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IMPACT OF EDDY CURRENT MINIMIZING STATOR TEETH IN ADDITIVELY MANUFACTURED ELECTRIC MACHINES

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Abstract

Additive manufacturing (AM) offers a promising pathway for producing components with complex geometries to improve the power density and efficiency of electric machines. However, manufacturing laminated flux-carrying components using AM remains impractical. To address this challenge, recent studies have explored complex geometric structures that minimize eddy currents, such as the Hilbert space-filling pattern, which can be readily fabricated through AM. These designs introduce intricate flux paths that alter the magnetic fields in the airgap and affect the machine's electromagnetic performance. This paper investigates the impact of such eddy-current-minimizing structures on machine performance by comparing a conventional laminated stator axial flux machine with two AM designs featuring the Hilbert stator structure, one with a laminated stator yoke and another with wider stator teeth. Results show that although AM enables the realization of flux-carrying components with complex topologies, design modifications are required to achieve performance comparable to traditional laminated machines. Furthermore, the AM design with wider stator teeth demonstrates approximately 10% higher efficiency than the design with a laminated yoke under low-speed, high-torque operating conditions, highlighting the potential of geometric optimization in enhancing the efficiency of additively manufactured electric machine stators.

1 Introduction

Power-dense and efficient electric machines are desirable in several applications including electric vehicles, robotic actuators, and industrial drive systems. Realizing these designs nearly always requires exploring the design space using shape and topology optimization techniques, often resulting in complex geometries that are difficult to fabricate using conventional manufacturing techniques. The use of additive manufacturing (AM) techniques to fabricate electric machine components with unconventional shapes to realize performance improvements is an area of active research interest, e.g. [1–3].

Conventional electric machines use electrical steel laminations (typically Fe-3wt%Si) to minimize the induced eddy currents in the flux carrying soft-magnetic components. However, laminated structures are discontinuous and not conducive to manufacture using AM techniques. Recent research, e.g. [4–7] has experimentally demonstrated the effectiveness of complex lamination-emulating geometric structures and high resistivity materials to minimize the induced eddy currents in additively manufactured soft-magnetic components. However, the complex flux paths introduced by these structures can impact the electromagnetic performance of the machine.

The author's previous research [5, 6] demonstrated the feasibility to additively manufacture axial flux PM machine (AFPM) stators with lamination-emulating Hilbert shaped

teeth and yoke. However this stator was found to reduce the machine torque capability by 22% compared to a conventionally fabricated laminated stator. Additionally, as shown in [5], the Hilbert shaped yoke is complex to manufacture, particularly at the interfaces with the stator teeth.

In this paper, two AM stators are designed to overcome the drawbacks observed in [5] and analyze the impact of the Hilbert structure on the machine's electromagnetic performance. These designs are based on the stator developed in [5] with two key design modifications:

1. AM design 1 has the same dimensions as the prototype stator in [5] but uses a laminated yoke to reduce the AM complexity.
2. AM design 2 uses 20% wider stator teeth than the first design to improve its torque capability.

The approx. 20% lower stator slot area in the second design due to wider teeth can be compensated using AM coils, which have been shown to achieve slot fill factors of approx. 70% [8], making this design feasible to manufacture (the prototype in [5] only achieved 40% fill factor using AWG 12 magnet wire).

The performance of the two AM stator designs is compared with that of a baseline conventional laminated stator using 3D FEA to assess the impact of the Hilbert space filling pattern,

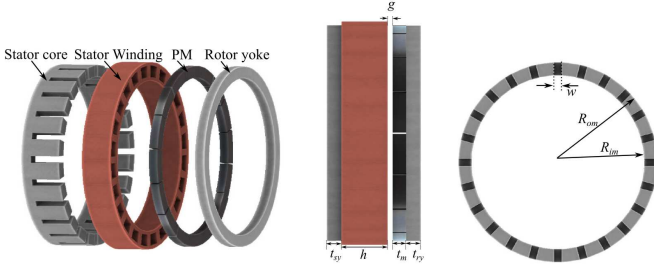


Fig. 1: CAD rendering of the AFPM design [5]

stator yoke structure, and wider stator teeth on machine performance. The results show that the wider stator teeth in AM design 2 result in reduced torque ripple, albeit with increased axial forces between the stator and the rotor. In addition, AM design 2 is up to 10% more efficient in the low-speed high-torque region, while AM design 1 is more efficient in the high-speed, low-torque operating region.

