Article:

Bentouati, S., Zhu, Z.Q. and Howe, D. (2000) Influence of design parameters on the starting torque of a single-phase PM brushless DC motor. IEEE Transactions on Magnetics, 36 (5 (Par). pp. 3533-3536. ISSN 0018-9464

https://doi.org/10.1109/20.908890

Influence of Design Parameters on the Starting Torque of a Single-Phase PM Brushless DC Motor

S. Bentouati, Z. Q. Zhu, *Member, IEEE*, and D. Howe

***Abstract*—The starting torque of a single-phase permanent magnet brushless dc motor is investigated, for both radial and parallel magnetization. Finite element analysis is used to assess the relative merits of alternative methods of introducing the required airgap asymmetry, *viz.* tapered airgap, stepped airgap, asymmetric airgap, and slotted teeth. The predicted results are validated experimentally.**

***Index Terms*—Brushless dc motor, electrical machine, permanent magnet, reluctance torque.**

I. INTRODUCTION

SINGLE-PHASE permanent magnet brushless dc motors are likely to be adopted for many low cost applications. However, with a smooth airgap single-phase excitation produces zero starting torque, and the direction of rotation is indeterminate [1]. In order to develop a starting torque and impart a preferred direction of rotation, an asymmetric airgap is employed as a means of introducing a reluctance torque component to complement the excitation torque. Fig. 1 illustrates four ways by which airgap asymmetry can be introduced, *viz.* tapered airgap, stepped airgap, asymmetric airgap, and slotted teeth, together with open-circuit field plots for both radial and parallel magnetization of the 2-pole, surface-mounted magnet rotor. Although the issue of starting torque has been investigated extensively, publications are usually restricted to a consideration of a specific motor topology [1]. In this paper, the relative merits of all four methods of introducing the airgap asymmetry, on both the starting torque and the net torque, are compared. Finite element predictions are validated against measurements, and motor designs, which result in a high specific torque, the required starting torque, and a relatively smooth torque waveform, are identified.

II. ANALYSIS OF ALTERNATIVE AIRGAP PROFILES

In order to ensure accurate predictions, the torque has been calculated by both Maxwell stress integration and from the rate of change of co-energy, particular attention being paid to the local and global finite element mesh discretization [2]. However, they gave essentially identical results. Throughout, the calculations are for a 2-pole/2-slot motor, for which the outside diameter and the active axial length are 76 mm and 87.5 mm, respectively, the minimum airgap being 1 mm, and the rotor having a bonded NdFeB ring magnet with radial thickness of 5 mm, an outside diameter of 36 mm, and a remanence of 0.5 T.

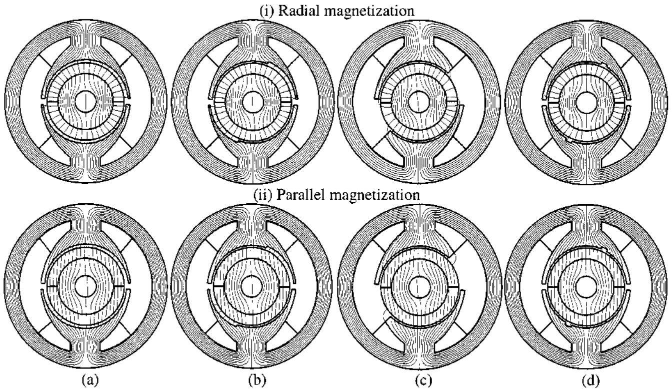


Fig. 1. Alternative topologies of single-phase permanent magnet brushless dc motor. (a) Tapered airgap; (b) Stepped airgap; (c) Asymmetric airgap; (d) Slotted teeth.

