Development of a Single Phase PM BLDC Motor from a Novel Generic Model

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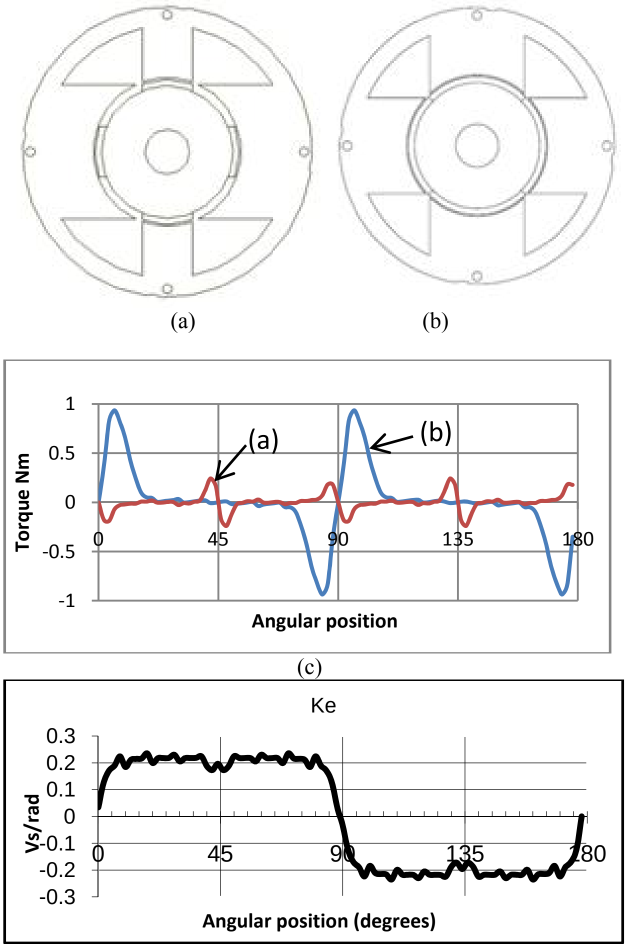
Abstract

The aim of this paper is to present a practical solution for a generic novel single phase PM BLDC motor model. This motor model is novel because it has an asymmetrical stator pole arc design that reduces the slot cogging torque and maintains the ideal square shape of the back EMF. Although the novel design has these ideal characteristics, it is not practical because 1) it has no starting torque at certain rotor positions, and 2) there is poor utilization of iron in the large stator poles. This paper presents the investigations to reduce the iron where necessary without deteriorating the back EMF shape, and to introduce a way to ensure the motor starts at all rotor positions. An accurate 2D finite element modelling (FEM) software package was used to analyse the magnetic field distribution inside the motor. As a result of this investigation it was feasible to transform the generic model into a practical model with minimum deviation from the ideal characteristics of the original generic model.

Key words: single phase BLDC, asymmetric stator arc poles, starting torque and back EMF.

1. Introduction

Single phase Permanent Magnet Brushless DC (PM BLDC) motors are deemed to have a low starting torque, and therefore, they are widely used in low starting torque and small power applications such as fuel pumps and PC cooling fans. One of the intensively researched issues for single phase PM BLDC motors is the reduction of the oscillations in the torque waveform, which are known as torque ripples, these are due to both stator current oscillations and motor topology [1, 2]. A novel generic model for a single phase BLDC motor has been developed which has a unique stator pole arc ratio, see figure 1(a), the small stator pole arcs are 3 times the width of the large stator pole arcs, and the rotor magnets have the same arc length as the small stator poles. The motor develops both reluctance and electromagnetic alignment torques, which is higher than conventional single phase PM BLDC motors. The novelty of the motor lies in the combination of the unique asymmetrical stator poles together with rotor magnets that coincides with the width of the small stator poles. This unique topology has the benefit of a fractional slot motor (fractional stator to rotor poles ratio) in reducing the cogging torque, but without the disadvantage of torque loss. Therefore, the model produces lower cogging torque compared to the standard symmetrical stator pole arc design shown in figure 1(b). This comparison of the cogging torques is shown in figure 1(c). In addition, the asymmetrical design produces a back EMF waveform which is close to the ideal square shape, see figure 1(d), and that is not the case for other asymmetrical stator topologies. This novel design was developed from the generic (constant air gap) model shown in 1(b). It was the result of some research into reducing the cogging torque due to the stator slots only by varying the pole arc widths and without the influence of a variable air gap, which is necessary to bias the rotational direction. Therefore, a practical model that has a starting torque at all rotor positions (especially when the rotor and stator poles are aligned) and more winding space needed to be developed. This paper presents different ways to implement a starting torque at the rotor-stator pole alignment positions by investigating different air gap profiles that have a minimal effect on the ideal back EMF shape. This work is combined with the other area of the development; to provide efficient utilization of the iron in the novel model, to reduce cost, and to create more winding space.



