Design and performance analysis of permanent magnet flux-switching motors using segmental permanent magnets

Yongqin Zhou, Lei Zhou, Bo Hu, and Ran Li

Abstract This paper proposes a structure of permanent magnet flux-switching motors (PMFSM) using “mixed” segmental permanent magnets, which is based on analysis of the structure and the operational principle of PMFSM. The paper researches the influence of tangential and radial segmental permanent magnets on motor’s electromagnetic torque, torque ripple and cogging torque respectively, which is based on the finite element analysis of a 12/10 three phase permanent magnet flux-switching motor. The research shows that the motors using this new structure can reduce torque ripple and cogging torque by comparing with the conventional permanent magnet flux-switching motor, and the motors have negligible influence on the other performances, such as the flux linkage and the induced voltage.

key words: permanent magnet flux-switching motor; finite element analysis; segmented permanent magnet; torque ripple; cogging torque

Classification: Power devices and circuits

1. Introduction

As stator extinction motor, permanent magnet flux-switching machine (PMFSM) uses dual salient structure in both stators and rotors, with permanent magnets in the stators and only a core in the rotors. PMFSM is gaining extensive attention since it was first raised by Emmanuel Hoang and etc [1], because it has the advantages of high torque density and power density in conventional permanent magnet synchronous motors, and it eliminates the shortcoming of large vibration and noise [2]. In [3], a new topology of multiphase PMFSM used for aerospace application was analyzed. Alternative 3-phase PMFSM topologies with potentially reduced stator pole number without introducing the unbalanced magnetic force were presented [4]. In [5], the influence of slots and rotor poles combinations on noise and vibrations in PMFSM was studied. The design, optimization and performances of outer-rotor PMFSM were studied in [6]-[9]. The design procedure of PMFSM was explained in [10]-[11]. PMFSMs used in electric vehicles were designed and analyzed in [12]-[15]. An analytical model of PMFSM was proposed in [16]. Torque characteristic of PMFSM was researched by winding function theory in [17]. Vector control strategy of PMFSM is studied in [18]-[21]. Control strategy of PMFSM based on current 3rd harmonic injection is studied in [22]-[26]. Adaptive fuzzy PI control strategy of PMFSM is studied in [27]. In conventional PMFSM, stator is divided into many core units, and permanent magnets (PMs) are placed among them. The shape and structure of PMs have a significant effect on the motor performance, but few literatures focus on the study in this filed. The influence of PM thickness on average torque is analyzed, and there is an optimum value of PM thickness [28]; PMFSMs using V-shape PMs are proposed and analyzed in [29]. The paper proposes a new structure of PMFSM on the basis of analyzing the structure and operational principle of the conventional PMFSM. In this new structure, PMs are divided into tangential and radial segments, and there is a gap between adjacent segments, while the same material as the core is placed in the gap. Therefore these stator units can be made as a single core, where PMs can be inserted directly into the core. The torque density and power density of PMFSM have been greatly improved because of permanent magnetic materials, and PMFSM performance can be influenced by the number of segments and the distance between two segments. The paper researches the influence of segmental permanent magnets on motor performance, which is based on the finite element analysis of a 12/10 three phase permanent magnet flux-switching motor, and the electromagnetic (EM) torque, torque ripple and cogging torque in the new PMFSM are compared with the conventional PMFSM. The research shows that the PMFSM with this new structure has the advantages of high EM torque, low torque ripple and cogging torque, and the results provide reference bases for the optimal design of PMFSM.

2. Topological structure and finite element model of conventional PMFSM

Conventional structure of 12/10 PMFSM is shown in Fig. 1, twelve PMs are placed among twelve stator coil units, and the concentrated windings are entwined the stator tooth, while the rotor has nothing except core. All the
twelve PMs are tangential magnetizing, and the magnetizing directions of adjacent two PMs are opposite. Four windings form a phase and they are differed by 90 degrees in space.

Operational principle of PMFSM is the flux linkage produced by PMs always exists and its direction remains unchanged, and the path of stator flux linkage is switched by the flux linkage produced by PMs as the rotor position changes, which can change the value and direction of flux linkage in the stator windings, thus generating induced voltage [30], as is shown in Fig. 2.