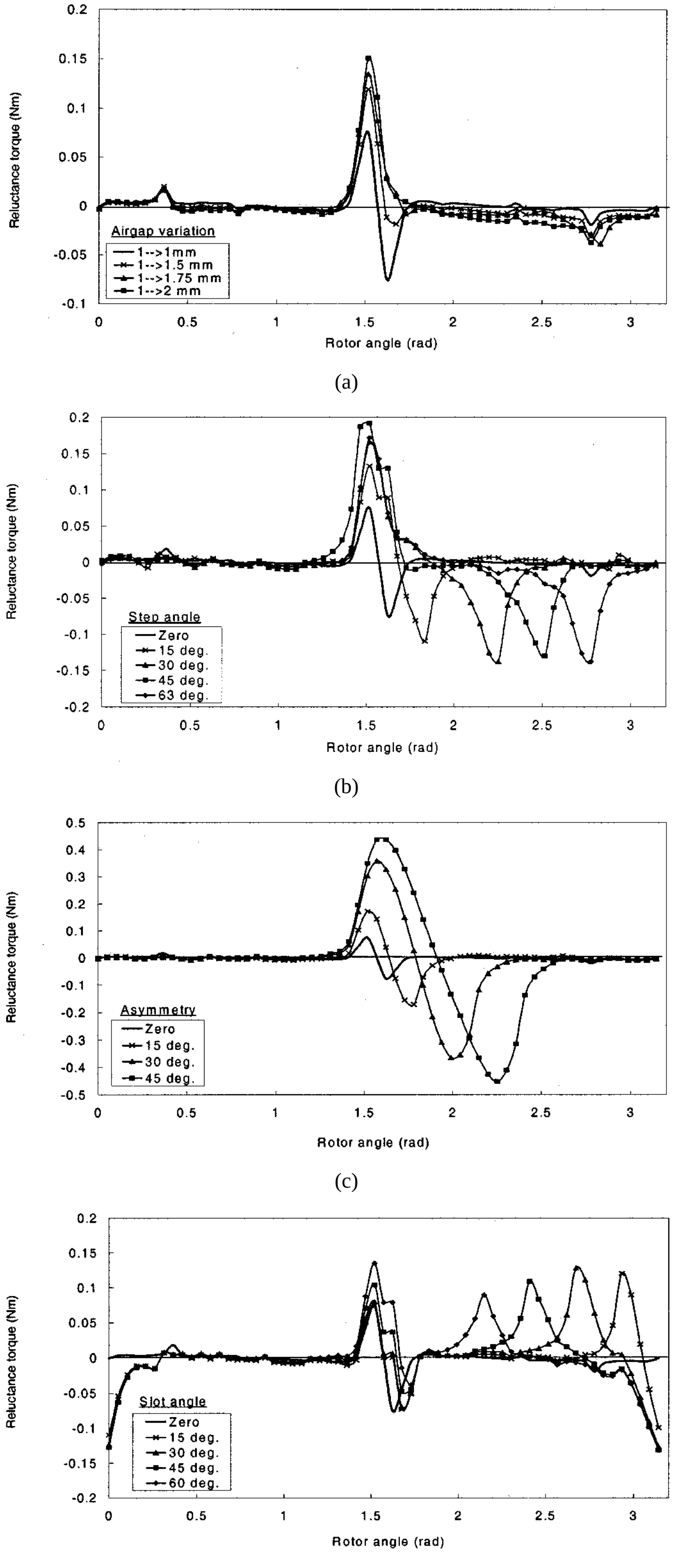
Figs. 2 and 3 show how the reluctance torque waveform varies as the airgap asymmetry is changed. As will be seen, the reluctance torque waveforms which result with a parallel magnetized rotor are essentially sinusoidal for all the motor topologies. Radial magnetization results in much more complex torque waveforms. With a uniform airgap, the reluctance torque waveform exhibits a positive peak and a negative peak of equal amplitude over a pole-pitch, due to the slot openings. With a tapered airgap and radial magnetization, Fig. 2(a), the torque waveform exhibits a positive peak which is significantly larger than the negative peak, the difference increasing with the airgap taper, since the reluctance torque is due primarily to the interaction of the edges of the magnets with the sides of the tooth-tips. As the taper is increased, the effect of the tooth-tip at one side of the slots, which produces the negative reluctance torque component, is reduced. Fig. 4 compares typical reluctance and excitation torque waveforms. With a stepped airgap motor, Fig. 2(b), the reluctance torque waveform may exhibit one positive peak and two negative peaks over a pole-pitch, although the negative peak associated with the tooth tips near the longer airgap is very small. Therefore, a stepped airgap is equivalent to having a wide slot opening, an increase in the width of the step resulting in an increase in the angular separation between the positive and negative torque peaks. However, the negative peaks have almost the same magnitude as the positive peaks, the resultant torque waveform, Fig. 5, can exhibit a high torque ripple, with zero or negative torque regions if the motor is not properly designed. The asymmetric airgap motor, Fig. 2(c), is very similar, although it only exhibits one positive torque peak and one negative torque

---

Manuscript received February 14, 2000.