2 Design Details

In this section, key details of the electric machine design are presented. Three AFPM designs, i) baseline design, ii) AM design 1, and iii) AM design 2 are analyzed in this paper. These designs are based on the AFPM design that was developed and characterized in [9]. All three designs use the same rotor geometry. The CAD rendering of the baseline design is shown in Fig. 1 and its key dimensions are listed in Table 1.

The baseline design uses a conventional stator made using 3% Si steel (Fe-3wt%Si) Arnon 5 laminations. This stator can be manufactured by machining slots into a tapewound core, as described in [5]. The AM designs use stator teeth with a Hilbert pattern, made using 6.5% Si steel (Fe-6.5wt%Si) similar to the AM stator design proposed in [5]. However, unlike the design in [5] which also uses a Hilbert stator yoke, the AM stators in this paper use a laminated yoke structure, to simplify the design and manufacturing.

Table 1 Baseline AFPM parameters from [9]

Parameter	Symbol	Value
Stator slots	Q	24
Rotor pole pairs	p	8
Rated current	$\hat{I}$	140 A _{pk}
Max. speed	$\omega_{\max}$	12,500 rev/min
Airgap length	g	2 mm
Stator core inner radius	R_{im}	71.5 mm
Stator core outer radius	R_{om}	82.3 mm
Rotor yoke thickness	t_{ry}	6.5 mm
PM thickness	t_m	5.3 mm
Tooth axial length	h	23 mm
Slot width	w	8 mm
Stator yoke thickness	t_{sy}	12 mm
Total stator axial length	$h + t_{sy}$	35 mm

The 6.5% silicon steel processed using metal AM has a lower saturation flux density than Arnon 5 [6]. It was also shown in [5] that the Hilbert stator with Fe-6.5wt%Si has approximately 30% lower iron content (mass) and 22% lower torque capability compared to a conventional stator of the same dimensions. To assess the impact of increasing the stator iron content on the electromagnetic performance of AM stators, the stator teeth of AM design 2 are made 20% wider than AM design 1 and the baseline stator as shown in Fig. 2b

The stator parameters for the proposed designs are compared with the baseline design from [9] in Table 2 and the proposed AM designs are shown in Fig. 2. The slot area for AM stator 2 is reduced due to wider stator teeth. However, this is not viewed as a major concern since the baseline and AM stator 1 assume slot fill factors of 40% which can be significantly improved using additively manufactured coils [8, 10] to achieve the same conductor current density and thermal performance, despite the reduced slot dimensions of AM stator 2.

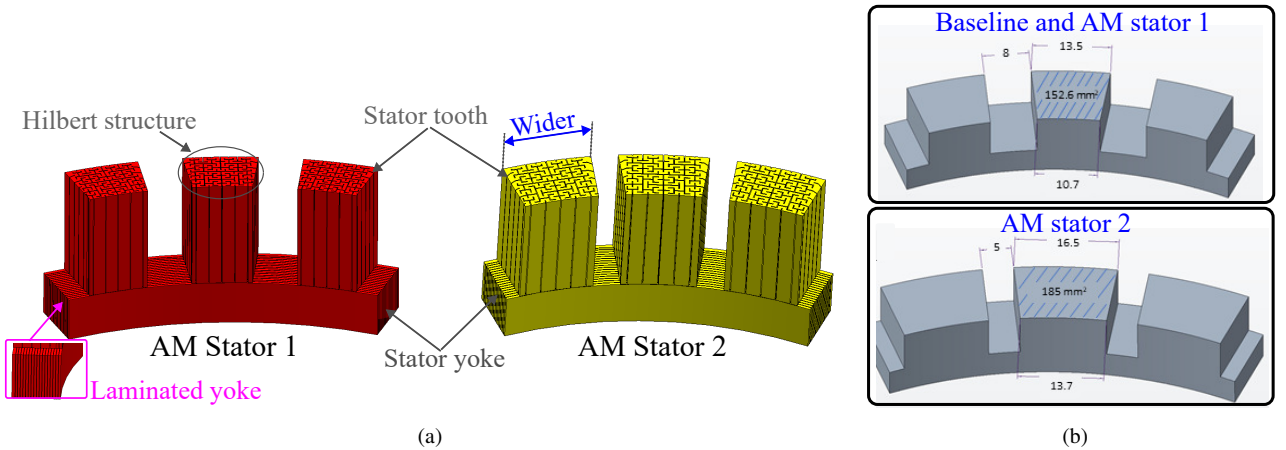


Fig. 2: Proposed AM stator designs: (a) tooth and yoke structures, and (b) tooth and slot dimensions. Both the stators use the same yoke design with 0.5mm thick laminations and a 0.1mm clearance between adjacent laminations.