(a) (b)

(c)

(d)

Figure 1, (a) The generic novel motor, (b) A generic standard single phase BLDC motor (c) cogging torque comparison between the two models, (d) back EMF shape of the generic novel motor.

2. Computing the Back EMF Shape

The back EMF for a single phase PM BLDC motor should be ideally square. The shape of the back EMF is proportional to the change in the flux linkage. The motor topology affects the change in flux linkage with respect to rotor angular position, and hence, this has an impact on the shape of the back EMF. The back EMF of the machine can be determined from:

$$e = \frac{d\Psi}{dt} \qquad (1)$$

$$\text{but} \quad \frac{d\Psi}{dt} = \frac{d\Theta}{dt}\frac{d\Psi}{d\Theta} \qquad (2)$$

Where e is the back EMF in volts, Ψ is the flux linkage in webers and Θ is the angular position in radians.

$$\text{Also} \quad \frac{d\Theta}{dt} = \omega \qquad (3)$$

hence from (1) to (3)

$$e = \omega\frac{d\Psi}{d\Theta} \qquad (4)$$

Where ω is the angular speed in rad/s and in the steady state it has a constant value. Therefore, $\frac{d\Psi}{d\Theta}$ determines the shape of the back EMF. Ideally for a flat back EMF $\frac{d\Psi}{d\Theta}$ has to be constant according to the following dc machine equation:

$$e = \omega K_e \quad (5)$$

Where K_e is the back EMF constant in Vs/rad.

Plotting $\frac{d\Psi}{d\Theta}$ is useful in realising the change in the back EMF shape when the topological design of the motor is changed. With the aid of FEM software $\frac{d\Psi}{d\Theta}$ can be calculated and plotted with respect to rotor angular position.

3. The Effect of Stator Pole Arc Width

Efficient utilization of iron is necessary to avoid wasting this material and to create more winding space. Otherwise, the magnetic loading in the large stator poles will be low and the electrical (winding) loading will be too high. In order to create more winding space some of the metal from the large stator poles was removed to implement a pole shoe design as shown in Fig 2.

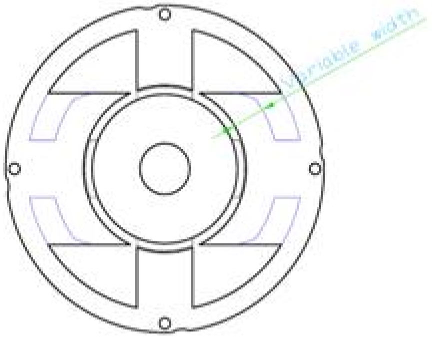
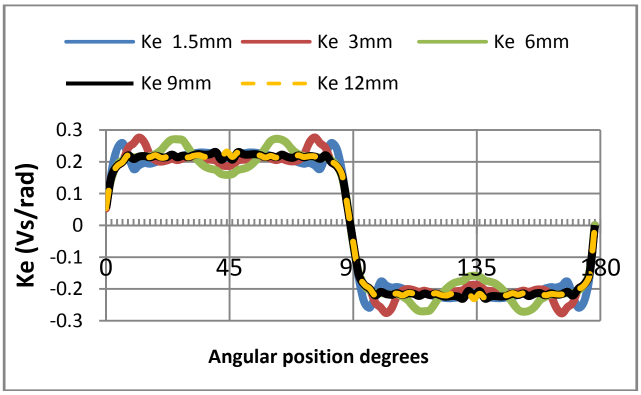
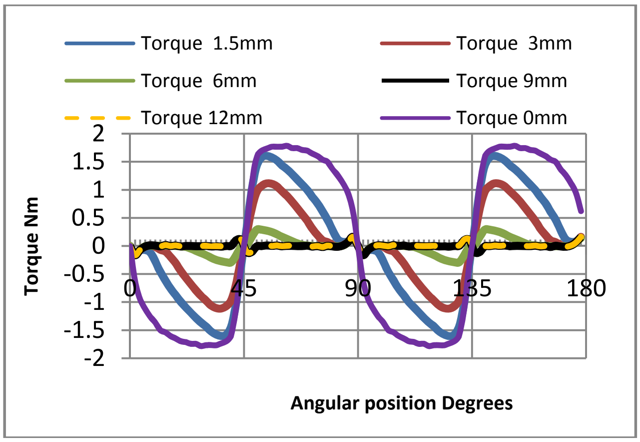


