Efficient Design and Material Strategies for High Power Density Axial Flux Permanent Magnet Motors

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***Abstract*— This paper explores design adjustments to enhance the efficiency with regards to co-design parameters of high-power motors of an axial flux yokeless and segmented armature (YASA) topology. The study examines the benefits and drawbacks of implementing tooth tips on the stator teeth. In particular, this paper proposes an alternating tooth tips arrangement that can still be implemented with pre-formed coils. For the motor under study, the alternating tooth tips can slightly increase efficiency relative to an open-slot design. Using soft magnetic composite tooth tips affixed to the teeth in a more conventional arrangement would provide even more efficiency, but would also increase manufacturing complexity. This paper also evaluates employing silicon or cobalt steel for the stator teeth with the same design; cobalt steel can boost the motor performance in comparison to grain oriented M6 material. Additionally, this paper discusses further modifications to the motor design regarding the tooth wound winding fabrication methods and tolerances. The manufacturability challenges and opportunities of the additive manufactured windings and edge bent windings with regards to their impact on toque production are provided, and pictures of the prototyped windings are shown to compare their thermal interfaces for the thermal management system functionality.**

Keywords*— *Axial flux machines, YASA, stator tooth tips, cobalt steel, high power density, electric aircraft, manufacturing, edge bending, additive manufacturing, winding.

I. Introduction

The demand for electrified vehicles in the transportation industry has led to an incredible ramp-up in electric machine design advancement. In the last decade, several electric machine topologies have been proposed to achieve higher power densities. While radial flux motors are the most mature technologies for mass manufacturing, there have been some design developments in axial flux machines for improved manufacturability, making them strong candidates to compete with conventional radial flux machines. The yokeless and segmented armature (YASA) motor, has the potential to offer superior torque density, particularly in weight-sensitive applications such as aerospace and electric aircraft, where it can meet the aggressive specifications required [1]-[5]. In the aviation-class synergistically cooled electric-motors (ASCEND) project, the US advanced research projects agency-energy (ARPA-E) targets a full electric powertrain with a 250 kW peak power at 5000 RPM [4], [6]-[9]. In this paper, the electric motor designed for these targets is an axial flux permanent magnet (PM) dual-rotor topology with a stator made of grain oriented electrical steel (GOES), as shown in Fig. 1 ([9]-[12]). The two rotors' PMs are arranged in Halbach arrays and segmented to reduce the eddy current losses induced in the magnets. This segmentation reduces the eddy current losses by 86% [9]. However, there are still significant AC losses in the stator windings, largely due to the rectangular wires and high fundamental frequency.

Stator tooth tips, as shown in Fig. 2, are known to reduce AC losses in the permanent magnets and stator windings [9],[13]-[17]. These tangential extensions can have triangular or rectangular cross sections. However, if the tooth tips are made of one piece with the stator teeth, the coils cannot be pre-formed and then slid over the stator teeth. Therefore, if the presence of tooth tips improves motor's performance, they need to be attached separately in the assembly process.

The tooth tips could be formed of soft magnetic composites (SMCs) [9],[13] or solid iron and then epoxied to the stator teeth after the windings have been placed, but this adds additional manufacturing steps. Therefore, we propose, as illustrated in Fig. 3, to include the tooth tips as part of the GOES tooth tips but only on one end of each tooth. The alternating tooth tips are

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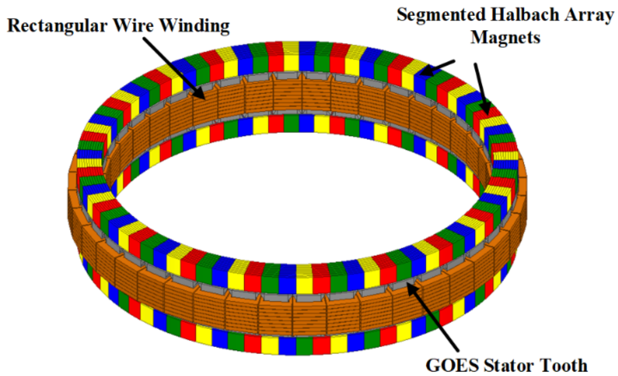


Figure 1: Motor design under study, axial flux YASA dual PM rotor.

