Analysis of Synchronous Reluctance Machine With 3D-Printed Axially Laminated Rotor Featuring Axially Alternated Layers

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This study delves into the strategic layer alternation along the axial direction to mitigate electromagnetic torque ripple and minimize eddy current losses within synchronous reluctance electric machine with 3D-printed axially laminated rotor. A meticulous comparative analysis is conducted, scrutinizing the printing depth in the radial direction alongside variations in the number of alternating layers to discern the optimal ratio. Emphasis is placed on implementing two distinct 3D sliced models: one incorporating current continuity between slices and the other without. The article meticulously delineates the nuances of these models and draws a comprehensive comparison with a full 3D FEM model, elucidating their respective merits and drawbacks.

Keywords:
electromagnetic torque ripple,
Eddy current losses,
synchronous reluctance machine,
3D-printed axially laminated rotor,
axially alternating layers (AAL)

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I Introduction

Advancements in 3D printing technologies have significantly expanded the possibilities in electrical engineering, particularly in electromechanics. Progress in powder management systems and post-processing techniques has increased accessibility for printing components of electric machines [1]. However, the optimal printing of high-speed electrical machines remains challenging, attributed to limited powder options and material compatibility issues during postprocessing [2].

A promising avenue is the 3D printing of an axially laminated (ALA) rotor, offering mechanical robustness against centrifugal loads. Nevertheless, industrial constraints impact component dimensions, potentially introducing imperfections in electrical machine design. Notably, increased pulsations in electromagnetic torque and rotor eddy currents arise as imperfections.

This paper examines axially alternating layers (AAL) in the rotor of synchronous reluctance machines to mitigate torque ripple and eddy current losses. Special attention is given to developing a 3D sliced model, providing computational efficiency compared to a full 3D model. The models are implemented using the commercial COMSOL software.

II Machine specification

This paper explores the synchronous reluctance machine with an ALA rotor with alternated layers depicted in Fig.1 with an expected maximum output power of 290 kW. The machine's specifications are detailed in Table 1.

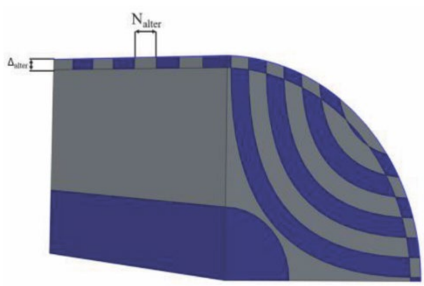

Figure 1: Quarter of ALA rotor construction with axially alternated layers

Table 1: Main machine specification

Parameter	Value
Maximum Power	290 kW
Speed	31500 rpm
Number of poles	4
Number of stator slots	36
Outer stator diameter	250 mm
Inner stator diameter	115 mm
Airgap	2 mm
Length	135 mm

III Modelling approach

A. FEM models of the machine with AAL

Two main models are considered: full 3D and sliced 3D, shown in Figure 2. The sliced model has two variations: with and without current continuity between the rotor slices.

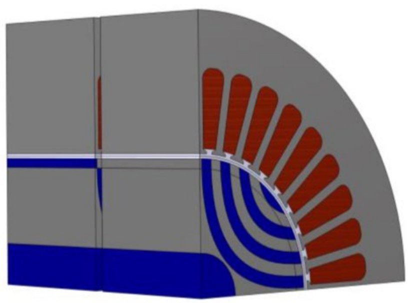

Figure 2: 3D sliced model of ALA rotor with AAL

A 3D sliced model [4] represents a packing along the z-direction of slices separated from each other. Unlike the full model, this approach does not require flux continuity between two different rotor configurations. This greatly simplifies the convergence of the FEM and increases the speed of calculations.

Importantly, in the 3D sliced model, slices must not be connected, i.e.,

$$L_{slice} = L/k_{slice}, k_{slice} > N_{slice} \tag{1}$$

where $L_{slice}$is the length of one slice, N_{slice} = N_{alter} is the number of slices, k_{slice} is the slicing factor and N_{alter} is the number of alternating layers.

The torque T and rotor eddy current losses P are then expressed as:

$$\begin{cases} T = \sum_{i=1}^{N_{slice}} T_i \left(k_{slice} / N_{slice}\right) \\ T = \sum_{i=1}^{N_{slice}} P_i \left(k_{slice} / N_{slice}\right) \end{cases} \quad (2)$$

B. Torque ripple approximation

During the simulation, it was found that electromagnetic torque ripple, depending on the printing depth, can be approximated as follows:

$$\Delta T(\Delta_{alter}) = \left(\Delta\mathrm{T}(0) - (1.25 - 0.25(-1)^{N_{alter}})\Delta\mathrm{T}(\infty)\right)e^{-5\frac{\Delta_{alter}}{t_{rib}}} + \Delta\mathrm{T}(\infty) \quad (3)$$

where Δ_{alter} is the radial printing depth, $t_{rib}$the rib thickness, $\Delta\mathrm{T}(0)$ is the torque ripple without AAL, and $\Delta\mathrm{T}(\infty)$ is the torque ripple for an even number of AAL with a fully inverted layer ($\Delta_{alter} \geq 0.75t_{rib}$, [5]).