Figure 2 Implementing a pole shoe design in the large stator poles of the generic model.

This modification in the stator iron can affect two characteristics: 1) the level and distribution of the flux linkage in the stator and hence the Back EMF shape, 2) the reluctance torque waveform. In order to determine the effect of this design change, different pole shoe (arc) widths were investigated in the FE model, ranging from the radial thickness of 1.5mm to 12mm as shown in figure 2. Figure 3 shows the results, six different models were simulated for arc widths of 1.5mm, 3mm, 6mm, 9mm, 12mm and 0mm (i.e. unmodified pole with no pole shoe). From the results it is obvious that the back EMF plots from the models with arc widths less than 9mm significantly deviates from the ideal square shape. The models with arc widths 9mm or above have a back EMF shape which is close to the ideal square shape. Comparing the reluctance torque graphs in figure 3b, it is clear that the models with arc widths of 9mm and 12mm have the same reluctance torque profile as the generic model with a low torque ripple. However, it can be seen that for arc widths less than 9mm there is an increase in the cogging torque level. This is due to the narrower arcs becoming saturated by the shorted flux from two adjacent rotor poles magnets. This saturation has the effect of negating the purpose of the long pole arcs, and the motor will effectively behave like the four pole motor shown in figure 4.



(a)



(b)

Figure 3, (a) The back EMF profile, and (b) the reluctance torque, as functions of rotor angular position.

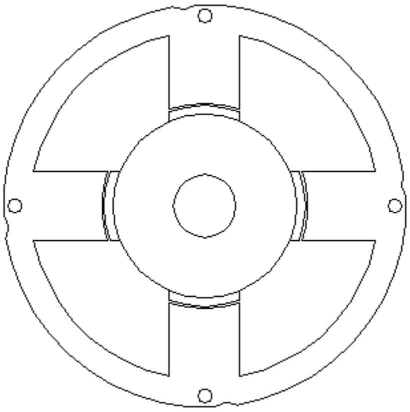


Figure 4 The effective stator topology when the long stator poles are saturated.

Based on the FEM results of the back EMF and reluctance torque graphs, the model with the arc width of 9mm has shown to be the best design, because there is a good balance between stator iron optimisation, a well preserved back EMF shape, and with a low cogging torque.

4. Overcoming the Null Points in the Torque Profile

Single phase BLDC motors, unlike three phase BLDC motors, exhibit zero torque points at certain rotor positions. This is because the stator flux in single phase BLDC motors is produced by a single winding which does not present a rotating magnetic field to the rotor when it is commutated. Therefore, when the rotor poles or magnets are aligned with stator poles at 0°, 90°, 180° and 270°, the angle between the rotor and stator fluxes is zero and there will be no electromagnetic torque exerted on the rotor. Figure 5 shows a typical excitation torque of a four pole single phase BLDC motor with an ideal flat back EMF.