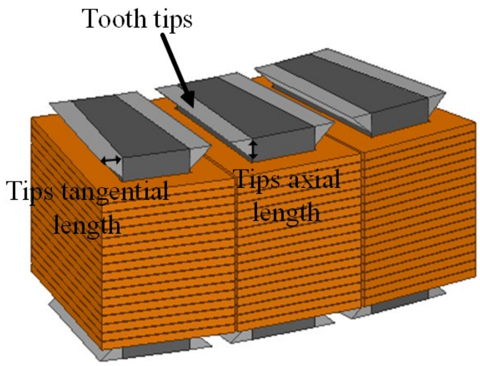


Figure 2: 3 stator teeth with tooth tips

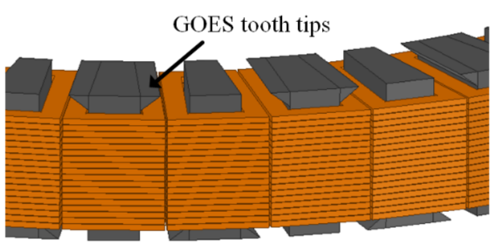


Figure 3. Alternating tooth tips orientation

compatible with pre-formed coils yet can reduce slotting harmonics to reduce eddy current losses in the magnets and can shield the stator windings from some of the rotor flux to reduce AC losses in the windings.

In general, silicon steel is widely used in electric motor manufacturing due to its cost-effectiveness and well-established performance characteristics [18], [19]. However, cobalt steel materials have a higher saturation flux density, making them a good candidate for high-performance electrical machines with their higher electrical resistivity and ability to conduct more magnetic flux [20]-[24]. Yet, these high-performance alternatives are less accessible and are usually an order of magnitude more expensive.

This paper provides a comparison of alternating tooth tips against added SMC or iron tooth tips and against the open-slot design on torque production, losses, and other related electromagnetic performance metrics of the machine.

TABLE I: SELECTED MOTOR PARAMETERS

Parameters	Values
Peak takeoff power (kW)	250
Cruise power (kW)	83
Takeoff speed (RPM)	5000
Cruise speed (RPM)	4000
Pole pairs	20
Number of stator teeth	42
Takeoff current density (A_{rms}/mm^2)	42.42

Moreover, the analysis and comparisons are extended to evaluate the electromagnetic (EM) motor characteristics with a different silicon steel alloy and cobalt steel. There are further discussions about axial flux motors' manufacturability potentials and challenges and how manufacturing limits on winding fabrication methods and tolerances affect the performance.

II. Electric Motor Design and Optimization Methodolody

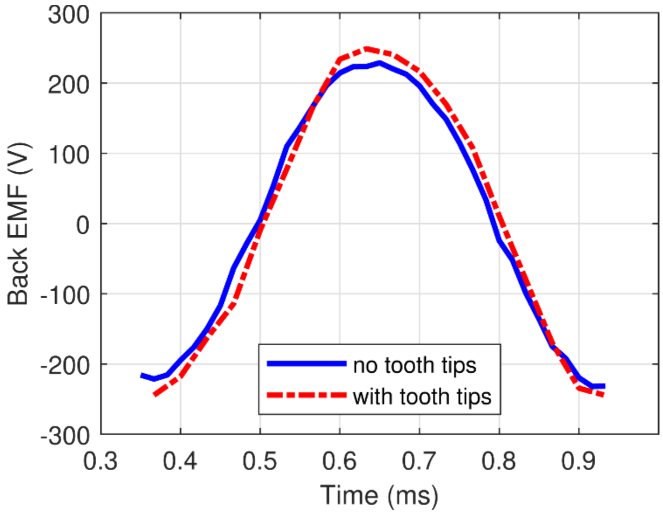
Following [9]-[12], the selected optimized design (Fig. 1) and some of its corresponding variables based on ASCEND program are provided in TABLE I. As stated in [9], [11] and [12] the motor cooling system employs coolant flowing through minichannel heatsinks on the outer end windings. A thermal energy storage system is proposed for the inner end windings to reject the excessive heat during takeoff and climb with the purpose of avoiding over-designing the thermal management system of the full electric powertrain [11].