The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Mappin St., Sheffield S1 3JD, UK (e-mail: Z.Q.Zhu@sheffield.ac.uk).

Publisher Item Identifier S 0018-9464(00)07966-8.



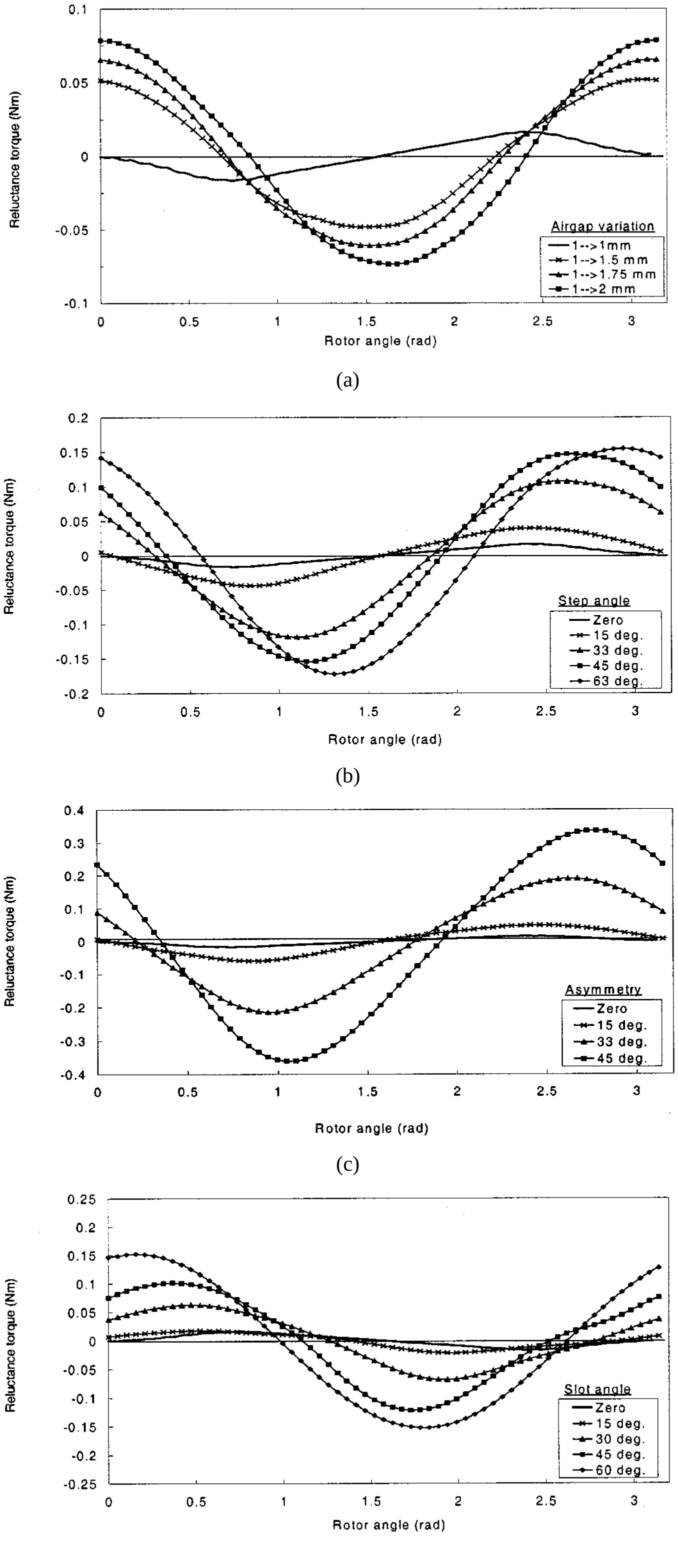
(a)

(b)

(c)

(d)

Fig. 2. Reluctance torque waveforms (radial magnetization). (a) Tapered airgap (b) Stepped airgap (c) Asymmetric airgap (d) Slotted teeth.