For conventional PMFSM design, teeth width, yoke height and slot width in the stator core unit are equal, and they are equal to the permanent magnet width and the width of rotor core. Lots of PMs are required when large size motors are designed using this method, which will increase the motor costs. The paper studies the effect of segmental PMs on PMFSM through finite element analysis of a 12/10 PMFSM. Main parameters of the PMFSM are shown in Tab. I.

### Table I Main parameters of the motor

| Parameters                  | Value     |
|-----------------------------|-----------|
| External stator diameter    | 90mm      |
| Internal stator diameter    | 55mm      |
| External rotor diameter     | 54 mm     |
| Internal rotor diameter     | 20 mm     |
| Core length                 | 25 mm     |
| PM width pole               | 7.5 degrees |
| Rotor tooth pole            | 7.5 degrees |
| Stator tooth pole           | 7.5 degrees |
| Average value of EM torque  | 4.92Nm    |
| Torque ripple               | 8.529%    |
| Amplitude of cogging torque | 164.25Nm   |
| PM material                 | NdFeb35   |

3. Effect of radial permanent magnet segments on PMFSM torque

Firstly, the paper analyzes the effect of radial PM segments on the torque performance of PMFSM. In torque performance, torque fluctuation is a very important performance. Torque fluctuation is mainly composed of two parts: cogging torque and torque ripple. Cogging torque is a harmonic torque existed in all motors using PMs, and the existence of cogging torque causes vibration and noise especially when motors are running at low speeds. So it is necessary to reduce the cogging torque in the motor design stage.

Torque ripple factor is defined as,

$$ T_{\delta} = \frac{T_{e \text{max}} - T_{e \text{min}}}{T_e} \quad (1) $$

Where $T_{e \text{max}}$, $T_{e \text{min}}$ and $T_e$ are maximum value of EM torque, minimum value of EM torque, and average value of EM torque respectively. Torque ripple is generated by the interaction of harmonics in current and harmonics in induced voltage. The harmonics in induced voltage are mainly related to the distribution of magnetic field generated by PMs in space.

By segmenting radial PM, the PM can be divided into 2 parts, 3 parts and 4 parts. When the gap between adjacent segments is not considered, effects of different number of radial segments on EM torque, torque ripple and cogging torque are shown in Tab. II. It is illustrated that the radial PM segments have little influence on EM torque, torque ripple and cogging torque.

### Table II Influence of radial PM segments on torque performance

| PM radial segments | No segments | 2 segments | 3 segments | 4 segments |
|--------------------|-------------|------------|------------|------------|
| EM torque/Nm       | 4.9920      | 4.9925     | 4.9925     | 4.9901     |
| Torque ripple/\%    | 5.679       | 5.650      | 5.648      | 5.711      |
| Cogging torque/nNm  | 321.6126    | 321.6126   | 317.5450   | 329.6052   |
Considering the gap between adjacent segments, this paper researches the effect of different distances between adjacent segments on torque, when PMs are divided into 2 parts, 3 parts and 4 parts respectively, and the same material (silicon steel sheet) as stator core is placed in the space between adjacent segments. When PMs are divided into different number of segments, the effects of different distances varied from 0 mm to 0.6 mm on the EM torque and cogging torque are shown in Fig. 4 to Fig. 6.

It can be seen from the figure that the average value of EM torque has a slight increase with the increase of the distance, and the value begin to decrease obviously when the distance is long enough. The torque ripple decreases with increasing radial distance, and cogging torque has the same trend. For the 12/10 PMFSM in this paper, the motor has the lowest torque ripple and cogging torque, and the average value of EM torque keeps constant when radial segments is 2 and the distance between adjacent segments is 0.5 mm, which means that the torque performance is better than before.

4. Effect of tangential PM segments on of PMFSM torque

When the gap between adjacent segments is not considered, effects of different number of tangential segments on EM torque and cogging torque are shown in Tab. III. It is shown in the table that motor torque performance is the best when then number of tangential segments is 2, because the average value of EM torque keeps constant, while torque ripple decreases and the maximum value of cogging torque falls. This paper studies the effect of different distances between adjacent segments on torque performance when the PM is divided into 2 tangential segments.