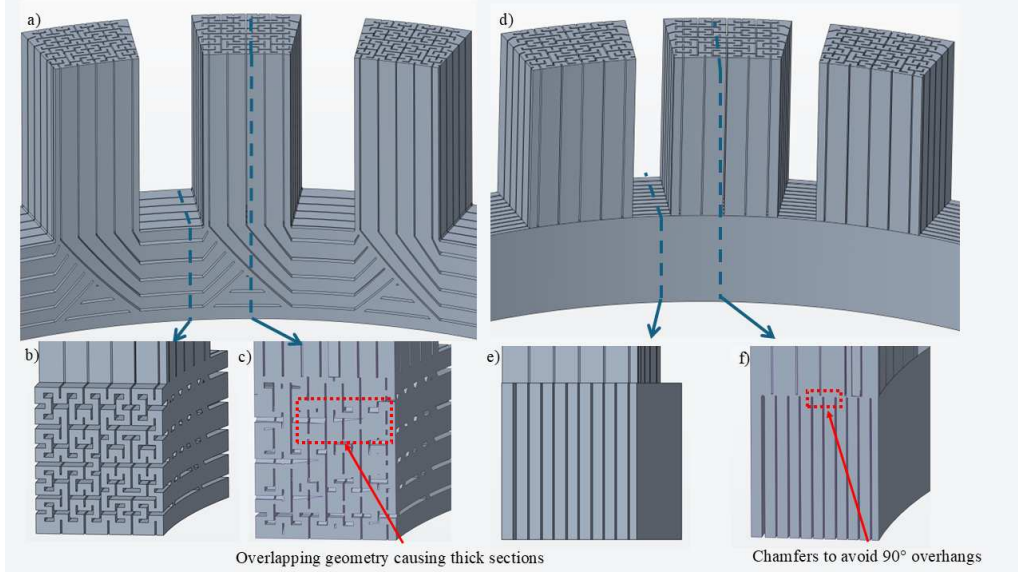


Fig. 3: (a) Original design with Hilbert pattern for teeth and yoke, showing the yoke cross-section (b) as well as the cross-section underneath the tooth (c) showing overlapping geometry. (d) Modified design (AM design 1 & 2) with the cross-section (e) including chamfers to prevent overhanging surfaces (f).

3 Stator Fabrication

The previous iteration of the additively manufactured stator fabricated in [5, 6] used Hilbert space filling curve geometry on both the yoke and the teeth (Fig. 3a). Whilst the Hilbert geometry was achieved in the yoke, this required multiple iterations of the stator with fine adjustment to successfully build this part, with a laborious trial and error approach. This geometry uses multiple surfaces which are horizontal and have an overhang angle of 90° (Fig. 3b), whereas AM designs are generally limited to overhang angles of 45° to ensure manufacturability. Research is progressing to enable much higher overhang angles, with in-situ control often used to reduce the energy input to the downskin surfaces, enabling higher angles as demonstrated in [11], but for simplicity in this study overhang angles were kept below 45° .

Furthermore, the interfacial region between the stator teeth and the yoke has three potential flux pathways, as illustrated in Fig. 6 of [5], which are flux being carried around the yoke, as well as flux coming into the tooth from either direction. Previously, all three flux pathways maintained the Hilbert geometry, which in the area underneath the tooth culminated in all three pathways converging at different angles, and the air gaps from one pathways were replaced with solid material from another pathway, per Fig. 3c.

In this study, the Hilbert pattern was maintained in the tooth geometry, as this was demonstrated to have a better performance than the AM laminated structure as shown in [7]. However, the yoke was replaced with a laminated structure, which was able to maintain a constant cross-section around the entire yoke, even underneath the stator teeth. To ensure the tooth didn't start with 90° overhanging surfaces, a 45° chamfer was added to interface between the laminated yoke and the Hilbert tooth as shown in Fig. 3f.

