Design of SMC core in Axial-Flux Motor with 3D Printing

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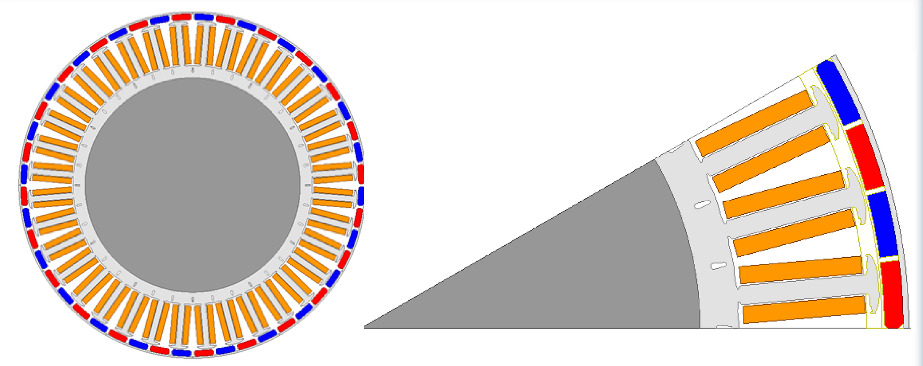
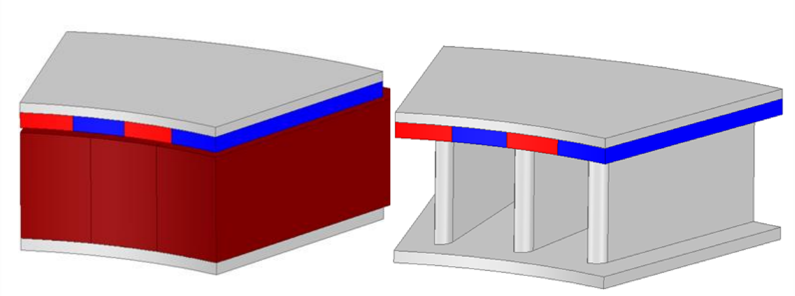
Abstract

Conventional Axial Flux Permanent Magnet Synchronous Motor rolls an amorphous electrical steel sheet to implement the shape of a stator or manufactures it with a mold. Therefore, three-dimensional structure production is limited, mass production is low, and manufacturing cost is high. Therefore, in this paper, the three-dimensional structure that could not be implemented in the existing Axial Flux Permanent Magnet Synchronous Motor is applied to the 3D printing technology with Soft Magnetic Composite(SMC) core instead of the existing electrical steel sheet, to the shape design and the performance of each was compared and analyzed.

1. Specification of motor



<Figure 1> Conventional Direct Drive Motor



<Figure 2> Radial Flux → Axial Flux

<Table 1> Conventional motor specification

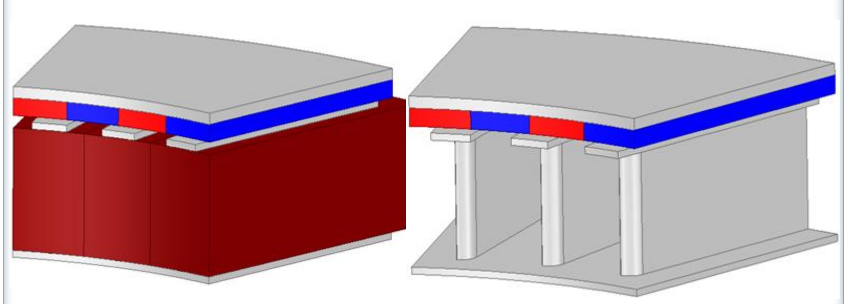
Parameter		Value	Unit
Performance	Pole / Slots	48 / 36	-
	Speed @ Washing	45	RPM
	Torque @ Washing	5.2	Nm
	Current @ Washing	0.835	A_{rms}
	No-load EMF @ 150RPM	35.09	V_{rms}
Winding	Material	Aluminum	-
	Diameter	0.9	mm
	Series Turns per Phase	124	turns
Magnet	Material	Ferrite 7BE	-
	B_r	0.41	T
	H_c	300	kA/m
	Magnetization Dead zone	0.5	deg

