Comparison of A Multi-Stage Axial Flux Permanent Magnet Machine with Different Stator Core Materials

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Introduction

This paper proposes a multi-stage axial flux permanent magnet machine (MAFPMM) and the properties with different stator core materials are analyzed.

- Stator core of silicon steel sheet, soft magnetic composite (SMC) and amorphous magnetic metal (AMM) is studied in finite element method (FEM) respectively.
- FEM result indicates that the three materials have almost equal influence on magnetic field distribution, no-load back-EMF, cogging torque, and output torque. Difference appears in terms of core loss.
- A prototype is fabricated using SMC stator core. The experimental result of the prototype is consistent with the FEM result.

Structure and Principle

Multi-stage yokeless and segmented armature NS Torus topology is adopted and Fig. 1 shows the structure of the MAFPMM. The mentioned MAFPMM has three rotors disks and two stator disks.

- Four PM layers on three rotors and two segmented yokeless stators are arranged in axial direction. Asymmetrical bidirectional magnet skewing technique is applied to minimize the cogging torque.
- Each set of armature winding is relatively independent and supplied by a separate power circuit.
- Flexible working modes are available such as single armature working, double armatures working in series mode, and double armatures working in parallel mode.

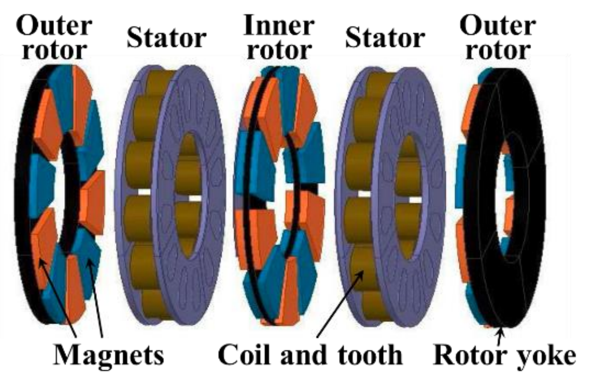


Fig. 1. Structure of the MAFPMM.

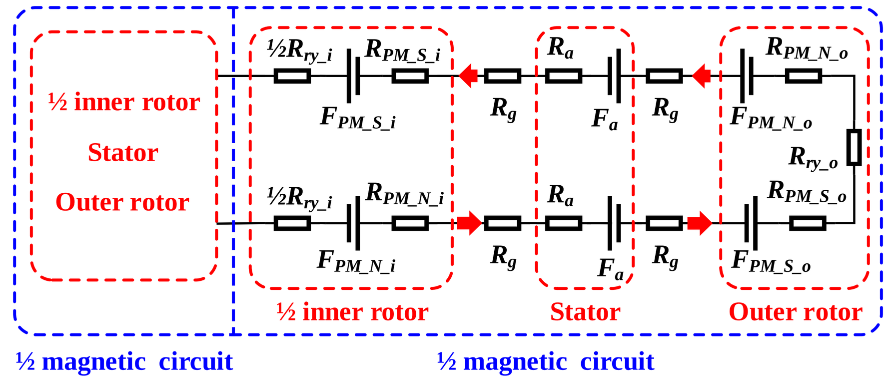


Fig. 2. Magnetic equivalent circuit model for main flux.

Comparison of material characters

In most conditions, silicon steel sheet can meet the requirements. SMC and AMM both are emerging materials in recent years. SMC is characterized by its 3-D magnetic properties and the ability to achieve complex structure. AMM is characterized by its high magnetic permeability and low losses.

DW310_35, Somaloy prototyping material, and Metglas 2605SA1 are selected as the candidates of silicon steel sheet, SMC, and AMM. Table I shows the character comparison of different materials.

Table I
Character comparison of different materials

Quantity	Silicon steel sheet	SMC	AMM
Saturation induction (T)	2.05	1.53	1.58
Maximum permeability	40000	430	250000
Coercivity (A/m)	30	200	4
Resistivity (μΩm)	0.45	280	1.3
Density(g/cm^3)	7.65	7.3	7.18
Curie temperature (°C)	750	700	395

- The saturation induction of silicon steel sheet is highest.
- In terms of maximum permeability and coercivity, AMM shows advantages.
- SMC is much superior than silicon steel sheet and AMM in aspect of resistivity.

Comparison of no-load back-EMF

Commercial software Maxwell is adopted and a 3-D FEM model is built. A 1/2 model is preferred to reduce the quantity of calculation due to the symmetry of the machine. The stator core material is set as silicon steel, SMC, and AMM, respectively. Fig.4 shows the comparison of flux density distribution. There is not obvious difference between the three maps.