4 Performance Evaluation

This section presents the performance evaluation of the baseline and the two AM AFPM designs. The FEA models are first described and the key results from 3D FEA analysis are presented.

4.1 Model Description

The 3D flux paths and the Hilbert structure necessitate using 3D FEA to accurately assess design performance. To minimize the design evaluation time, design symmetry was used to only model $1/8^{\text{th}}$ of the design (2 poles and 3 slots). The 3D FEA model for the baseline design is shown in Fig. 4. Similar models were created for the other two designs by only modifying the stator per Table 2 and Fig. 2a. The resistivity of the stator materials and the yoke stacking factor are listed in Table 2. The AM stators have a low stacking factor for the yoke since a minimum clearance of 0.1mm is necessary between adjacent laminations (a limitation of the available AM equipment).

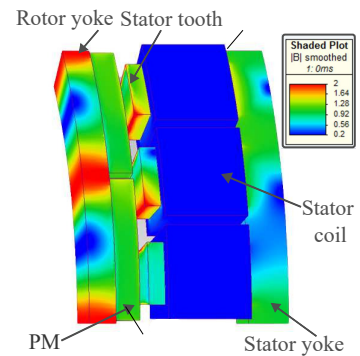


Fig. 4: 3D FEA model of the baseline stator.

Table 2 Baseline and proposed stator parameters

Design	Material	Tooth	Stator yoke	Tooth dimensions	Resistivity	Yoke Stacking Factor
Baseline	Fe-3wt%Si	Laminated ^a	0.127mm lam ^a	Same as Table 1	$52\mu\Omega\text{-cm}$	0.93
AM Design 1	Fe-6.5wt%Si	Hilbert	0.5mm lam ^b	Same as Table 1	$82\mu\Omega\text{-cm}$	0.83
AM Design 2	Fe-6.5wt%Si	Hilbert	0.5mm lam ^b	22% wider than baseline	$82\mu\Omega\text{-cm}$	0.83

^a Commercial Arnon 5 (0.127mm) laminations are used. ^b AM laminated structures using Fe6.5wt%Si. Minimum thickness is limited to 0.5mm and min spacing between lams to 0.1mm due to AM equipment capability.

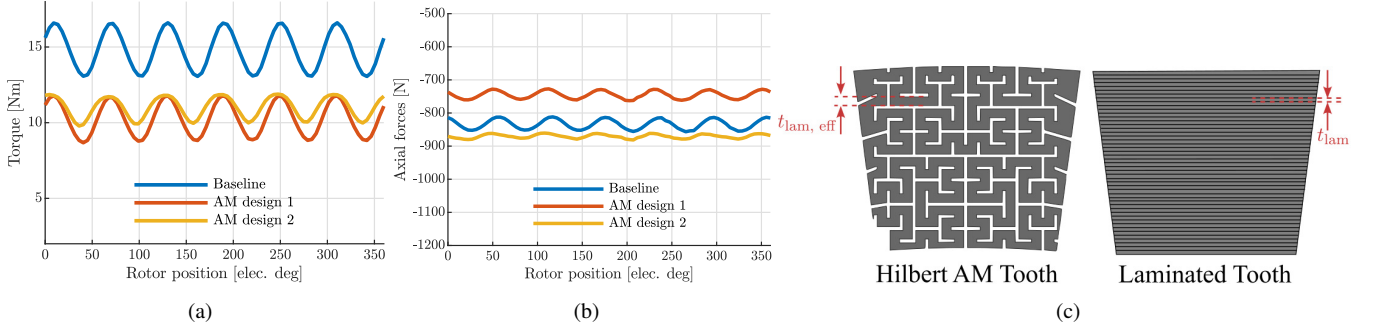


Fig. 5: 3D FEA results: (a) Torque v/s rotor position; (b) Axial forces v/s rotor position; (c) Definition of effective lamination thickness $t_{\text{lam, eff}}$ [5].

