Furthermore, the effect of armature reaction on the flux density distribution in magnets is reduced by using the tooth shaping technique (See Fig. 10).

TABLE II. THE INFLUENCE OF TOOTH SHAPING ON MAXIMUM FLUX DENSITY

Maximum flux density (Tesla)	
Proposed model	Basic model
2.0892	2.1679

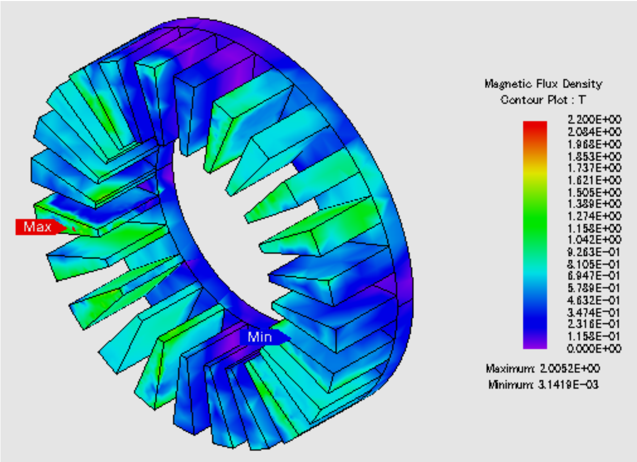

Figure 6. The flux density distribution in stator core of proposed model in t=0.00316 (s).

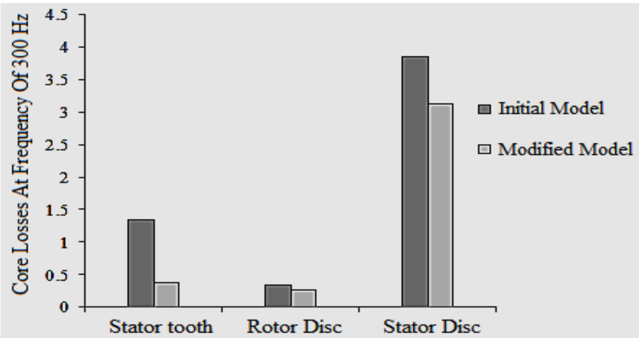

Figure 7. The core loss in frequency 300 (Hz).

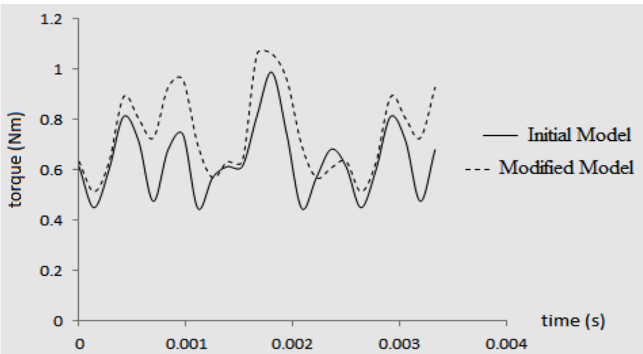

Figure 8. The output torque comparison.

V. CONCLUSION

In this paper, the core loss reduction was performed in AFPM motors. With respect to the results obtained through FEA, It was shown that the magnetic saturation can be reduced by using the tooth shaping technique. For this reason, the core loss was reduced by 72.76 percent.

Furthermore, the output torque was increased by using the trapezoidal teeth whereas the torque ripple was not almost affected by this technique. The influence of armature reaction on magnets was also decreased by using the tooth shaping.

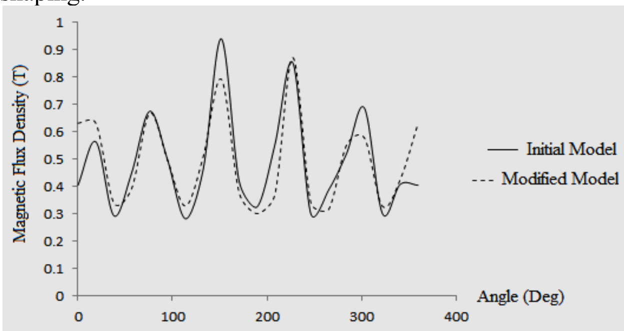

Figure 9. The comparison of air gap flux density in t=0.00316 (s).

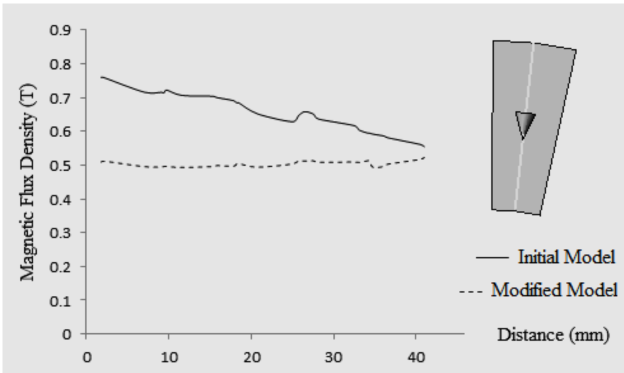

Figure 10. The comparison of air gap flux density inside magnet in t=0.00316 (s).

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