Parameter	Value[mm]
Stator Outer Diameter	273
Stator Inner Diameter	178.3
Stator tooth width	5
Rotor outer Diameter	288
Rotor Inner Diameter	275
Magnet Thickness	5
Air Gap	1
Bs0	8.05
Hs0	1.3
Hs1	1.1
Hs2	32.39
Stack_Stator	21
Stack_Magnet	30

<Table 2> Axial Flux Motor Design Specification

Parameter	Value [mm]
Outer Diameter (Stator & Rotor)	288
Inner Diameter (Stator & Rotor)	178.3
Teeth Thick	21.5
Magnet Length	54.85
Magnet Depth	3.1
Stator Thick	2.4
Rotor Thick	2
Airgap Length	1

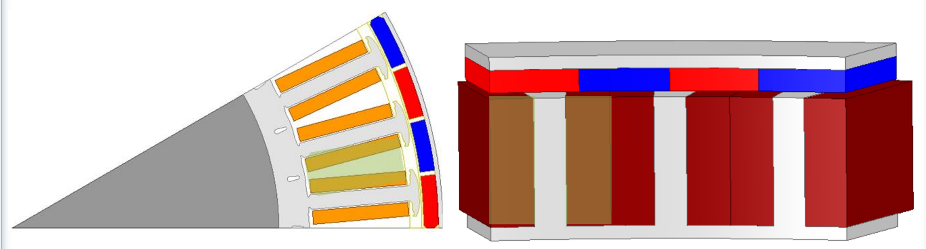
2. Proposed Model Design



<Figure 3> Axial Flux Motor Shoe Model

<Table 3> Shoe Model Motor Design Specification

Parameter	Value [mm]
Outer Diameter (Stator & Rotor)	288
Inner Diameter (Stator & Rotor)	178.3
Teeth Thick	21.5
Magnet Length	54.85
Magnet Depth	3.1
Stator Thick	1.2
Rotor Thick	2
Shoe Thick	1.2
Airgap Length	1



<Figure 4> DD Motor & Axial-Flux Motor Fill Factor

<Table 4> Fill factor & Permanent Magnet Usage

Direct Drive Motor Spec

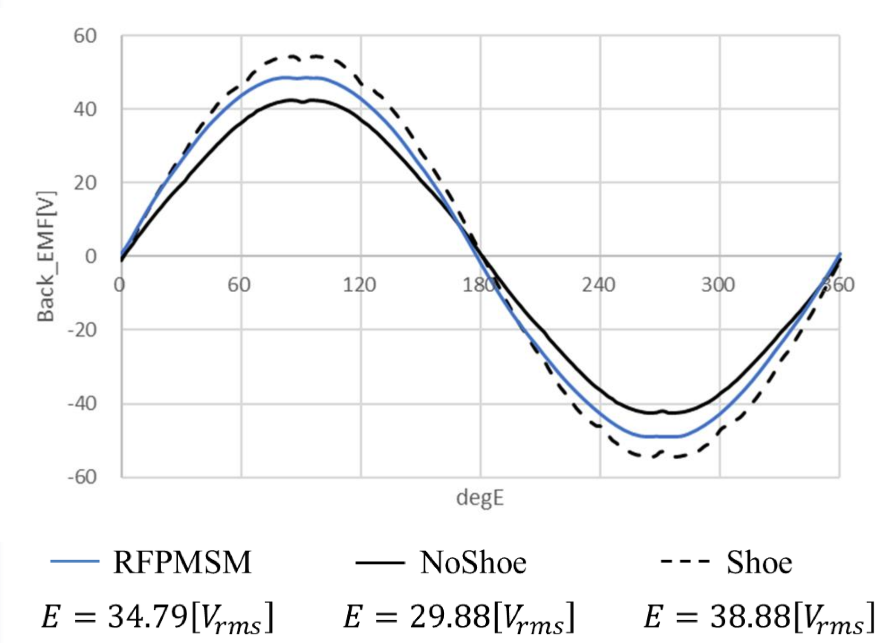
Slot Area[mm^2]	Number of Turn	Coil cross-section area[mm^2]	Total Coil Area [mm^2]	Coil Fill factor[%]
504	124	0.64	78.89	31.30