IV Results

Figure 3 shows a comparison of 3D FEM, 3D sliced model and approximation (3) for torque ripple with an even number of AAL.

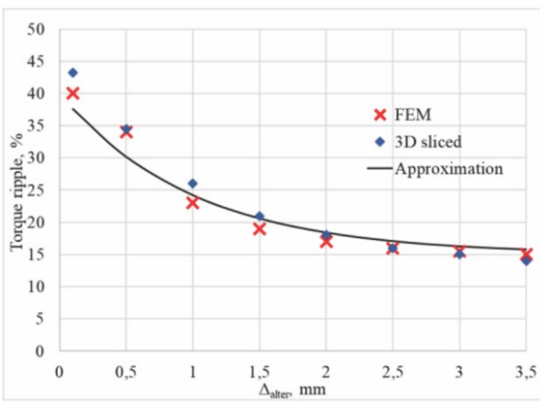

Figure 3: 3D FEM and approximation comparison for torque ripple

Figure 4 compares rotor eddy current losses as a function of radial print depth and number of layers.

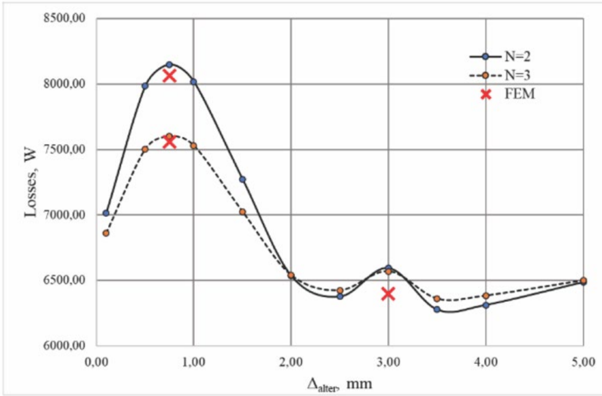

Figure 4: Losses comparison

It should be noted that the eddy current losses of the rotor and torque ripple don't depend on the increase in the number of layers and are determined only by the even or odd number of alternating layers. The dependence on the printing depth can be determined from Figure 4.

Thus, from a design point of view, Figures 3 and 4 show that it is possible to select the optimal radial depth of layer alternation such that the torque ripple can be significantly reduced and eddy current losses slightly reduced.

IV Conclusion

The effect of AAL on a synchronous reluctance machine with a 3D-printed ALA rotor was investigated. A noteworthy reduction in electromagnetic torque ripple was observed. Both eddy current losses and torque ripple were found to be influenced by the radial print depth, as well as the regularity of the AAL. Moreover, it was demonstrated that an even number of layers effectively minimizes torque ripple, albeit with a potential loss increase if the print depth is inappropriate. Conversely, an odd number of layers provides a less effective reduction in ripples but mitigates the risk of excessive losses at a shallower printing depth. Consequently, the optimal compromise for minimizing losses and attenuating torque ripples is achieved through an even number of AAL with a sufficiently substantial printing depth ($\Delta_{alter} \geq 0.75 t_{rib}$).The complete manuscript will expound a comprehensive elucidation of the simulation methodology.

References

[1] H. Tiismus, A. Kallaste, A. Belahcen, A. Rassõlkin and T. Vaimann, "Challenges of Additive Manufacturing of Electrical Machines," 2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Toulouse, France, 2019, pp. 44-48, doi: 10.1109/DEMPED.2019.8864850.

[2] Aamer Nazir, Ozkan Gokcekaya, Kazi Md Masum Billah, Onur Ertugrul, Jingchao Jiang, Jiayu Sun, Sajjad Hussain, “Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials,” Materials & Design, vol. 226. Elsevier BV, p. 111661, Feb. 2023. doi: 10.1016/j.matdes.2023.111661.

[3] “Additive Manufacturing using Multi-Material 3D Powder Printing Technology” Grid Logic, [Accessed: February 15, 2024]. Available: https://www.grid-logic.com/ “Motor Tutorial Series” COMSOL Multiphysics, [Accessed: February 15, 2024]. Available: https://www.comsol.com/model/motor-tutorial-series110261.

[4] Ogata, K. (2010). Modern Control Engineering (5th ed.). Prentice Hall.