In the 3D finite element analysis (FEA) performed for the previous optimization study, tooth tips sizing variables were kept constant at 3 mm (axial height) by 2 mm (tangential length). The tooth tips had triangular cross sections. In this paper, the axial height and tangential width of the triangular cross section are swept, and each design is simulated in 3D with Ansys Maxwell. The stator teeth are made of grain oriented M6 silicon steel. Since the purpose of this study is the tooth tips arrangement and sizing in particular, the rest of the model is untouched and is evaluated at peak power for aircraft takeoff ([4]).

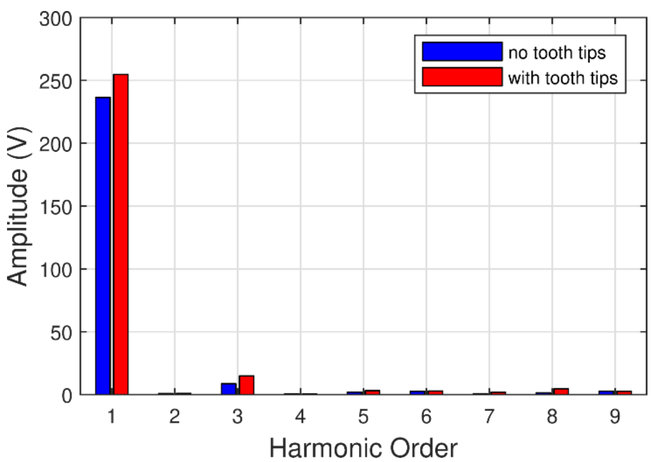
In the next sections, the FEA study is broadened to evaluate the tooth tips with rectangular cross sections as well as impact of different electric steel assignments to the stator teeth.

III. Simulation Results

Relative to the open-slot stator configuration, adding the tooth tips can improve the back emf and make the airgap smoother; this also helps in toque pulsation and cogging torque in other PM electric machines [14],[15], [26]. Fig. 4(a) shows the back emf of the ASCEND motor with and without the tooth tips. The graph shows a slight improvement in increasing the back-emf and Fig. 4(b) presents the harmonic content of the Fig. 4(a) back-emf.



(a)



(b)

Figure. 4: (a) Transient back emf over one cycle at 5000 RPM speed with and without tooth tips (b) back emf harmonic contents with and without tooth tips

Fig. 4(b) confirms that the fundamental harmonic of back-emf increases with using tooth tips in the stator, thus, the motor produces a higher torque for the same amount of current.

Considering the original tooth tips arrangement on every single tooth, Fig 5 provides the efficiency results employing the three different materials, solid steel, GOES or SMC. The results show that tooth tips in this design are capable of improving motor efficiency from almost 93.5% to 94%, which in the 250-kW full power operating point is 1.4 kW less heat, about an 8% reduction.

This amount of loss reduction can make a considerable positive impact on the drivetrain operation with the compact sizing (OD 30 cm) and the small thermal interfaces. Moreover, Fig. 5 shows that having tooth tips with the optimum sizing regardless of their material is advantageous. However, the SMCs slightly exceed the performance of the solid steel or GOES.

However, in the manufacturing, bonding 4 tooth tips to each of the 42 stator teeth would be a significant endeavor. Therefore, the motor with the different SMC tooth tips sizes is compared to a GOES tooth tips alternating arrangement.

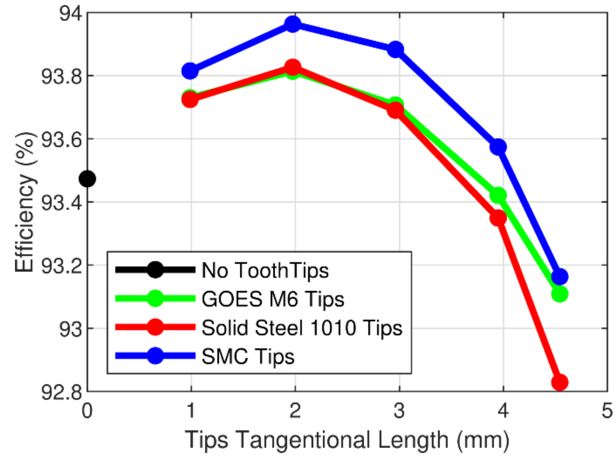


Figure 5. Electric motor efficiency at different tooth tips tangential length and different materials.