AFPMSM Spec

Slot Area[mm^2]	Number of Turn	Coil cross-section area[mm^2]	Total Coil Area [mm^2]	Coil Fill factor[%]
368	90	0.64	57.26	31.12

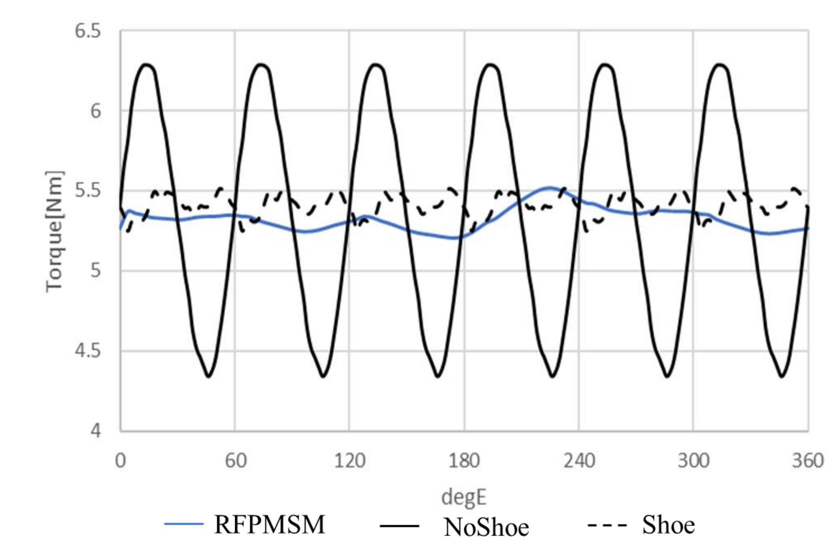
Motor	Total Magnet cross-section area [mm^2]	Magnet Depth [mm]	Total Magnet Volume [mm^3]
RFPMSM	345.74	30	10,372.14
AFPMSM	3348	3.1	10,378.8

3. BEMF & Torque



<Figure 5> BEMF comparison

Conventional RFPMSM $= 0.835[A_{rms}]$ → NoShoe $I = 0.935[A_{rms}]$; Shoe $I = 0.735[A_{rms}]$



<Figure 6> Torque comparison

<Table 5> Current, Torque, Torque Ripple Comparison

Parameter	RFPMSM	NoShoe	Shoe
Current [A_{rms}]	0.835	0.935	0.735
Torque [Nm]	5.32	5.35	5.41
Torque Ripple [%]	5.88	36.30	4.85

