Design and Optimization of A Novel Axial-Radial Flux Permanent Magnet Machine

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Introduction

This paper proposes a novel axial-radial flux permanent magnet machine (ARFPMM). The design and optimization process for high torque density and low cogging torque is presented.

- **T-type SMC core**, **axial rotor**, and **radial rotor** are applied to support axial-radial flux path and make full use of the space.
- Different types of radial rotor are analyzed in finite element method (FEM) to improve the power density.
- Bidirectional magnet skewing technique is applied to minimize the cogging torque.
- The comparison of the initial and revised model shows the validation of the PM radial rotor and the bidirectional PM skewing technique in the ARFPMM.

Structure and Principle

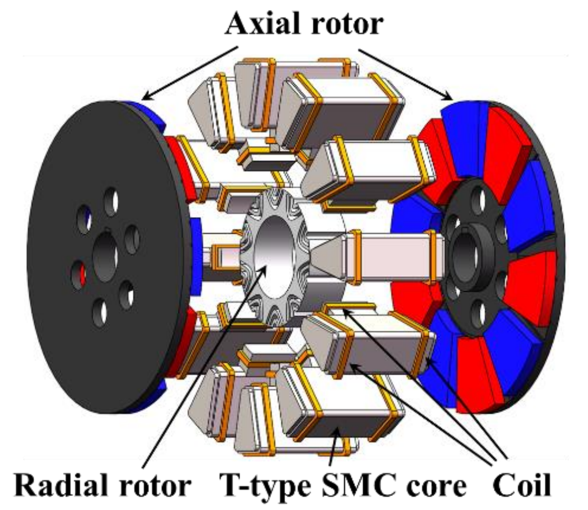


Fig. 1. Structure of the ARFPMM.

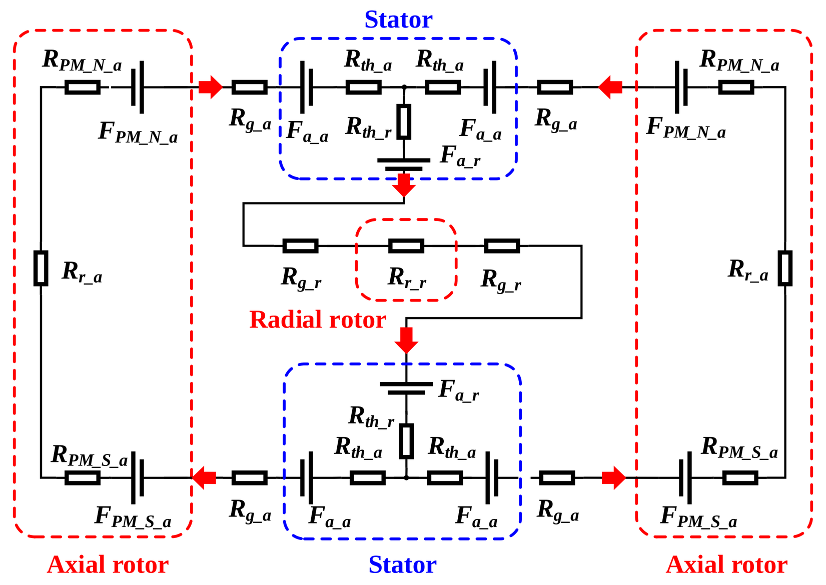


Fig. 2. Magnetic equivalent circuit model for main flux.

Fig.1 shows the structure of the mentioned ARFPMM which has the features of T-type SMC core, axial rotor, and radial rotor.

- The stator core is made up of soft magnetic composite (SMC) which is isotropous in magnetic and thermal characteristics.
- Individual concentrated winding is applied. The three-part coils are wound around the three teeth.
- NdFeB magnets are preferred, and different radial rotors can be used.

Power density improvement

Different radial rotors are analyzed to improve the torque and then improve the power density. Fig. 3 shows the three rotors.

- Rotor (a) is a ring-shape lamination, serving as a contrast.
- Rotor (b) can produce a large difference between L_d and L_q, aiming to provide additional synchronous reluctance torque.
- Rotor (c) has surface-mounted permanent magnet, aiming to provide additional permanent-magnet torque.

The three radial rotors are applied to the ARFPMM respectively, while keeping the other parts invariable.