Fig. 6 shows the simulation results. While the black point in each plot represents a motor without the stator tooth tips, each line corresponds to a specific axial height for the tooth tips with different tangential lengths. The solid lines provides the results with the GOES tooth tips on alternating teeth (Fig. 3), and dashed lines corresponds to the SMC tips on each tooth (Fig. 2). The lines (solid and dashed) each are for a specific tooth tips height size.

The rotor torque in Fig. 6(a) shows a slight increase with small tips, especially small SMC tooth tips on each tooth. Small tooth tips allow each tooth to collect more flux from the rotor, but, as the tooth tips get larger, leakage flux between adjacent teeth increases, reducing torque. This leakage flux is especially significant with tooth tips on every tooth. Fig. 6(b) shows how the tooth tips' presence in the model decreases losses in the windings because they shield the windings from the PM flux. However, extending the tips tangentially beyond 3 mm with 3 mm axial height increases the winding losses as leakage flux that passes partway through the tooth tips and through the windings increases. Although the PM segmentation reduces the induced eddy current losses in the PMs from 1.56 kW to 0.21 kW [9], employing the tooth tips reduces the PM losses even more by reducing slotting harmonics, as shown in Fig. 6(c). Fig. 6(d) combines the results of previous plots in addition to core losses to compare the efficiency of each point. The overall efficiency including the copper losses, core losses, and the rest of the AC losses can be improved by 0.5% with the optimal SMC tooth tips on each tooth; this is significant with the aggressive program targets. Nonetheless, SMCs are relatively brittle ([25]) and would have to be affixed to each tooth after the pre-formed coils are placed over the teeth. On the other hand, the GOES tooth tips on alternating teeth solve these challenges but can only improve the efficiency by up to about 0.2%.

Fig. 6(e) presents the axial force data on one rotor at no load condition. The structural designs are based on the maximum forces the parts experience, which is at no load. The amount of axial force has direct correlation with the rotor torque [9] and airgap surface area. Therefore, as shown in the graph, the larger the tooth tips make the airgap surface area larger, increasing the force. Here, the alternating tooth tips configuration has the

