Journal of Applied Physics

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Cite as: J. Appl. Phys. **99**, 08R312 (2006); https://doi.org/10.1063/1.2171122
Published Online: 21 April 2006

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# Effect of design variables on starting torque of single phase flux-reversal machine

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(Presented on 3 November 2005; published online 21 April 2006)

This article introduces a single phase flux-reversal machine (FRM) and presents the design method to improve its starting torque. The effects of the design parameters on the characteristic and starting torque are analyzed by the finite element method. The design variables considered are tapered airgap, stepped airgap, slotted teeth, and asymmetric PM width. As a result, we can find the best model in producing starting torque of a single phase 2/3 FRM. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2171122]

## I. INTRODUCTION

The flux-reversal machine (FRM) is a brushless doubly salient permanent magnet machine proposed by Miller in 1997.[1] The FRM has the advantages of both the SRM and the permanent magnet brushless dc motor. It has the same structure as SRM, but high-energy magnets are placed on the surface of the stator pole.

The FRM has bipolar flux and MMF variation with rotor position and it naturally has a low inductance, therefore, it has a low electrical time constant. This feature, combined with its simple construction and low rotor inertia, appear to make the FRM attractive as a low-cost high-speed machine.[2]

However, in case of single phase FRM, it has no starting torque such as the single phase PM brushless dc motor and other single phase PM motors. The starting torque can be improved by using a cogging torque which is produced by a permanent magnet.[3] This article investigates a rotor/stator geometrical variable that influences the starting torque through a two-dimensional (2D) finite element method. And a good method which has little loss of the back electromotive force (EMF) (torque constant) and good starting torque is suggested.

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## II. ANALYSIS MODEL

Figure 1 shows the cross section of the single phase 2/3 FRM. It has a two-pole stator and three-pole variable reluctance rotor. The permanent magnet material is sintered Nd–Fe–B. The air gap was designed to be 0.5 mm to obtain a reasonable permeance coefficient value.

## III. STARTING TORQUE OCCURRENCE SCHEME

To develop starting torque in single phase FRM, the methods that are used in permanent magnet machine can be

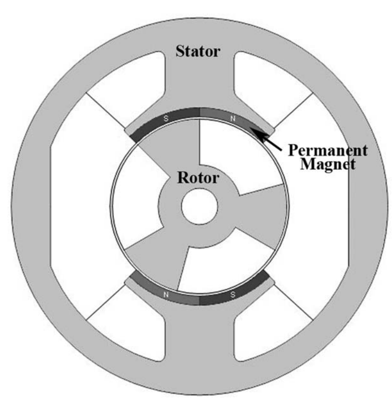


FIG. 1. Single phase 2/3 FRM.

 

applied. And here, four ways which can improve starting torque easily, viz. tapered airgap, stepped airgap, asymmetric PM width, and slotted teeth, are applied in the initially planned FRM.

Figure 2 shows the conceptual figure of the four cases that are introduced in this article. Figure 3 shows the cogging torque and back emf of each model. It shows one cycle of cogging torque and a half cycle of the back emf.

In Fig. 3, the $x$ axis is the moving angle of rotor [Deg], the main $y$ axis (left $y$ axis) is the magnitude of the back emf [V], and the second $y$ axis (right $y$ axis) is the magnitude of cogging torque [N m]. And in this graph, the black dotted line is the back emf while the empty box line is the cogging torque.

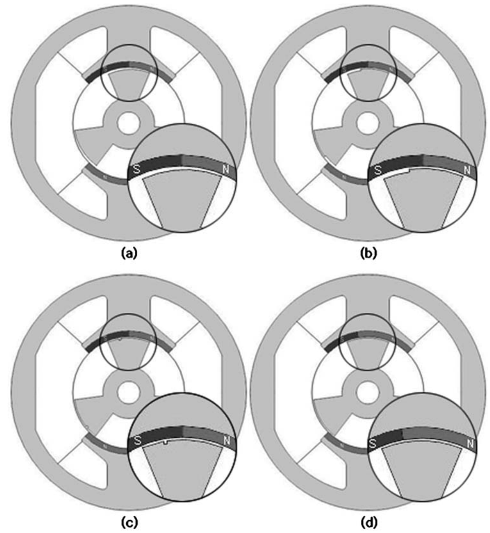


FIG. 2. Alternative topologies of single phase FRM: (a) tapered airgap; (b) stepped airgap; (c) slotted teeth; and (d) asymmetric PM width.

### A. Tapered airgap

Figure 2(a) shows the tapered airgap. Analysis of this model is done while increasing the airgap asymmetry. As it is shown in Fig. 3(a), as the airgap variation is larger, the cogging torque wave form is shifted more against the wave form of the original model. Inspecting the cogging torque which has 0 back emf, as it has larger airgap variation, the cogging torque is larger. Therefore this model is useful for improving the starting torque. However, if the airgap variation is larger, the amplitude of the back emf decreases slightly.

