Evaluation of a Simple Lamination Stacking Method for the Teeth of an Axial Flux Permanent-Magnet Synchronous Machine with Concentrated Stator Windings

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***Abstract*—In this paper, a simple lamination stacking method for the teeth of an axial flux permanent-magnet synchronous machine with concentrated stator windings is proposed. In this simple lamination stacking method, only two lamination profiles are used and are stacked alternately. To evaluate the performance of this stacking method, a comparison is made between the proposed method with two profiles and a conventional stacking method that uses different profiles for each lamination layer, using a multilayer 2D finite element model.**

***Index Terms*—Permanent magnet generators, axial flux machine, finite element methods, lamination stacking, concentrated stator windings**

I. INTRODUCTION

In this paper, a dual-rotor-single-stator axial flux permanent-magnet synchronous machine (AFPMSM) topology with concentrated windings [1] is considered (Fig. 1(a)). As the concentrated winding is a double layer winding, each coil is wound around one tooth: this topology allows to prepare an entire tooth i.e. an iron core and winding. The stator can then be assembled by combining the pre-built individual teeth: in this way a modular stator concept is introduced (Fig. 1(b)).

Instead of using soft magnetic composites (SMC) for the stator teeth cores [2], thin laminated grain oriented (GO) material is used because of its higher permeability [3].

Thanks to the short end-windings, copper losses in concentrated windings are lower comparing to distributed windings. On the other hand the iron losses in thin laminated grain oriented material are low [4]. The high power density of the AFPMSM [5] together with the low iron and copper losses allows to construct a high performance electrical machine that may be very suitable for direct drive wind turbines and traction applications.

As the iron section varies with the diameter, each lamination layer has a different geometry, which makes the construction complex and expensive. To overcome the use of a different lamination profile for each layer, in this paper a simple lamination stacking (SLS) method is proposed and evaluated. In this SLS-method only a limited number (2 in this paper) of lamination profiles is used. By stacking the lamination profiles alternately, a complex 3D-geometry can be obtained (Fig. 2). Once the lamination stacking is completed, the concentrated winding can be wound around the tooth and a pre-built module is finished. By the alternating stacking of the lamination profiles, zones with full- and partial overlap are introduced with an iron filling factor of 100% and 50% respectively. This paper examines the extent to which this zone with partial overlap affects the performance of the machine, and therefore, this SLS-method is compared with a conventional lamination stacking (CLS) method, which uses different lamination profiles for each layer.

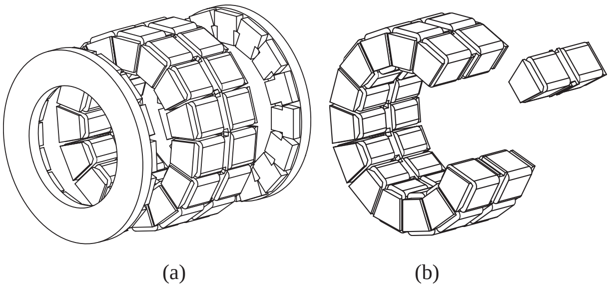
(a) (b)

Fig. 1. (a) dual-rotor-single-stator AFPMSM, (b) modular stator construction.

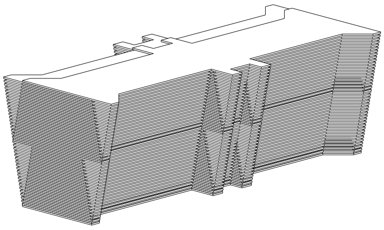

Fig. 2. Obtaining a complex 3D by alternating stacking of 2 lamination profiles leads to zones with full- and partial overlap of the lamination profiles.

II. FINITE ELEMENT MODELS

A. Multilayer 2D finite element model

To evaluate the no-load electro-motive-force (EMF), cogging torque, full-load torque and no- and full-load losses, a multilayer 2D finite element model (FEM) is used [6]. In the multilayer 2D-FEM (Fig. 3), 6 different 2D-models at different radii are considered. To get the global solution, the contributions of all layers are added. In the 2D-models for the SLS-method, the zones with full and partial overlap are given different material properties.

B. 3D finite element model

In the multilayer 2D-FEM, each layer is considered individually. This implies the hypothesis that the flux in the teeth has no radial component. Actually, a radial flux component would be perpendicular on the lamination planes and thus induce eddy currents in this lamination. In order to avoid radial flux, the magnet shapes were adapted to the lamination stacking

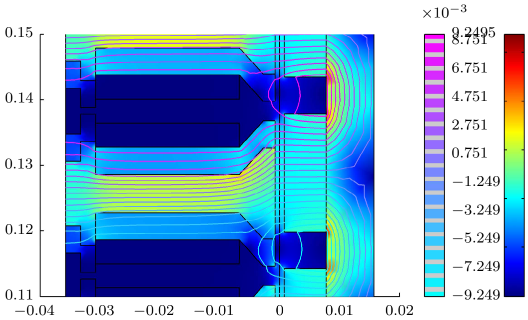

Fig. 3. Layer 3 of the multilayer 2D FEM: zones with full- and partial overlap are given different material properties.

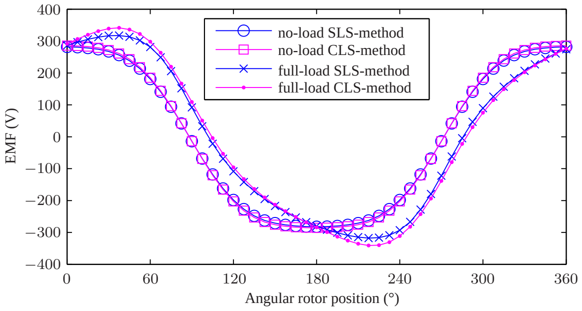

Fig. 4. No-load and full-load EMF-waveforms for the SLS- and CLS-method.

method: the width of the upper and lower half of the T-shaped magnets (Fig. 1(a)) were chosen in a way that they result in the same flux density levels in all different layers when the magnet is aligned with a tooth.