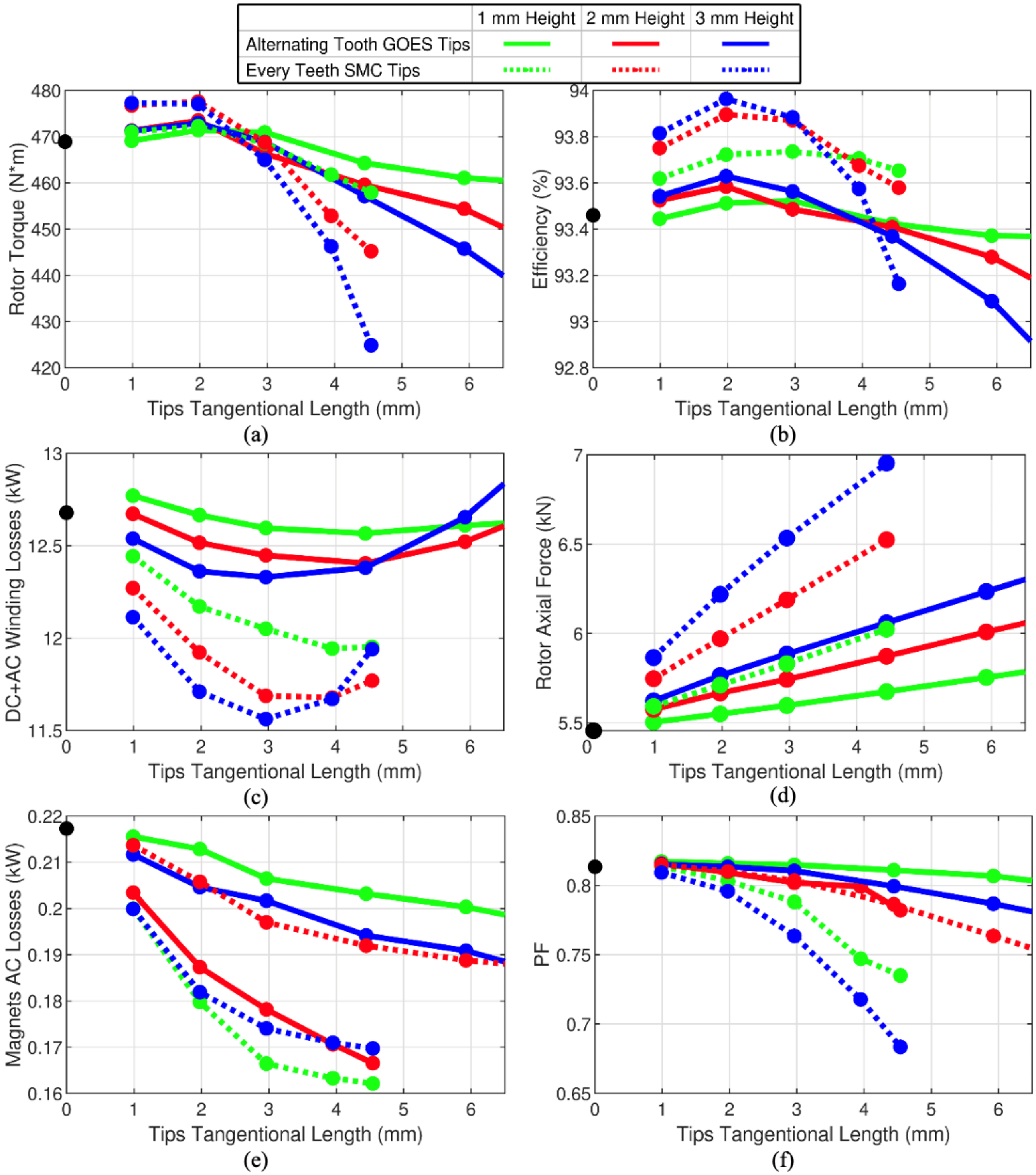


Figure. 6: Tooth tips effect on (a) rotor torque, (b) total AC and DC losses in windings, (c) AC permanent magnet losses, and (d) overall motor efficiency (e) rotor no load axial force (f) power factor

advantage of lower airgap surface area that can reduce the force by 500 Nm relative to having the SMC tooth tips on each stator tooth. Lowering the axial forces allows a lighter and less complex rotor structure.

By increasing the size of the tooth tips, and their proximity to an adjacent one, the stator leakage inductance increases, which decreases the power factor, as shown in Fig, 6(f).

To serve the purpose of shielding the rectangular wire windings from high frequency AC losses, the tooth tips can be different shapes and not necessarily triangular. For that reason,

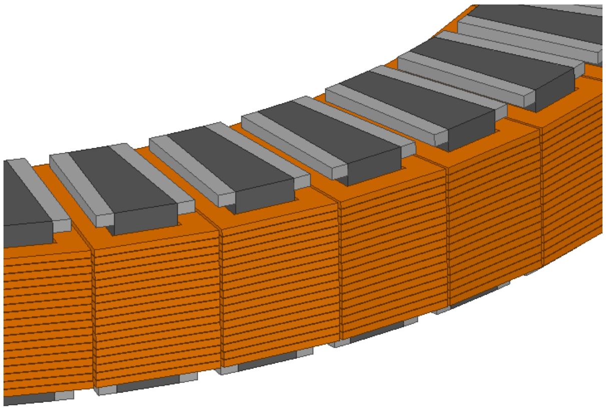


Figure 7: Rectangular cross section tooth tips

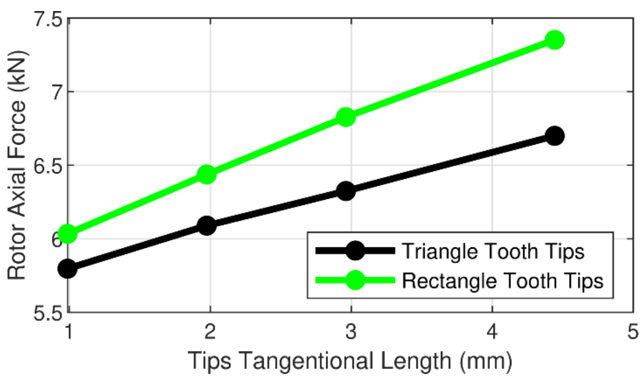


Figure 8: Rotor no load axial force with triangular cross section tooth tips and rectangular ones.