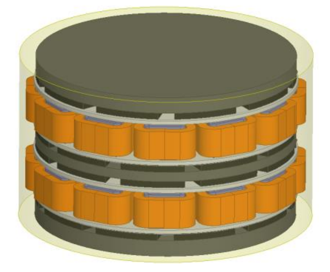
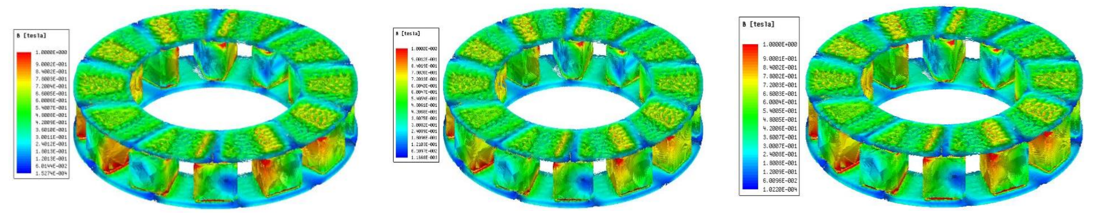


Fig. 3. 3-D FEM model.



(a) Silicon steel sheet (b) SMC (c) AMM

Fig. 4. Flux density distribution.

The maximum phase no-load back-EMF of the machine is 126.01V, 124.94V, and 126.05V, respectively. The difference is less than 1%. The reluctance of air-gap is much higher than stator core, so the different permeability of the three stator core materials will not result in obvious difference in no-load back-EMF.

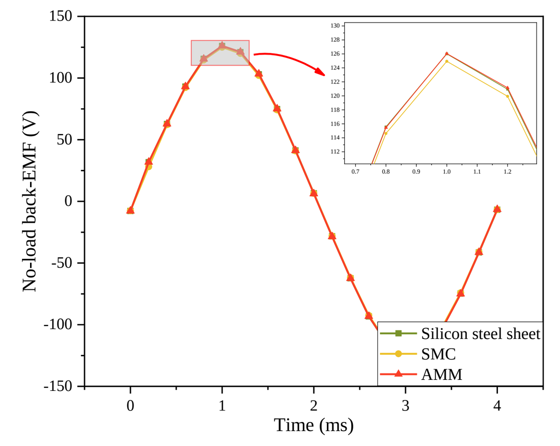


Fig. 5. No-load back-EMF comparison.

Comparison of cogging torque and output torque

The peak cogging torque of AMM is 0.33 Nm while it is 0.327 Nm of silicon steel sheet, showing an increase of 0.92%. The result shares the same reason with the no-load back-EMF.

Supplying the same armature current, the average output torque is 12.39 Nm, 12.26 Nm, and 12.42 Nm respectively. The average torque shows little difference while the torque ripple of AMM is much lower than that of silicon steel sheet and SMC.

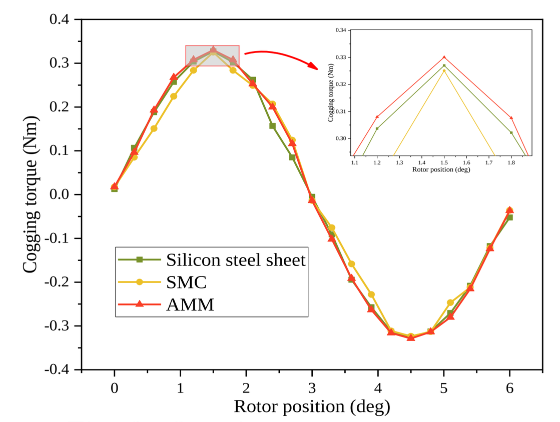


Fig. 6. Cogging torque comparison.

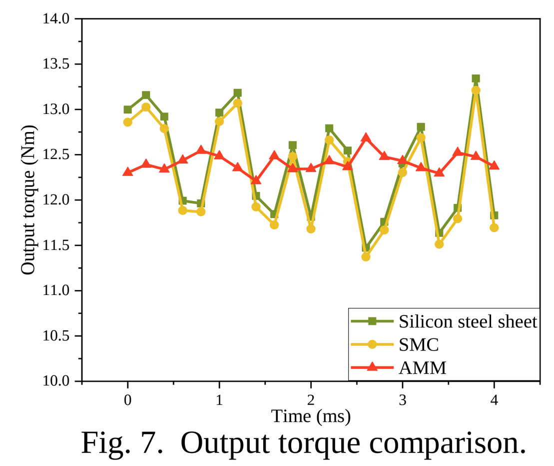


Fig. 7. Output torque comparison.

Comparison of core loss

Core loss consists of hysteresis loss P_h and eddy-current loss P_e. Hysteresis loss is proportional to the area of hysteresis loop and the alternating frequency of magnetic field. The hysteresis loss and eddy-current loss can be expressed by equation (1) and (2), respectively.

$$P_h = K_h f \int HdB \quad (1)$$

$$P_e = C_e f^2 B_m{}^2 \Delta^2 V \quad (2)$$

As shown in Table I, visible difference exists in aspect of saturation induction, coercivity, and resistivity, which will cause difference in core loss.