III. Simulations and Comparison

Using the multilayer 2D-FEM, a no- and full-load working condition is simulated for an AFPMSM with 100 mm inner diameter, 148 mm outer diameter and 70 mm axial tooth length. The EMF-waveforms are shown in Fig. 4. Because the cogging torque of a configuration with 16 magnets and 15 teeth is very low, the torque in Fig. 5 is calculated over only 2 pole-pitches ($2\tau_\mathrm{p}$). In Table I, a comparison between both stacking methods for different parameters is made.

TABLE I
Comparison simulation results SLS- and CLS-method.

Parameter	SLS	CLS	%
peak no-load EMF [V]	281.98	285.81	98.66
peak full-load EMF [V]	317.01	340.12	93.21
peak cogging torque of $2\tau_\mathrm{p}$ [Nm]	0.4239	0.3225	131.46
peak full-load torque of $2\tau_\mathrm{p}$ [Nm]	-2.6027	-2.6658	97.64
full-load torque [Nm]	-21.39	-21.94	97.53
no-load iron-loss [W]	28.23	28.26	99.89
full-load iron-loss [W]	31.48	32.16	97.88
output power [W]	4480.8	4594.4	97.53
efficiency [%]	96.60	96.66	99.93

Table I shows that the SLS-method has a lower output power. Because iron losses for the SLS-method are also lower, the efficiency of both stacking methods is almost the same. As the filling factor is only 50% in the outer zones, the effective slotwidth opening increases, resulting in an increase of the cogging torque.

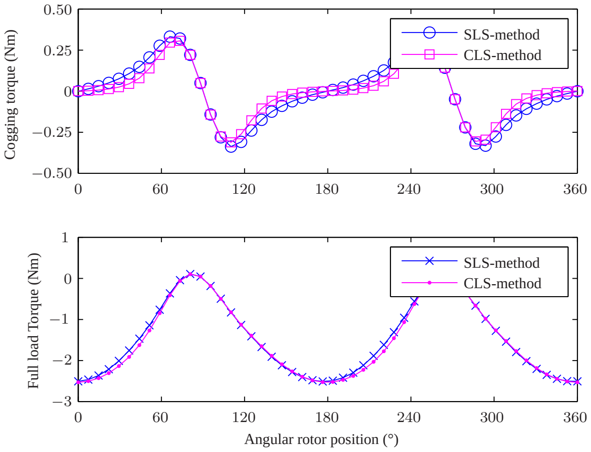

Fig. 5. Cogging torque and full-load torque for the SLS- and CLS-method calculated over 2 pole-pitches.

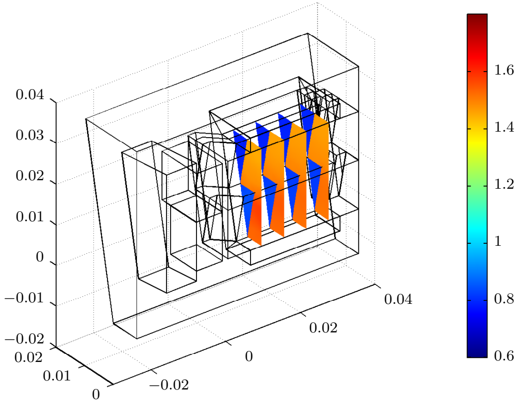

Fig. 6. Slice plot of the magnetic flux density level.

The 3D-FEM shows that when the width of the upper and lower half of the T-shaped magnets are adapted to the lamination stacking, the flux density level in the tooth is constant in radial direction (Fig. 6).

This comparison shows that the performance of the SLS-method is comparable to the CLS-method, however the construction is much simpler.

References

[1] J. Cros, and P. Viarouge, “Synthesis of High Performance PM Motors With Concentrated Windings,” *IEEE Transactions on Energy Conversion*, Vol. 17, No. 2, pp. 248-253, Aug. 2002.

[2] F. Marignetti,and V. D. Colli, “Thermal Analysis of an Axial Flux Permanent-Magnet Synchronous Machine,” *IEEE Transactions on Magnetics*, Vol. 45, No. 7, pp. 2970-2975, Jun. 2009.

[3] W. Fei, and P. C. K. Luk, “An Improved Model for the Back-EMF and Cogging Torque Characteristics of a Novel Axial Flux Permanent Magnet Synchronous Machine With a Segmental Laminated Stator,” *IEEE Transactions on Magnetics*, Vol. 45, No. 10, pp. 4609-4612, Oct. 2009.

[4] D. Kowal, P. Sergeant, L. Dupre, and A. Van den Bossche, “Comparison of Nonoriented and Grain-Oriented Material in an Axial Flux Permanent-Magnet Machine,” *IEEE Transactions on Magnetics*, Vol. 46, No. 2, pp. 279-285, Jan. 2010.

[5] Y. P. Yang, Y. P. Luh, and C. H. Cheung, “Design and Control of Axial-Flux Brushless DC Wheel Motors for Electric Vehicles-Part I: Multiobjective Optimal Design and Analysis,” *IEEE Transactions on Magnetics*, Vol. 40, No. 4, pp. 1873-1882, Jul. 2004.

[6] A. Parviainen, M. Niemela, and J. Pyrhonen, “Modeling of axial flux permanent-magnet machines,” *IEEE Transactions on Industry Applications*, Vol. 40, No. 5, pp. 1333-1340, Sept.-Oct. 2004.