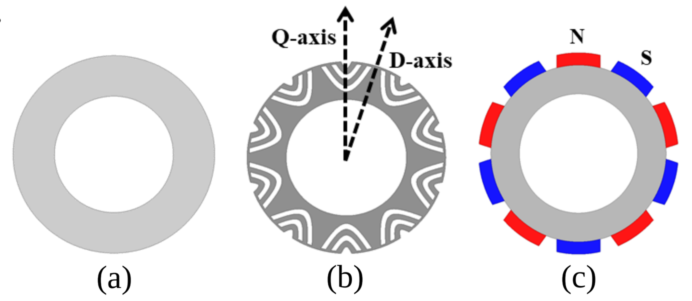
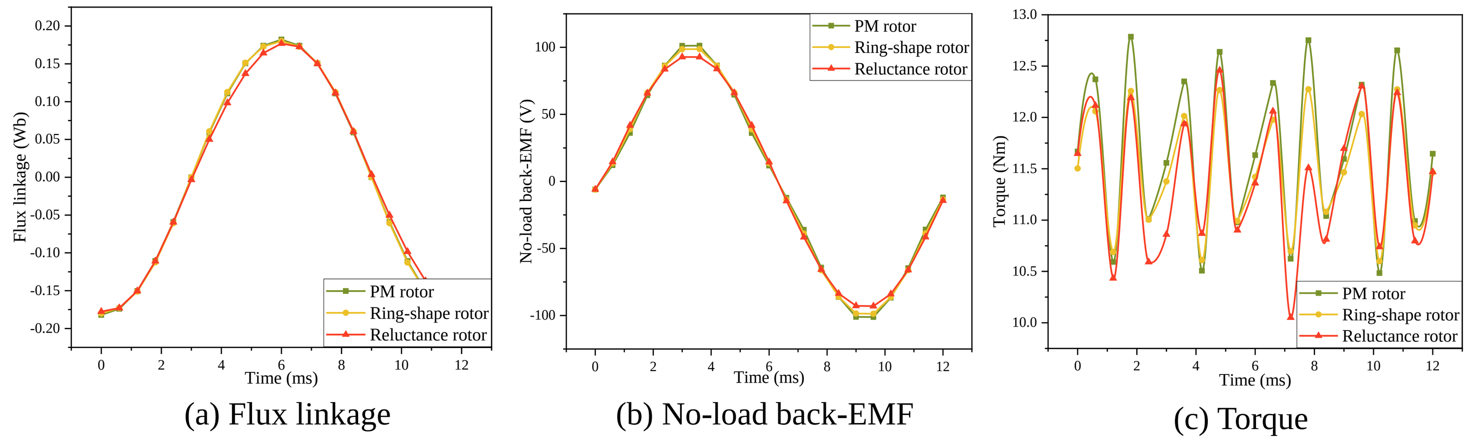


Fig. 3. Structure of the three radial rotors.

Fig. 4 shows the comparison of flux linkage, no-load back-EMF, and torque between the three radial rotors. In the aspect of flux linkage, it shows the trend of "PM rotor > ring-shape rotor > reluctance rotor". As for torque and no-load back-EMF, it is the same as the trend of flux linkage.



(a) Flux linkage (b) No-load back-EMF (c) Torque

Fig. 4. Comparison of performance between different radial rotors.

- The ring-shape rotor is more homogeneous in radial direction and has smaller reluctance, leading to less flux leakage and higher no-load back-EMF.
- The application of fractional-slot concentrated-winding make it difficult to implement the synchronous reluctance torque.
- PM rotor can enhance the flux linkage and generate higher torque.

Cogging torque reduction

As an intrinsic and crucial issue in PM machines, cogging torque usually causes undesired effect such as vibration and noise. PM skewing technique is applied in the ARFPMM to reduce the cogging torque. Fig. 5 illustrates the PM skewing technique. The influence of skewing mode, skewing angle α, and position angle β on cogging torque is analyzed.

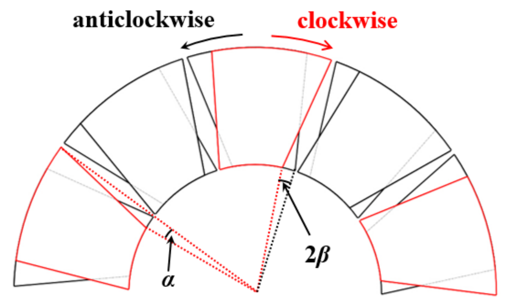


Fig. 5. PM skewing technique.