4.2 Torque and Axial Forces

Each design was analyzed using transient 3D FEA at the rated speed of 12,500 rev/min and rated current of 140A under max. torque per ampere (MTPA) condition. The electromagnetic torque on the rotor computed using 3D FEA for all three designs over one electrical period is plotted in Fig. 5a. It can be seen from Fig. 5a that the AM designs have lower torque compared to the baseline design. The average torque of AM designs 1 and 2 are approx. 29% and 24% lower than the baseline design. Furthermore, the wider stator teeth of design 2 results in approx 18.5% torque ripple, which is a significant reduction compared to AM design 1 (approx. 30% ripple) and the baseline design (approx. 22% ripple). These results demonstrate the effectiveness of increasing the stator tooth width to improve the average torque and reduce torque ripple in AM stators with eddy current minimizing geometries.

Single rotor, single stator AFPM designs can have significant unbalanced axial forces between the stator and the rotor. The axial forces on the rotor for the three designs are plotted in Fig. 5b. It can be seen that AM design 2 has the highest axial forces, compared to the other two designs, which can be attributed to the increased stator teeth surface area at the airgap. The low axial forces of AM design 1 relative to the baseline stator design are a consequence of the air regions introduced by the Hilbert pattern which reduce the iron on the stator teeth surface at the airgap.

4.3 Losses and Efficiency

The losses in each component is computed from the 3D FEA analysis for all the three designs. Since the Hilbert pattern in

the stator teeth can impact the airgap fields, the eddy current losses in the rotor PM and yoke can also change for the AM designs despite the same rotor dimensions. The stator copper losses are analytically computed.

The average losses in each component for each design are listed in Table 3. The stator copper loss was analytically computed to be 630W assuming AWG 12 conductors and using the resistivity of copper. It can be seen from Table 3 that the losses in the stator teeth and yoke are significantly higher for the AM designs compared to the baseline design. This is attributed to the approx. 4 times larger effective lamination thickness ($t_{\text{lam, eff}}$ in Fig. 5c) for the AM designs compared to the 0.127mm thick Arnon 5 laminations used in the baseline stator.

The AM stators however have lower eddy current losses in the PM and rotor yoke, which can be attributed to the attenuation in the airgap magnetic field compared to the baseline design. Among the two AM designs, the AM design 2 has higher stator losses and lower rotor losses. The higher stator losses can be attributed to increased iron content in the stator while the lower rotor losses can be attributed to the wider teeth that reduce the airgap harmonic fields due to the slotting effect.

The losses computed using 3D FEA in Table 3 can be used to derive the torque-speed-efficiency maps for the three designs across the operating range. These efficiency maps are plotted in Fig. 6. It can be seen from Fig. 6 that the AM designs are not as efficient as the baseline laminated design. An efficiency difference map is plotted in Fig. 6d for AM design 1 and 2. It can be seen that AM design 2 with wider teeth is more efficient at low speed, high torque conditions, while AM design 1 is more efficient at higher speeds. This is due to the higher torque capability of AM design 2, which results in lower copper losses at any given torque condition.