### B. Stepped airgap

Figure 2(b) shows the stepped airgap. Here, the step height is the same as airgap of the original model which is 0.5 mm and analysis of this model is done while increasing the step angle. As is shown in Fig. 3(b), as the step angle is larger, the cogging torque wave form is more shifted against the wave form of original model. The cogging torque at the point when the back emf is 0 becomes larger as the step angle also increases. Therefore this model is useful to improve the starting torque. When the step angle is increased, the variation of amplitude of the back emf is small compared to the tapered airgap.

### C. Slotted teeth

Figure 2(c) shows the slotted teeth. The slot width is 2° from the rotation axis and its depth is 0.5 mm. The position

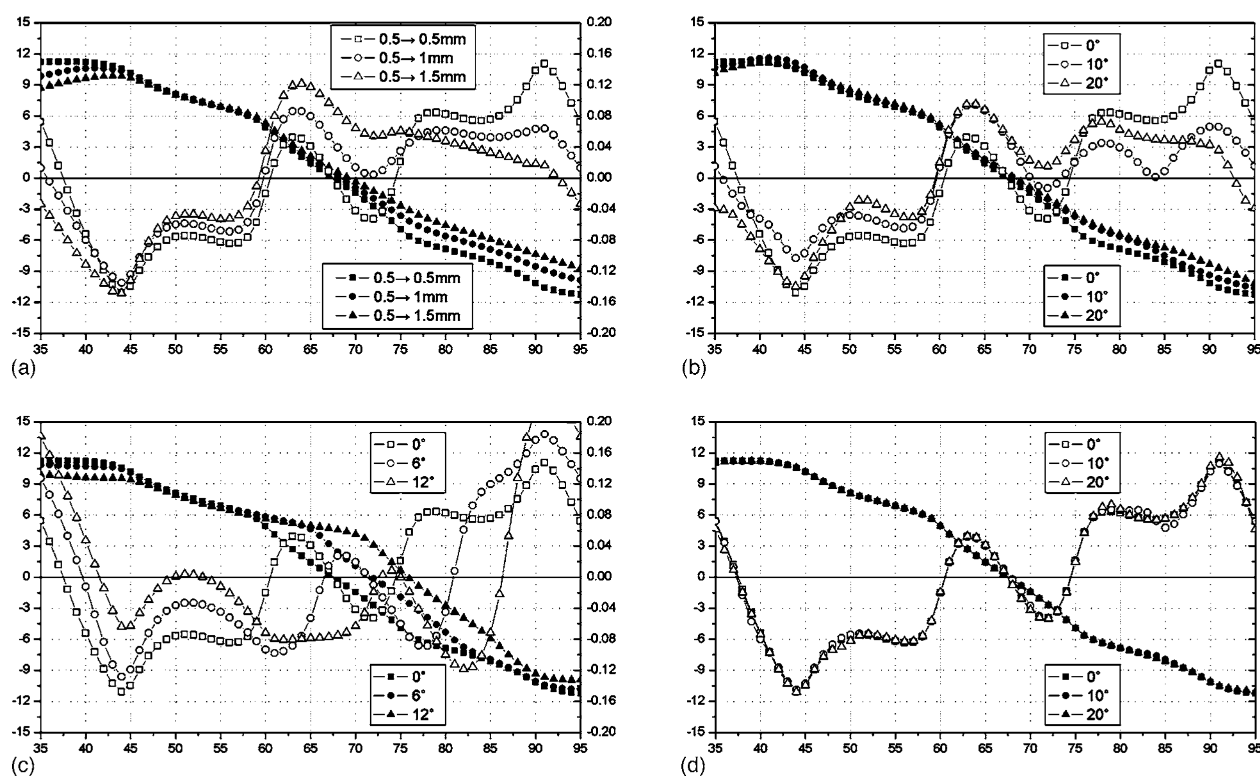


FIG. 3. Cogging torque and back EMF waveforms: (a) tapered airgap; (b) stepped airgap; (c) slotted teeth; and (d) asymmetric PM width.

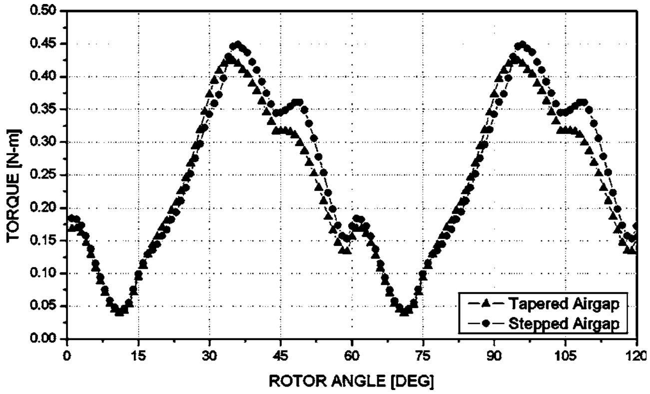


FIG. 4. Comparison of the total torque of tapered airgap and stepped airgap, when the starting torque is the same.

of the slot was varied during the analysis procedure, where the initial position is the left edge of the pole. As is shown in Fig. 3(c), the effect of using slotted teeth was not large enough to consider. The cogging torque has a value near 0 when the back emf value is 0. Therefore, this model is useless for improving the starting torque.