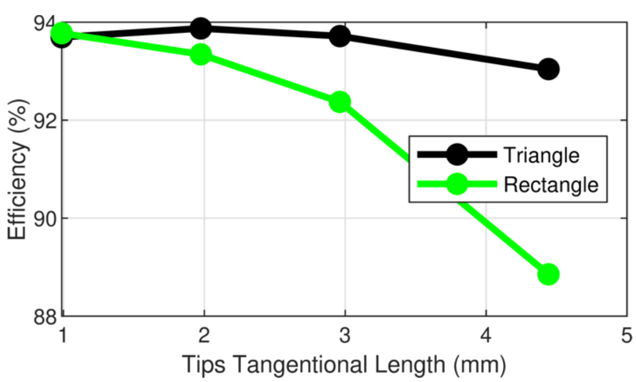


Figure 9: Overall efficiency of the motor with triangular cross-section tooth tips and rectangular cross-section tooth tips at takeoff condition at 3 mm tips height.

the analysis is expanded to rectangular cross section tooth tips as well (Fig. 7). Fig. 8 compares the no load axial force on the triangular and rectangular tooth tips, and Fig. 9 compares the overall efficiency counting the magnets loss, core losses and winding AC and DC losses, with the triangular and rectangular tooth tips. The designs with rectangular tooth tips experience larger axial forces because rectangular tooth tips can accommodate more flux from the rotor permanent magnets before saturating. The designs with rectangular tooth tips also experience lower efficiencies because they accommodate more leakage flux before saturation, reducing the torque per amp.

IV. Stator Material Selection

In electric motor design, core material selection is essential to suit the application and operating condition. In this design, the core material of base model is M6 GOES, which has previously been implemented and tested in dual-rotor axial flux motors [13],[19].

In order to investigate the possible paths to save more losses in the electric motor design to reduce the load on the thermal management system, the impact of using other electrical steel materials is also evaluated on the selected design. In particular, another grade of silicon steel, M3, and a cobalt steel grade, Hiperco50A are evaluated.

Table II lists the simulation results of the motor with the same design to obtain the 250 kW takeoff specs (478 Nm at 5000 RPM). In these three cases, the current is adjusted to produce 478 Nm torque.

Hiperco50A is a high performance soft magnetic alloy composed of approximately 49% cobalt, 49% iron, and 2% vanadium that is non grain oriented (NGO). The higher saturation induction of Hiperco50A allows the design to operate at a lower current density; therefore, the winding losses (DC copper losses and high frequency AC losses), which are the dominate source of losses in the motor, are lower than the silicon electrical steel teeth. However, the higher saturation flux density increases the eddy current losses induced in the magnets with Hiperco50A material. The grain oriented (GO) M6 material has the weakest performance at the takeoff operating condition because it suffers from high core losses due to its inherent high core losses coefficient compared to M3, which is a different grade of silicon steel. Hiperco50A has a higher mass density than the M6 and M3, which explains the slight increase in the motor total mass for that column. In the Table II designs, tooth tips are absent. In Fig. 10, the SMC tooth tips analysis with 3 mm axial height is applied to the Hiperco50A designs to study how tooth tips are advantageous with higher saturation magnetization material. The Hiperco50A designs are significantly more efficient than the M6 designs. The Hiperco50A designs experience lower core losses because the Hiperco50A laminations are thinner. Additionally, winding

TABLE. II. MOTOR PERFORMANCE AT TAKEOFF CONDITION WITH SILICON AND COBALT STEEL STATOR TEETH

Criteria	Teeth material		
	M3	M6	Hiperco-50A
Rotor Speed (rpm)	5000	5000	5000
EM Torque (Nm)	478	478	478
Core loss (kW)	1.91	5.35	1.64
Magnet loss (kW)	0.32	0.32	0.42
Winding loss (kW)	13.63	14.42	11.14
Efficiency (%)	94.05	92.56	94.98
Mass (kg)	7.77	7.72	7.86
GO/NGO	GO	GO	NGO