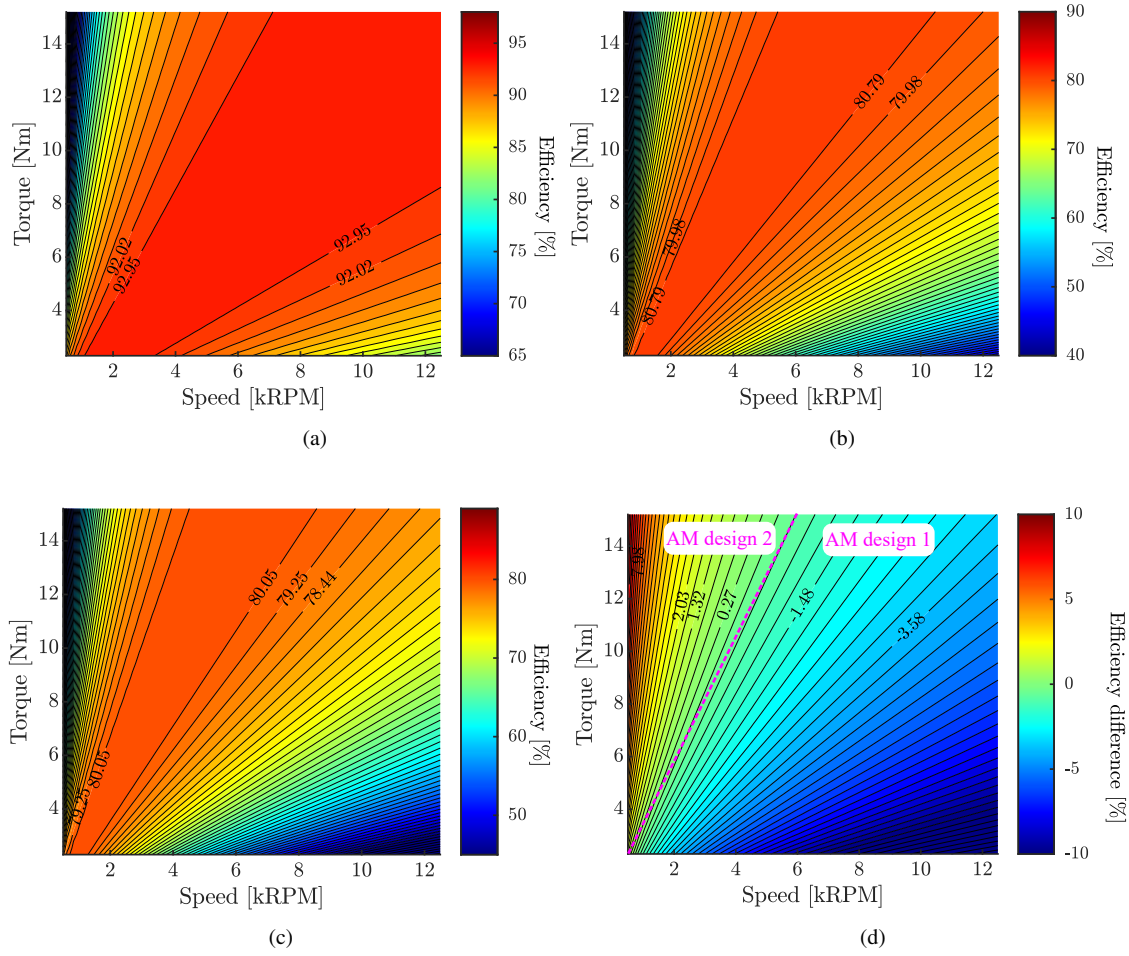


Fig. 6: Efficiency maps for: (a) Baseline design; (b) AM design 1; (c) AM design 2. (d) Efficiency difference between the two AM designs; AM design 2 is more efficient to the left of the dashed line and AM design 1 is more efficient to its right.

Table 3 Loss components of AFPM designs at 12,500 rev/min and rated torque

Design	Stator teeth [W]	Stator yoke [W]	PM [W]	Rotor yoke [W]
Baseline	366.6	168.5	69.3	42.5
AM Design 1	2574.5	1095.1	47.9	3.1
AM Design 2	3313.2	1390.4	32.1	2.2

5 Conclusions

This paper investigated the influence of two additively manufactured stator geometries, each incorporating eddy-current-limiting features, on the performance of axial flux machines. The comparative analysis highlights the promising capability of AM technology to tailor magnetic paths in ways that are challenging or impossible to achieve with traditional laminated stators. In particular, the findings show that increasing stator-tooth width is a promising pathway to recover the torque deficit observed when transitioning from a laminated reference stator to an AM design.

The results in this paper indicate that the wider-tooth AM stator (Design 2) not only improves the average torque output but also reduces torque ripple relative to the original AM

geometry (Design 1). These improvements demonstrate how geometric freedom in AM can be strategically leveraged to enhance electromagnetic performance. However, the increased tooth volume leads to higher stator losses at higher operating frequencies. Despite this, under high-torque, low-speed conditions where eddy current losses are less dominant, AM Design 2 achieves approximately a 10% improvement in efficiency.

Ultimately, the results in this paper confirm that AM technology can be effectively used to fabricate parts with 3D magnetic circuits in electric machines, enabling performance that approach those of conventional laminated stators when proper design optimization is applied. While the laminated stator still exhibits higher torque capability and benefits from the use of very thin laminations to minimize eddy current losses, AM stators offer distinct advantages for machine topologies

with inherently three-dimensional flux paths. This includes axial-flux and other non-traditional motor architectures, where conventional laminations become difficult, costly, or impractical to manufacture. Consequently, AM stators are particularly promising for topology optimized next-generation electric machines that rely on complex magnetic circuits and require geometric flexibility beyond the limits of conventional laminated parts.

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