**Table III** Influence of tangential PM segments on torque

| Tangential segments | No segments | 2 segments | 3 segments | 4 segments |
|---------------------|-------------|------------|------------|------------|
| EM torque/Nm        | 4.9920      | 4.9935     | 4.9884     | 4.9913     |
| Torque ripple/%     | 5.679       | 5.673      | 5.781      | 5.536      |
| Cogging torque/mNm  | 321.6126    | 320.9021   | 323.3247   | 319.9277   |
The effect of different distances between adjacent segments on torque performance is shown in Fig. 7 when the number of tangential segments is 2.

In this paper, the torque performance with different distances among radial and tangential segments is analyzed, and the results are shown in Fig. 9.

It can be seen from the figure that torque ripple and cogging torque reduce dramatically with the increase of distance between adjacent segments, while the average value of EM torque rises at first and then drops.

5. Effect of “mixed” PM segments on PMFSM torque

Based on the above comparative analysis, this paper proposes a structure of PMFSM using “mixed” segmental PMs, which means that each PM in conventional PMFSM is divided into 4 parts, using both radial and tangential arrangements. The same magnetic material (silicon steel sheet) as stator core is placed in the space between adjacent segments, as is shown in Fig. 8. At the same time, this new structure can reduce the use of PM, with larger PM utilization and lower cost of motor fabrication.

It can be seen from the figure that the torque performance of PMFSM is greatly improved, with using this new structure. The combination of the spacing can be selected according to the different design requirements of the motor. For example, in order to obtain the minimum torque ripple, 0mm radial distance and 0.5mm tangential distance can be selected, and the torque ripple can be decreased from 5.679% to 4.613%. In order to obtain the minimum cogging torque, 0.3mm radial distance and 0.4mm tangential distance can be selected, and the cogging torque can be decreased from 321.61mNm to 260.71mNm.
6. Effect of “mixed” PM segments on other performances of PMFSM

The flux linkage and the induced voltage of PMFSM with non-segmented PMs are compared with those of PMFSM with this new structure, and the obtained results are shown in Fig. 10 and Fig. 11 respectively.

![Fig. 10 Three phase flux linkages before and after segmentation](image)

![Fig. 11 Three phase induced voltages before and after segmentation](image)

It can be seen from the figure that the three phase flux linkage curves are standard sine waves, and the change of three phase flux linkage curves after segmentation is quite small. The three phase induced voltage curves are almost sine waves, and the change after segmentation is also quite small. The Fourier transform of the induced voltage is done, and the obtained frequency spectrum is shown in Fig. 12.

![Fig. 12 Frequency spectrum of the induced voltage](image)

As can be seen from Fig. 12, there are no even harmonics in PMFSM induced voltage, and there are only a small amount of 3rd, 5th and 7th harmonics. There is a rise in the amplitude of fundamental wave, while other harmonics keep constant after dividing PM into segments.

7. Test results

The torque curve in two types of motor are tested, as shown in Fig. 12.

![Fig. 12 Torque curve comparison](image)

After calculation, the suppression effect of torque ripple is shown in Tab. IV. The table shows that this proposed PMFSM can reduce torque ripple effectively.

| Table IV | Experiment results |
|----------|-------------------|
|          | Conventional PMFSM | Proposed PMFSM |
| Torque ripple in FEA/% | 5.68 | 4.61 |
| Torque ripple in Test/%  | 5.86 | 4.83 |

8. Conclusion

1. Regardless of the effect of gap, the number of radial PM segments has little influence on torque performance in PMFSM, while the number of tangential PM segments has certain influence on torque performance, and the torque performance is the best when PM is divided into 2 tangential parts.
2. Considering the gap effect, when PM is divided into 2 radial segments with suitable distance, torque ripple and cogging torque in PMFSM can be reduced dramatically; when PM is divided into 2 tangential segments with suitable distance, torque ripple and cogging torque in PMFSM can be reduced enormously.
3. When selecting suitable radial and tangential distance between adjacent segments, torque ripple can be reduced from 5.68% to 4.61% (the reduced percentage is 18.84%), and cogging torque can be reduced from 321.61mNm to 260.71mNm, while other performances are almost unchanged.
4. PMFSM with “mixed” segmental PMs proposed by this paper has the advantages of high PM utilization and low cost.

Acknowledgments

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