(a)

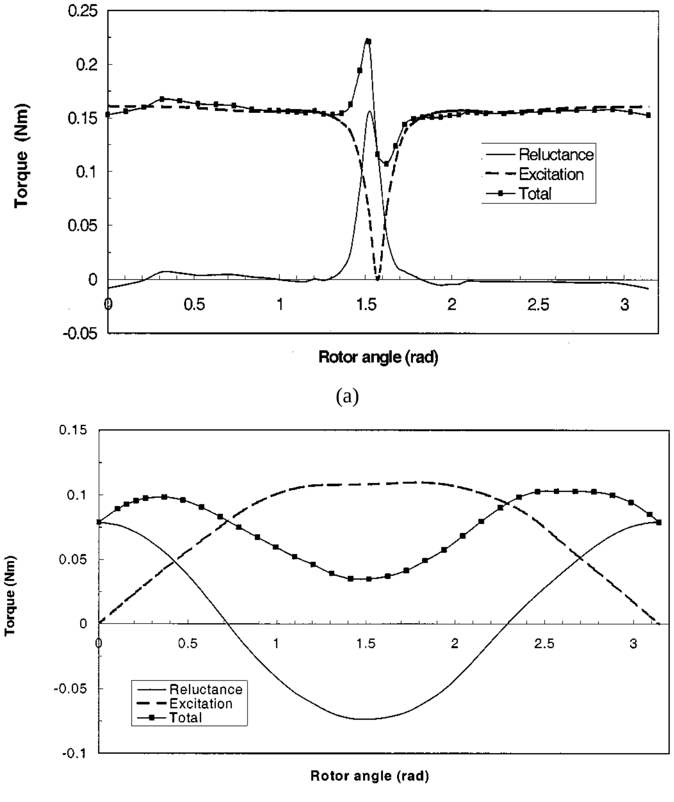
(b)

(c)

(d)

Fig. 3. Reluctance torque waveforms (parallel magnetization). (a) Tapered airgap (b) Stepped airgap (c) Asymmetric airgap (d) Slotted teeth.

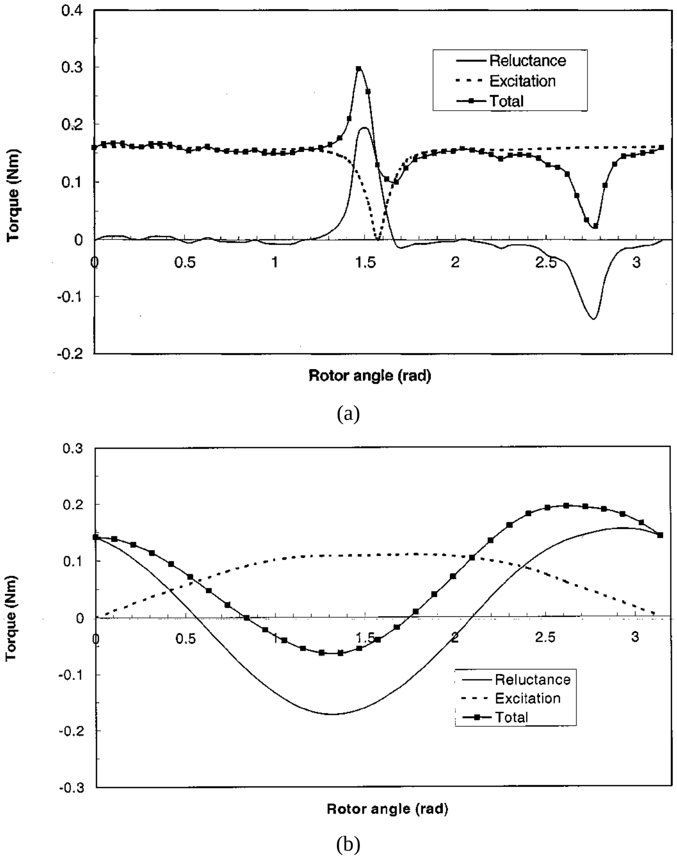
peak over a pole-pitch. Increasing the airgap asymmetry increases the angular separation between the positive and negative torque peaks, which are relatively large and almost equal, since the resultant slot openings are wide and deep. Hence, the resultant torque may also exhibit a high torque ripple and negative torque regions. The slotted teeth design, Fig. 2(d), results in two negative torque peaks and two positive peaks over a pole-pitch, due to the additional slot. Again, the values of the peak positive and negative reluctance torques are almost equal. However, in this case, the additional slots can provide only a limited starting torque capability, unless they are made relatively large.