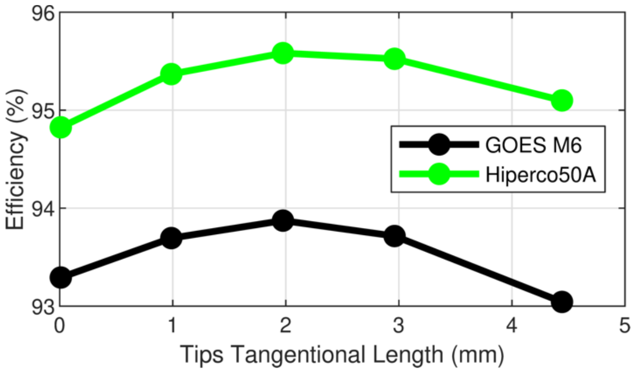


Figure. 10: Impact of using 3 mm height SMC tooth tips with Hiperco50A stator teeth on overall efficiency.

losses are lower with Hiperco50A because the current can be reduced while maintaining the same torque. Still, the different core materials have a similar trend of efficiency improvement with presence of SMC tooth tips.

V. Stator Design Correction Due to Manufacturing Constraints

In the original motor design, for simplicity and faster simulation, the model did not consider some fabrication challenges. Therefore, in the fabricating stage of the motor it is necessary to review the effects of design modifications for fabrication. These modifications are mainly related to the sharp edges and corners on the stator teeth and windings and the tolerances.

Fig. 11 shows the cross-section of one stator tooth with its coil and its transition from a simple design intended to be implemented with additive manufacturing to a more realistic one intended to be implemented with edge-bending.

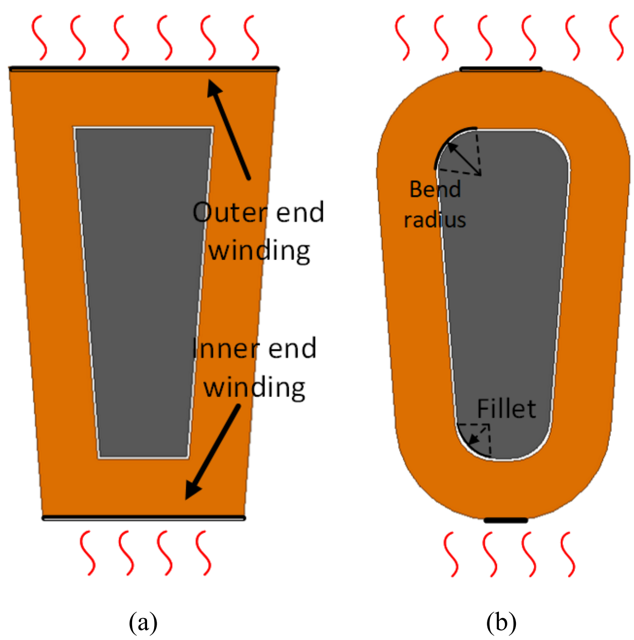


Figure 11. Stator tooth cross section (a) simple design (b) fabricating model. Red squiggles indicate the surfaces where heat is removed.

Wire edge bending technology is a mature manufacturing technique that can fabricate the non-conventional tooth wound coils in axial flux motors. Fig. 12 shows a picture of single edge-bent coil for the ASCEND motor. However, this manufacturing method limits the inner coil bend radius of at least 3 mm.

Alternatively, with the recent developments in additive manufacturing (AM) technology, the copper windings can be 3D printed (Fig. 13), thus the inner and outer bend radius can be as small as 1 mm. Fig. 14 shows a model of the full stator with edge-bent windings.

The different fabrication methods for the winding have two major impacts on powertrain operation; one is on the EM performance and torque production of the motor. Fig. 15 shows the rotor torque with these two manufacturing approaches and the simple initial design. The larger bend radius required for edge-bending reduces the torque more, as the cross-sectional area of the tooth is reduced, but the difference in torque is only about 2%. The other impact of different winding fabrication method is on rejecting heat. As stated in [9], the majority of the heat is removed through the stator end windings with mini-channeled heatsinks and the thermal energy storage approach[9], [11], [12]. The effective contact area on the winding thermal interfaces is crucial. The flatter and smoother the windings' end turns are, the lower thermal resistances will be for cooling the motor. Fig. 11 simply depicts how the bend turn radiuses affect the flatness of the end winding surfaces and introduces challenges on the heat rejection system. In this


Figure 12: Edge bent winding for ASCEND stator.