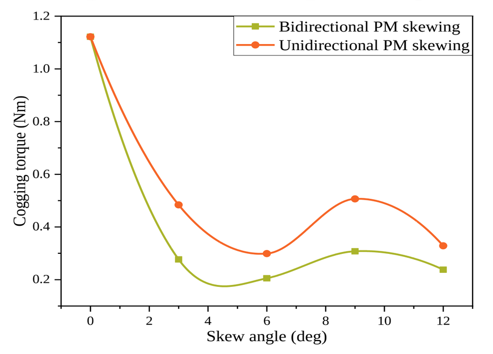
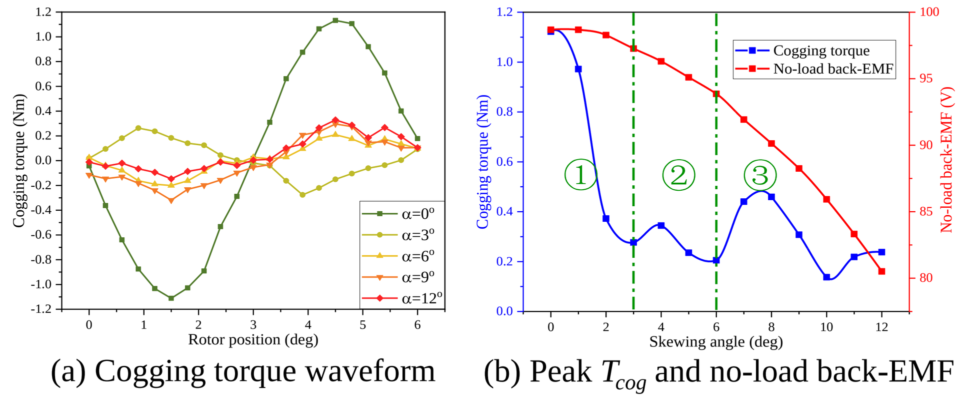


Fig. 6. Influence of different PM skewing modes

- Three combinations exist including no PM skewing, unidirectional PM skewing, and bidirectional PM skewing. Fig. 6 shows that bidirectional PM skewing is more remarkable.
- The optimal skewing angle α can be calculated by the equation in ideal condition. But it usually varies in practice.

$$\alpha = \frac{2\pi}{LCM(Z, 2p)}$$

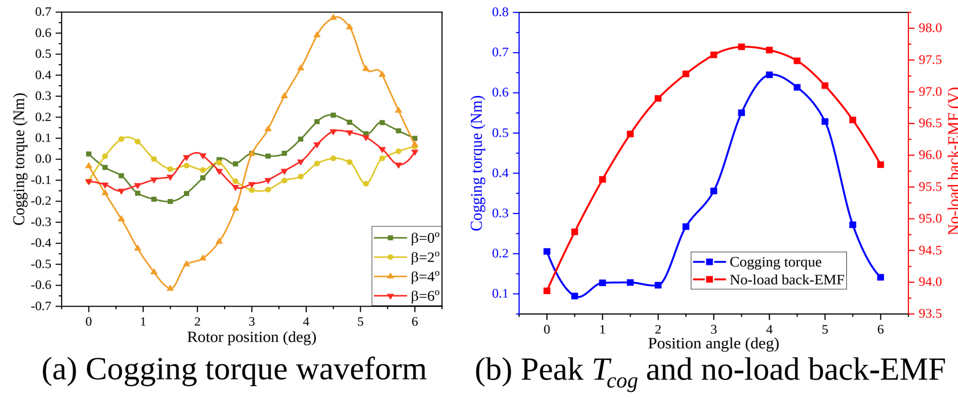
- The point α=6° shows an appropriate performance in balancing the cogging torque and the no-load back-EMF.



(a) Cogging torque waveform (b) Peak T_{cog} and no-load back-EMF

Fig. 7. Influence of different skewing angles.

- To reach high no-load back-EMF and low cogging torque, the point β=2° can be considered as an appropriate choice.