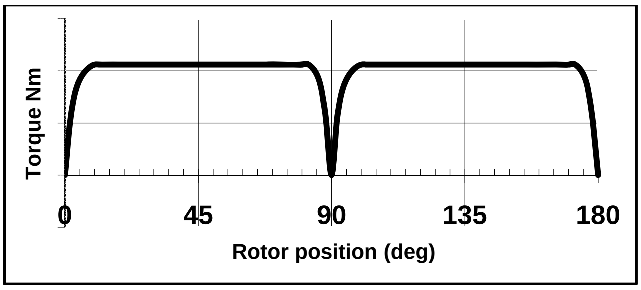


Figure 5 Excitation torque of a 4 pole single phase BLDC motor with flat back EMF

All the methods used to overcome the ‘dead points’ problem in single phase BLDC motors are based on providing reluctance torque by creating an asymmetrical (non constant) air gap that enhances the excitation torque, especially at the alignment positions. Figure 6 demonstrates ideally how the reluctance torque due to air gap asymmetry and in conjunction with the excitation torque produces a constant net torque.

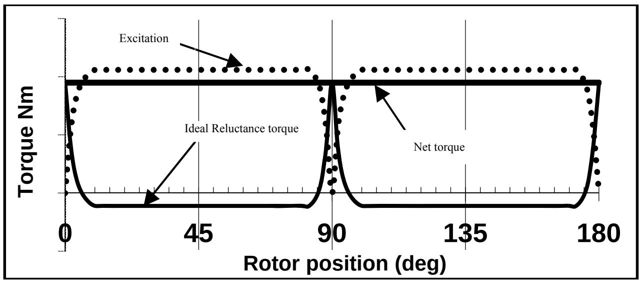


Figure 6 Ideal reluctance torque to eliminate ‘dead points’ in the torque produced by a single phase BLDC motor.

The area under the positive part of the reluctance torque graph should always be equal to the area under the negative part. Therefore, the ideal reluctance torque profile requires a peak at the alignment positions and a low negative torque spread evenly elsewhere.

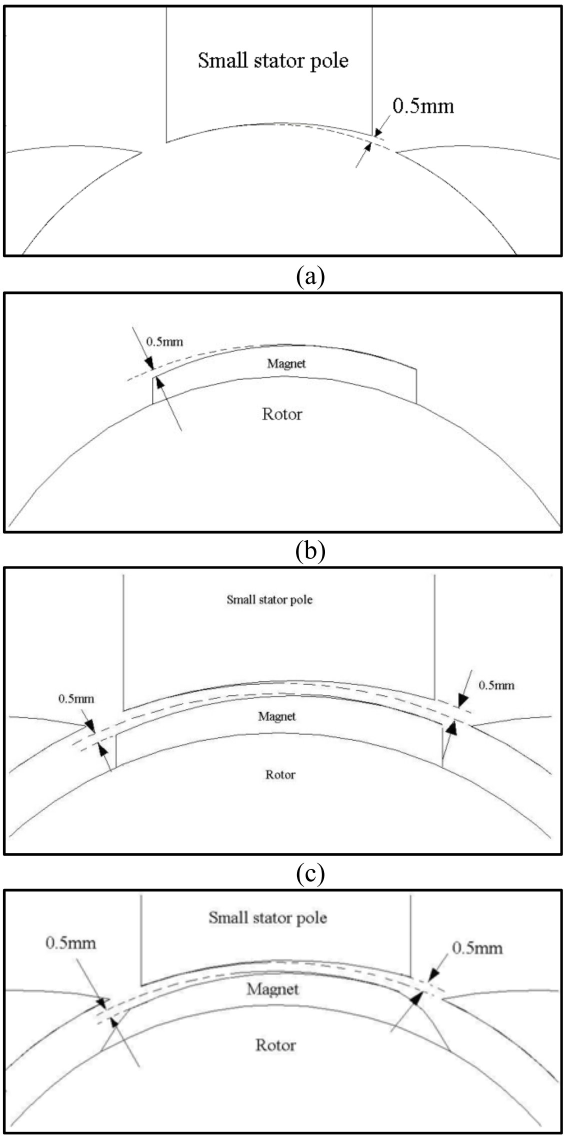
Bentouati [3] has investigated a range of different air gap profiles and it was concluded that the tapered air gap is the most appropriate design because of it’s smooth resultant torque. However, this investigation was applied to a standard single phase BLDC motor with symmetrical stator poles, and the air gap asymmetry was achieved by modifying the stator poles only. In this paper different asymmetrical air gap designs for the novel motor is presented, where the asymmetry in the air gap is achieved not only by altering the profile of the stator poles but also by altering the surface profile of the rotor magnets or a combination of both methods.