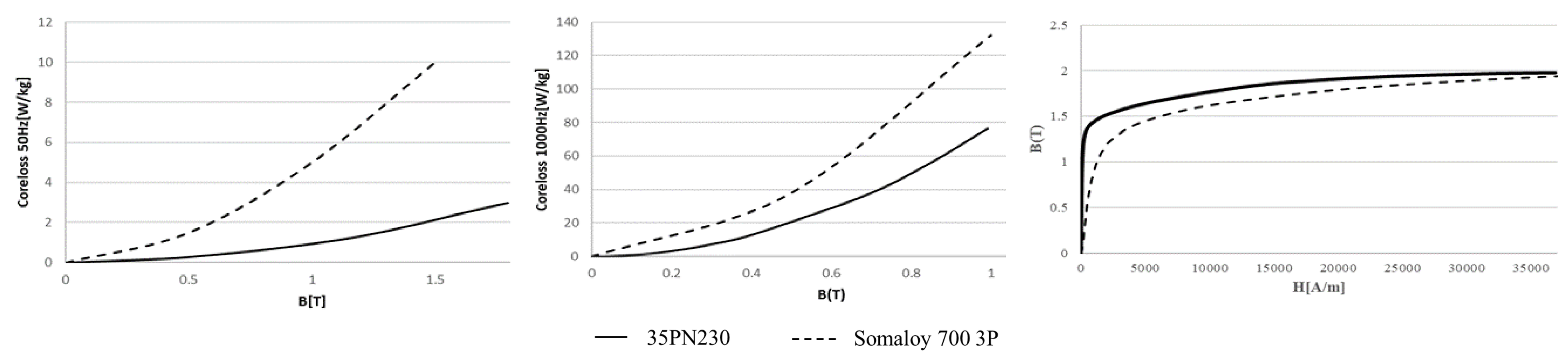
- **Comparison of BEMF of Conventional DD and Axial-Flux Motor**
  - Compare to DD Motor
  - NoShoe model **Low BEMF**
  - Shoe model **High BEMF**
- **Current to satisfy target torque**
  - NoShoe **0.935[Arms]**
  - Shoe **0.735[Arms]**

<Table 6> Comparison the motor performance and loss

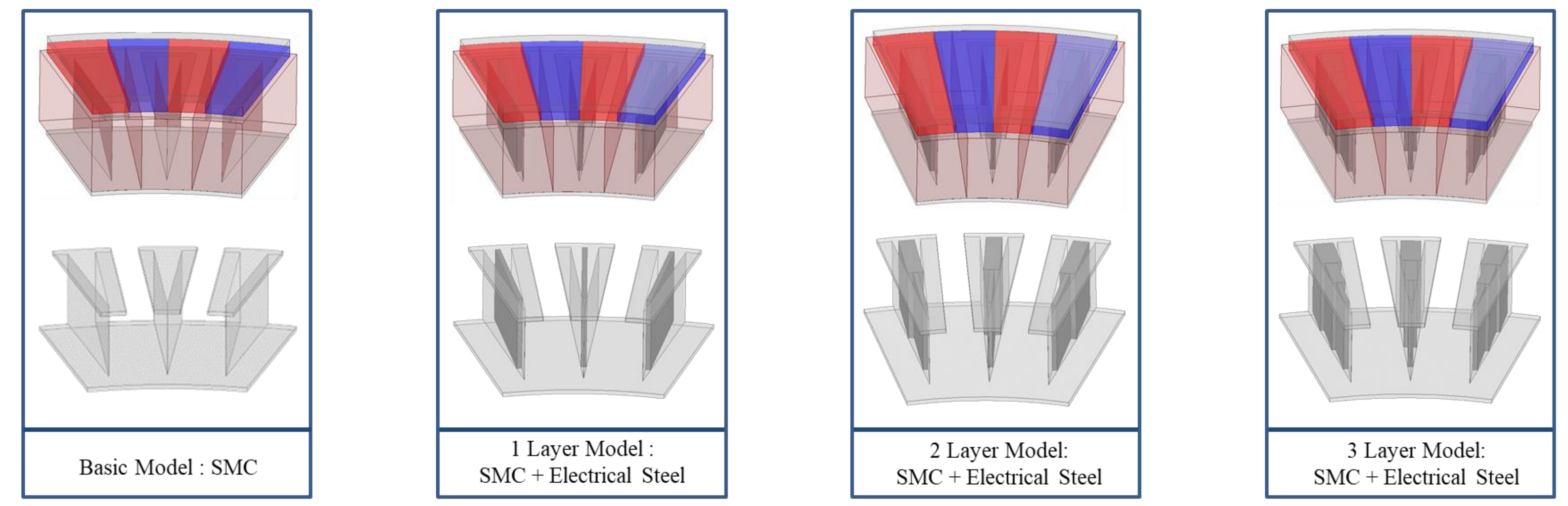
Model	Parameter	UDD Motor	Axial-Flux Motor	
			NoShoe	Shoe
Basic_Model	Back_EMF [V_{rms}]	34.79	29.88	38.88
	I [A_{rms}]	0.835	0.935	0.735
	Torque [Nm]	5.32	5.35	5.41
	Copper loss [W]	11.18	17.17	10.61
	Core loss [W]	2.17	3.52	3.21
	Power [W]	24.65	25.21	25.49