Figure 13: Additively manufactured copper coils for ASCEND stator.

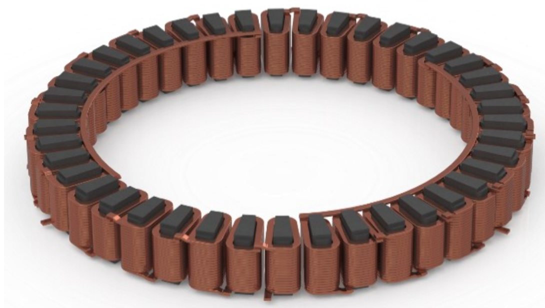


Figure 14: Full stator model with edge-bent windings

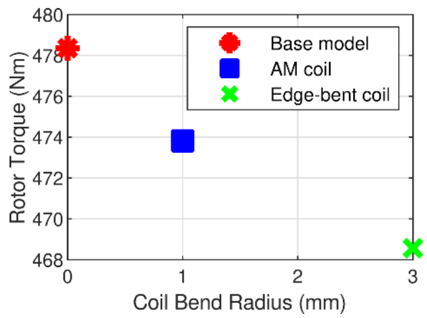


Figure 15: EM torque comparison between base model, AM coils and edge-bent coil.

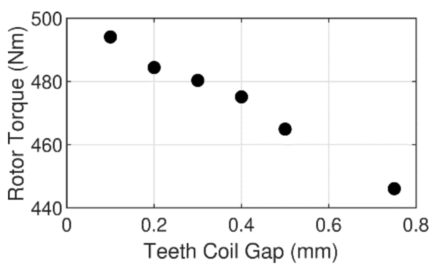


Figure 16: Rotor torque variation at different gaps between coil and tooth

design, the AM coils have the flat thermal interface on the outer end windings reduced by about 11%, while the edge-bent coil loses almost 74% of the area.

Nonetheless, insulating AM coils is a challenge and the technology need to be developed to reliably perform in high voltage, high frequency electric motor operations. However, [27] presents a promising path to develop axial flux motor fabrication using AM method in near future.

Fig. 16 shows the impact of varying the gap between tooth and coil for the 2.5 mm chamfer and 3 mm coil bend radius for edge-bent wires. (The coil is kept the same and the tooth is changed). The results show that small (<1 mm) changes in this gap can affect the torque by more than 10%, so maintaining tight tolerances is quite beneficial, as tolerances will affect how much of a gap is required.

Fig. 17 presents a similar analysis for the total volume of PMs taking the associated space on the rotor; the drop in the total volume is to accommodate the tolerances' variation or the epoxy thickness to attach the segmented magnets together. The results show a linear variation of the torque at different magnets' volume.

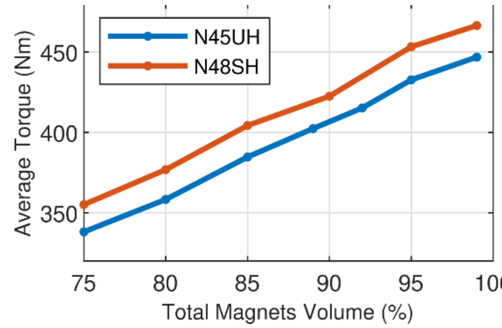


Figure 17: Torque variation at different permanent magnet volumes due to tolerances for Neodymium magnet grades N45UH and N48SH

VI. Conclusions and Future Works

In this paper, the tooth tip design for a YASA motor is studied. We propose to incorporate the tooth tips as part of the GOES tooth but only on one end of each tooth (Fig. 3). The analysis and comparison against previously proposed SMC tooth tips placed on both ends of each tooth shows that the alternating topology can improve the efficiency by 0.2%, while the SMC tips can improve the efficiency by 0.5%. However, the alternating topology simplifies the assembly process since the tips are already included with every fabricated tooth for a pre-formed winding. The paper also includes evaluation of different stator teeth material based on commercialized silicon and cobalt alloys. The results show an improvement of 2.4% in efficiency by using Hiperco50A in comparison to grain oriented M6 at the motor takeoff condition. Moreover, challenges and potentials on prototyping the motor are discussed, and two different methods of additive manufacturing and edge bending coils are briefly evaluated with respect to their impact on EM characteristics and system level thermal management.

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