Implementing an asymmetrical air gap design affects the ideal shape of the back EMF. So the investigations were aimed at finding the most optimum design that has a good starting torque at all rotor positions, and, with minimum influence on the ideal shape of the back EMF.

5. FEM Results of Asymmetrical Air Gap Designs

The four asymmetrical air gap designs considered for the analysis are shown in figure 7. The designs are implemented on the model concluded in section 3.

7(a) is the design where the small stator pole arcs are tapered to produce a total air gap variation from 0.5mm to 1mm across the pole surface. In 7(b) only the rotor magnets are tapered to produce an air gap variation from 0.5mm to 1mm. 7(c) is a combination of 7(a) and 7(b) where both the small stator poles and rotor magnets are tapered. 7(d) is the same design as 7(c) but with smoothed rotor magnet edges.



(a)

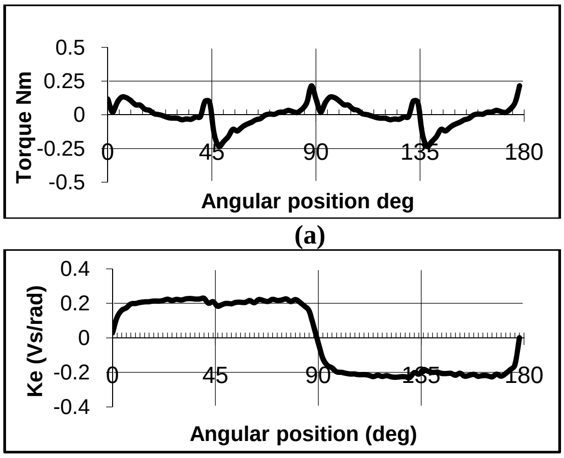
(b)

(c)

(d)

Figure 7 Asymmetrical air gap topologies. (a) tapered small stator poles, (b) tapered rotor, (c) a and b combined, (d) tapered small stator poles with smoothed tapered rotor magnets.

Figures 8-11 show the FEM results of the reluctance torque and back EMF shape graphs of the four designs described above. It can be seen that the reluctance torque profiles and back EMF shapes are influenced by the different air gap designs. Referring to figure 8, the reluctance torque from the design in figure 7(a) does not produce sufficient torque at the aligned positions (0°, 90°and 180°), and falling to zero torque at 5 degrees passed the alignment positions. This design also exhibits a ripple torque with a negative peak of 0.25 Nm at the unaligned positions (45°, 135°, 225°) which is undesirable if smooth net torque is required.

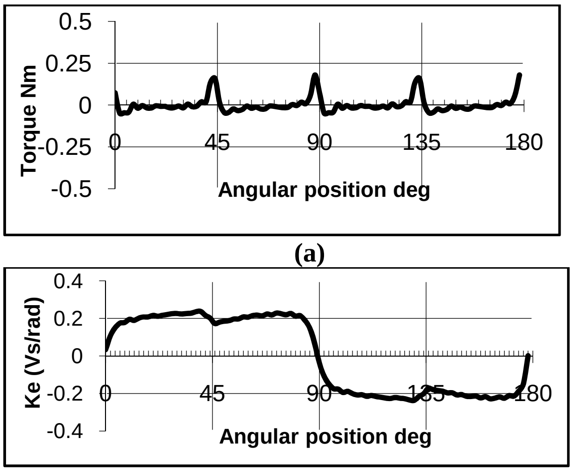


(a)

(b)

Figure 8 The results of the ‘tapered small stator poles’ design. (a)seluctance torque, (b) shape of the back EMF

Figure 9 shows the results of reluctance torque and back EMF graphs from the design shown in figure 7(b). It can be seen that the negative peak in the reluctance torque waveform is reduced. However, there is not enough torque produced at the alignment positions. The configuration has caused a slight distortion to the shape of the back EMF at 45°, but it is reasonably close to the ideal square shape.