### D. Asymmetric PM width

Figure 2(d) has an asymmetric PM width. In this model, the airgap is constant but the permanent magnet pole width ratio varies. In this case, the ratio of the N pole width to the total pole width was increased during the analysis. As is shown in Fig. 3(d), both wave forms are shifted, and the cogging torque has a value near 0 when the back emf value is 0.

Although the cogging torque wave form is shifted, as the back emf wave form is also shifted in the same direction, this model is useless for improving the starting torque. When the S pole width is increased, the result is that both wave forms are symmetric to the *x* axis but it has same property.

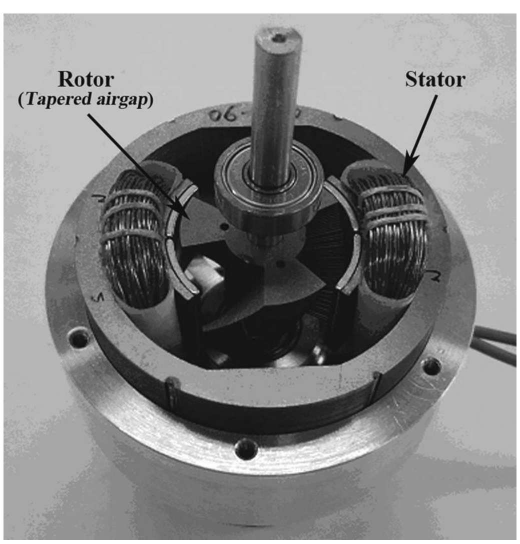


FIG. 5. The manufactured FRM that has tapered airgap.

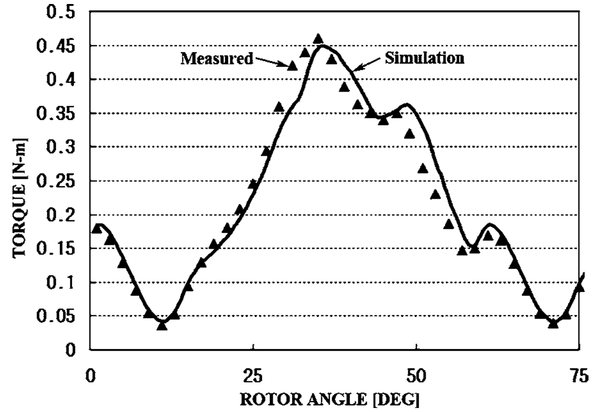


FIG. 6. The measured torque.

## IV. DISCUSSION AND EXPERIMENTAL RESULT

As discussed above, only the tapered airgap and stepped airgap are useful for improving the starting torque and other methods are useless for improving the starting torque. Comparing the tapered airgap with the stepped airgap, the tapered airgap is comparatively effective in improving the starting torque but it decreases the back emf. So, the total torque is decreased and the stepped airgap is less effective for improving the starting torque compared with the tapered airgap, but the back emf is not decreased compared with the tapered airgap. Therefore, this method does not have much effect on the amplitude of the total torque of this FRM model.

Figure 4 is a torque graph of the FRM model that has a tapered airgap and a stepped airgap when rated current is applied. In both graphs, the starting torque is the same and its amplitude is 0.04 N m. As it is shown in this figure, both models have no point where the total torque is zero and the torque is always positive. Also, the maximum torque value of the stepped airgap case is slightly larger than the tapered airgap case. Therefore, either can be chosen, depending on the application.

To prove the propriety of the analysis results, we built the prototype FRM that has a tapered airgap for the experiment as shown in Fig. 5. Figure 6 shows the measured torque graph when rated current is applied. We can see that the experimental results closely match those obtained from the simulation.

## V. CONCLUSIONS

The starting torque is the most important factor of single phase FRM. In this article, several methods which can improve starting torque have been suggested and the experiment has been performed. Judging from features of the starting torque, back emf and total torque by current, tapered airgap, or stepped airgap is the most appropriate, and either can be chosen, depending on the application.

[1]R. Deodhar, S. Anderson, I. Boldea, and T. J. E. Miller, IEEE Trans. Ind. Appl. **33**, 925 (1997).
[2]C. X. Wang, I. Boldea, and S. A. Nasar, IEEE Trans. Energy Convers. **16**, 74 (2001).
[3]S. Bentonati, Z. Q. Zhu, and D. Howe, IEEE Trans. Magn. **36**, 3533 (2000).