4. Core loss reduction design

- **Suggesting a method to reduce core loss**
  - Loss of low speed motor occurs mostly in the **Copper Loss**
  - Low frequency conventional 35PN230 material & Axial-Flux Somaloy material **Core loss & Initial Curve comparison**
  - Core loss in high frequency is **1.7times higher** than 35PN230 based on 1[T]
  - Core loss in low frequency is **5times higher** than 35PN230 based on 1.5[T]
  - Insert the **Stator Teeth part electrical steel sheet into 1, 2, 3 Layer** as core loss reduction method

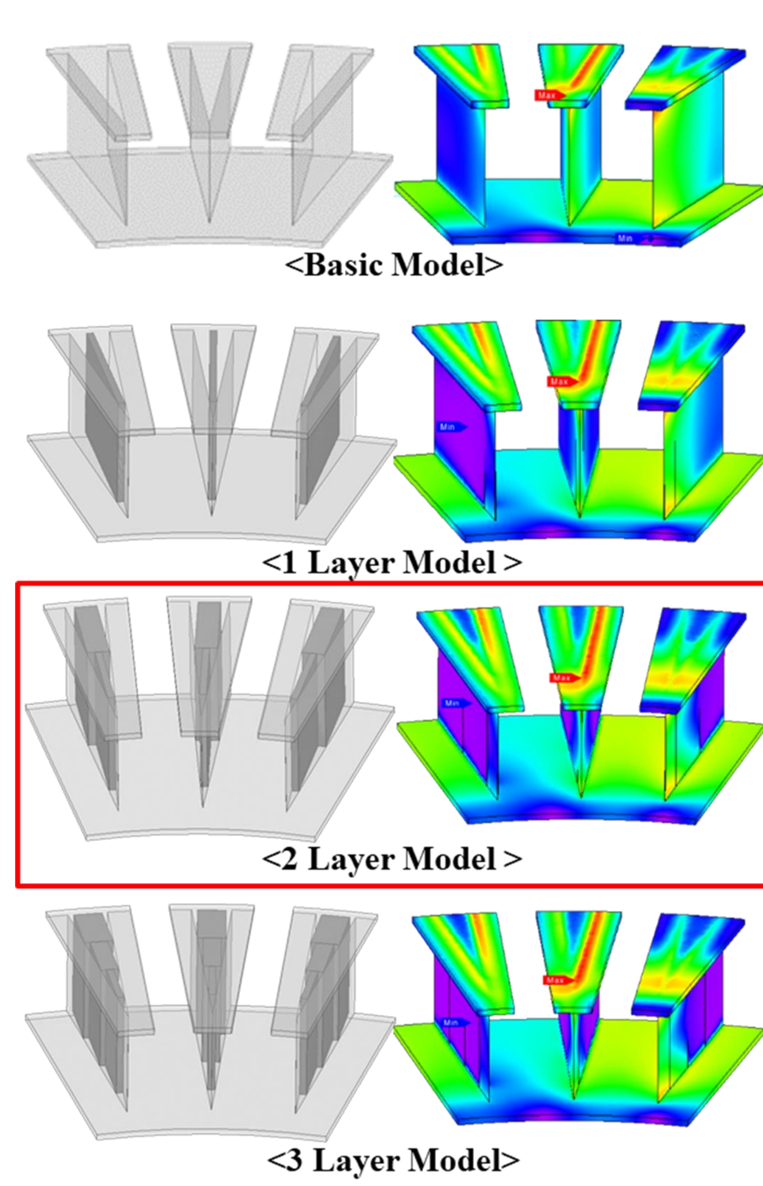


<Figure 7> Core loss & Initial Curve



<Figure 8> Core loss reduction Proposed Model

5. Performance Comparison



<Basic Model>: Back_EMF $= 38.88[V_{rms}]$, THD $= 1.72$[%], Torque $= 5.41$[Nm], Core loss $= 3.21$[W], Power $= 25.49$[W]

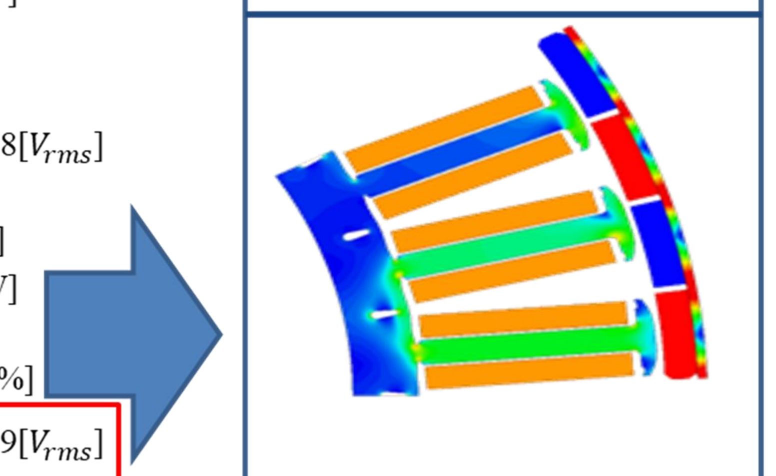
<1 Layer Model>: Back_EMF $= 39.68[V_{rms}]$, THD $= 1.65$[%], Torque $= 5.52$[Nm], Core loss $= 2.68$[W], Power $= 26.01$[W], Core ratio $= 27.81$[%]

<2 Layer Model>: Back_EMF $= 39.99[V_{rms}]$, THD $= 1.60$[%], Torque $= 5.62$[Nm], Core loss $= 2.46$[W], Power $= 26.48$[W], Core ratio $= 59.59$[%]

<3 Layer Model>: Back_EMF $= 40.13[V_{rms}]$, THD $= 1.61$[%], Torque $= 5.58$[Nm], Core loss $= 2.39$[W], Power $= 26.30$[W], Core ratio $= 71.50$[%]

<Figure 9> Proposed Shoe model Performance

RFPMSM Specification



Back_EMF $= 34.79[V_{rms}]$
THD $= 1.46$[%]
Torque $= 5.32$[Nm]
Core loss $= 2.17$[W]
Power $= 24.65$[W]

<Figure 10> DD Motor Performance

6. Conclusion

The existing DD motor is compared with the newly proposed Axial-Flux motor in this paper. One of the proposed model was a Shoe-free model made of SMC core molded and compared with the AFPMSM using Shoe using 3D printing. Core loss compared to SMC core used better electrical steel sheet for the existing model, in this paper SMC core and electrical steel sheet were combined to propose the stator shape of the new axial flux motor. Since the core loss of the model including the shoe is larger than that of the existing target model through the FEM analysis, the final model in which the electrical steel is inserted into the stator teeth using the newly proposed SMC core was compared and analyzed through the FEM analysis. The core loss of the model which the electrical steel sheet is separated and inserted in three layers among the models incorporating the two core materials shows a similar core loss to existed target motor. Therefore, if a motor using 3D printing is developed in the future, various Axial Flux type motor shapes will be developed.