- The core loss of AMM is much lower than silicon steel and SMC.
- In area one, the core loss of SMC is higher than silicon steel sheet. Opposing situation appears in area two.

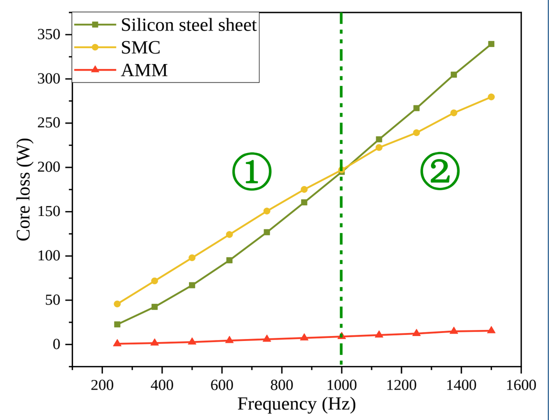


Fig. 8. Core loss comparison.

Prototyping and experiment

Considering the special structure and the processing difficulties, SMC is determined as the core material to fabricate the prototype.

- The no-load back-EMF of series mode at rated speed is 123.87 V while the FEM result shows 124.90 V.
- The output torque under rated current is 11.07 Nm while the FEM result shows 12.26 Nm.
- The cogging torque is 0.35 Nm while the FEM result shows 0.325 Nm.

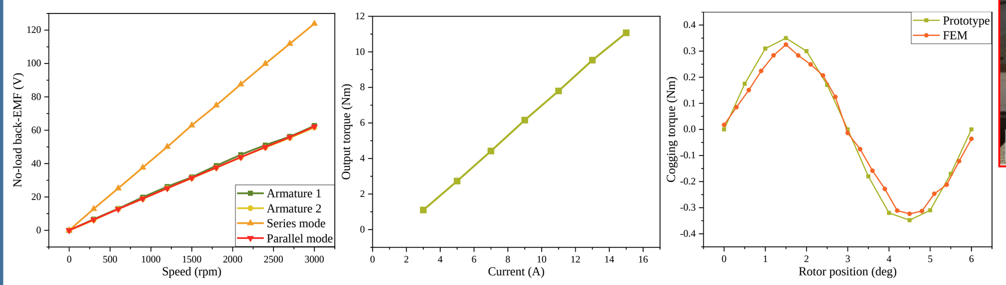


Fig. 9. (a) No-load back-EMF. (b) Output torque. (c) Cogging torque.

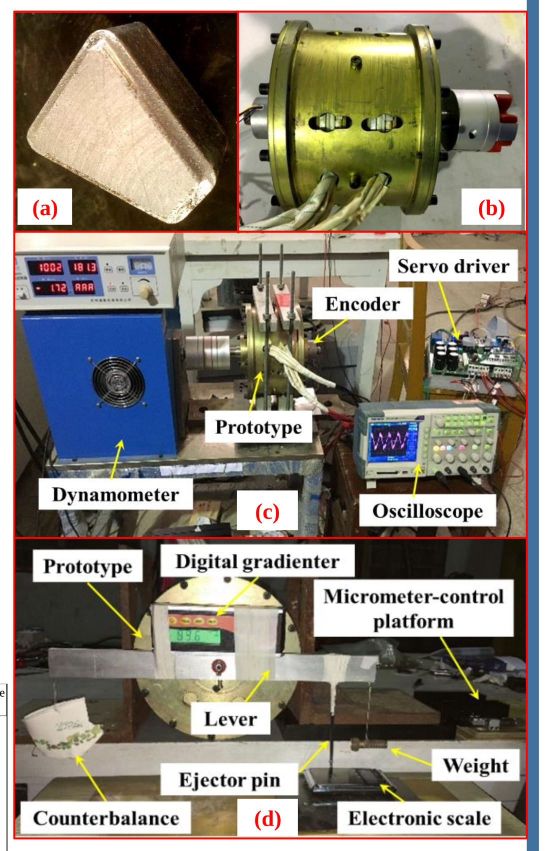


Fig. 9. (a) SMC core. (b) Prototype. (c) Experiment platform. (d) Cogging torque measurement.

Conclusion

A MAFPMM is introduced. Silicon steel sheet, SMC, and AMM are used to build a 3D FEM model respectively. The FEM result shows that the three materials perform equally in many aspects. As for core loss, AMM has advantages over SMC and silicon steel sheet. SMC has advantages in medium-high frequency conditions while silicon steel fits low frequency conditions. A prototype using SMC core is fabricated. The experiment confirms the validity of machine design and material analysis.