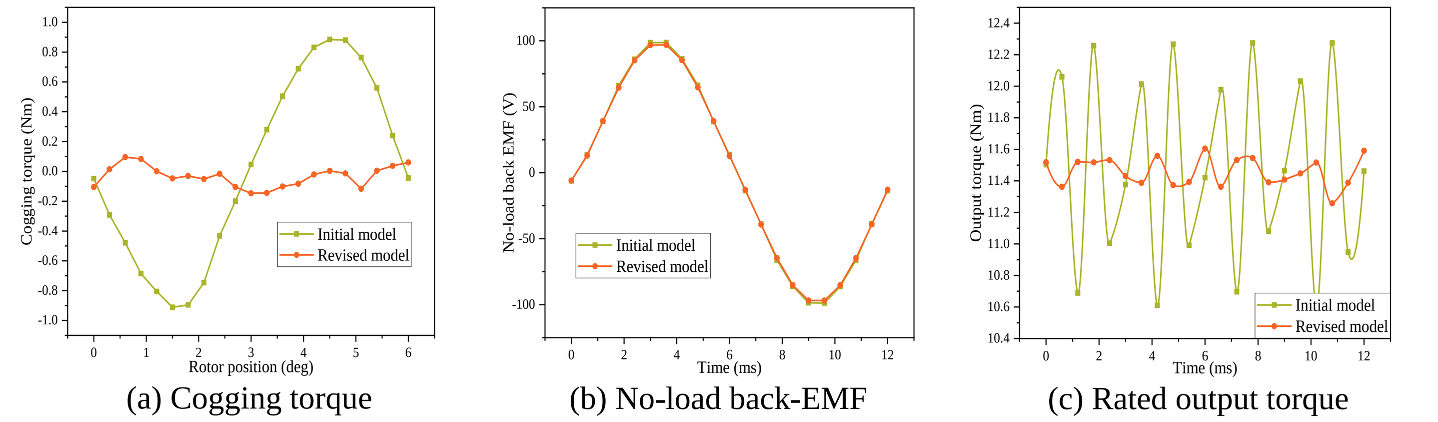


(a) Cogging torque waveform (b) Peak T_{cog} and no-load back-EMF

Fig. 8. Influence of different position angles.

FEM verification

The PM radial rotor and bidirectional PM skewing technique are determined to be applied. The skewing angle and positon angle are determined to be 6° and 2° respectively. Comparison work is carried out between the initial and revised model and the result is shown in Fig. 9.



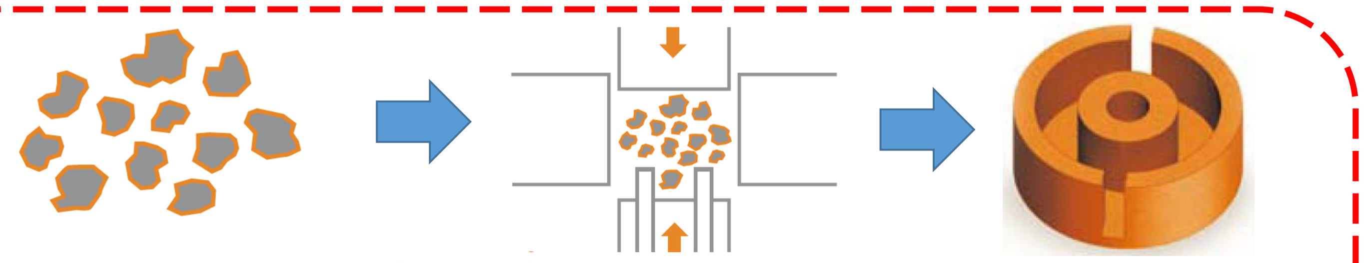
(a) Cogging torque (b) No-load back-EMF (c) Rated output torque

Fig. 9. Comparison of the performance between the initial and revised model.

- Cogging torque: 0.8978 Nm → 0.1215 Nm, **86%** reduction!
- No-load back-EMF: 98.68 V → 96.89 V, 1.8% reduction.
- Output torque:11.48 Nm → 11.45 Nm, 0.3% reduction.

Conclusion

The prominent contribution is the proposal of a novel axial-radial flux permanent magnet machine. Different radial rotors are analyzed and the PM radial rotor is determined to improve the output torque. Proper combination of skewing angel and position angle can reduce the cogging torque by 86%. The no-load back-EMF and output torque shows a slightly reduction due to the compensation of PM radial rotor.



Manufacture and machinability of SMC.

- surface-insulated Fe-particles, pressing, and thermal processing.
- Drilling, turning, milling.