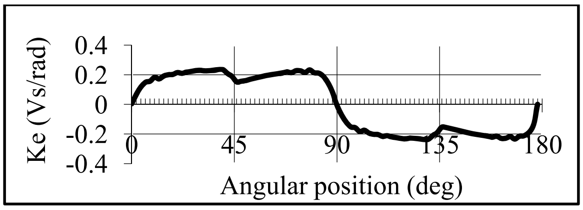


(a)

(b)

Figure 9 Tapered rotor magnets, (a) reluctance torque, (b)shape of the back EMF.

Figure 10 shows the results of the design in 7(c) where the small stator poles and rotor magnets are tapered. Combining 7(a) and 7(b) has produced a back EMF shape that is close to the ideal square shape and a high level of starting torque of 0.25 Nm at the alignment positions. However, the only drawback is the high ripple in the reluctance torque at the unaligned positions of 45° and 135°. This ripple in the reluctance torque at these positions occurs when two of the rotor magnets are aligned with the long stator arc, precisely while the edges of the magnets cross the stator slots (between 40° to 50°). To reduce this ripple the tapered rotor magnet edges were smoothed out as shown in figure 7(d) and the results are shown in figure 11.



(a) these graphs are in the wrong order

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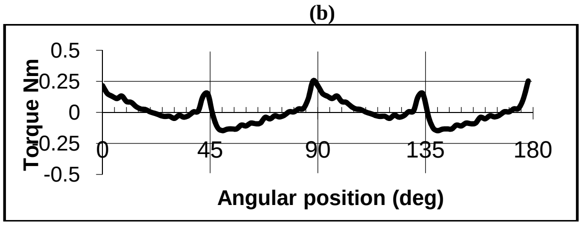
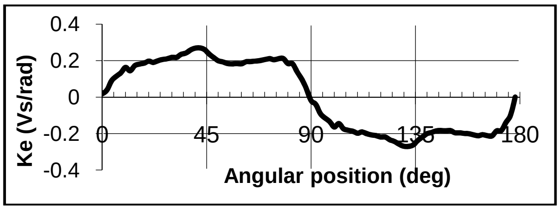


(b)

Figure 10 Tapered small stator poles with tapered rotor magnets, (a) reluctance torque, (b) back EMF shape.

Comparing the waveforms before and after smoothing the edges of the magnets (figures 10 and 11) it is obvious that smoothing the rotor edges has reduced the reluctance torque ripple at 45° and maintains a good starting torque at 90°. The back EMF shape shows a slight distortion but it is still considered to be reasonably close to the ideal square shape.



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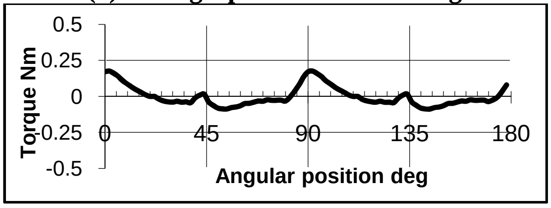

(b)

Figure 11 Tapered small stator poles with smoothed tapered rotor magnets, (a) Reluctance torque, (b) Shape of back EMF

6. Conclusions

In this paper a generic model of a novel single phase PM BLDC motor has been presented with improvements. The aim was to transform the generic novel model into a practical model that has efficient iron utilization, low cogging torque, and high starting torque at any rotor position, which is necessary for any unidirectional single phase BLDC motor. Using FEM software many different designs were investigated and from the results it was concluded that implementing a pole shoe design can reduce the iron utilisation in the generic model without compromising the ideal back EMF shape. It was also found that tapering the small stator poles and rotor magnets, with smoothed edges on the magnets, produced the best results for continuous torque production at any rotor position and with a near flat back EMF. Therefore, the new improved design has not detracted from the ideal characteristics of the generic model.

7. References

[1] J. R. Hendershot and T. Miller, *Design of Brushless Permanent-Magnet Motors*: Oxford University Press, 1994.

[2] L. Sun, Q. Feng, and J. Shang, "Drive of Single-Phase Brushless DC Motors Based on Torque Analysis," *Magnetics, IEEE Transactions on,* vol. 43, pp. 46-50, 2007.

[3] S. Bentouati, Z. Q. Zhu, and D. Howe, "Influence of design parameters on the starting torque of a single-phase PM brushless DC motor," *Magnetics, IEEE Transactions on,* vol. 36, pp. 3533-3536, 2000.