(a)

(b)

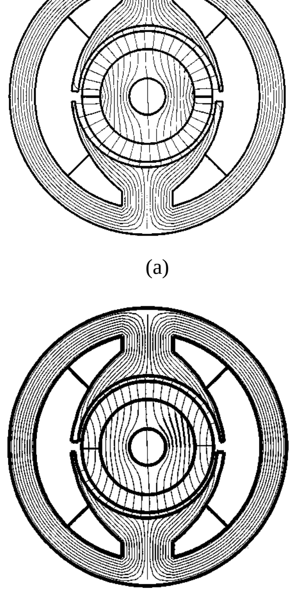
Fig. 4. Torque components in tapered airgap motor. (airgap variation from 1–2mm). (a) Radial magnetization (b) Parallel magnetization.



(a)

(b)

Fig. 5. Torque components in stepped airgap motor. (63° step). (a) Radial magnetization (b) Parallel magnetization.



(a)

(b)

Fig. 6. Influence of pole transition of impulse magnetization on field distribution. (a) Ideal radial magnetization (b) Actual magnetization.

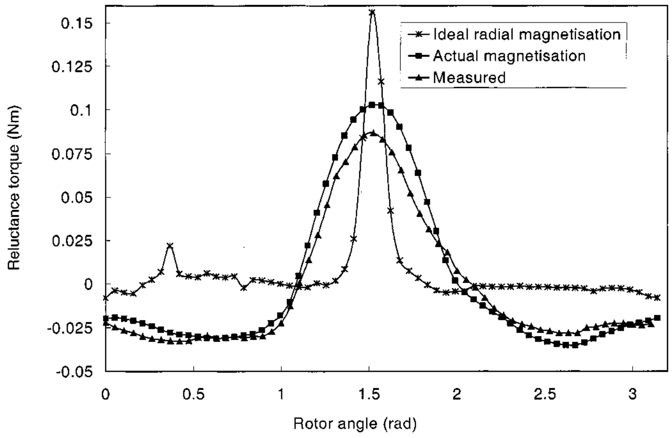


Fig. 7. Influence of magnetization transitions on reluctance torque.

In summary, although it is usually possible to obtain the required unidirectional starting torqueusing any of the four methods, a tapered airgap is most effective, in terms of minimum torque ripple, for both radial and parallel magnetized magnets.

III. INFLUENCE OF IMPULSE MAGNETIZATION AND EXPERIMENTAL VALIDATION

The foregoing analyzes have assumed idealized magnetization distributions, with "sharp" transitions between poles. In practice, the pole transitions which result after impulse magnetization can significantly influence the reluctance torque. By way of example, Figs. 6 and 7 compare the reluctance torque waveform and open-circuit field distribution of a tapered airgap motor, in which the airgap varied from 1–2 mm, when equipped with both an idealized radially magnetized rotor and a rotor which has been impulse magnetized in a custom designed radial-field fixture. It will be seen that, in general, good agreement is achieved between the predicted and measured reluctance torque waveforms.

IV. CONCLUSION

Starting torque is one of the most important considerations in the design of single-phase permanent magnet brushless dc motors. Finite element methods have been used to investigate the effectiveness of various methods of introducing the required reluctance torque, and it is concluded that a tapered airgap is the most appropriate, since it results in a smoother resultant torque waveform. It has also been shown that the magnetization transition regions have a significant influence.

REFERENCES

[1] C. Koechli, Y. Perriard, and M. Jufer, "One phase brushless dc motor analysis," in *Proc. Int. Conf. on Elect. Mach.*, 1998, pp. 639–644.

[2] D. Howe and Z. Q. Zhu, "The influence of finite element discretization on the prediction of cogging torque in permanent magnet excited motors," *IEEE Trans. on Magn.*, vol. 28, pp. 1080–1083, 1992.