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# Cogging-Torque Reduction Techniques in Axial Flux Permanent Magnet Machine

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***Abstract:*** Axial flux Permanent magnet (AFPM) machines are popular due to their higher power density and reduced size. In recent years development of electrical drives and other direct drive applications, axial flux machines are gaining more attention. AFPM machines have a problem of cogging torque that needs to be tackled carefully. Cogging torque produces electrical noise and torque ripples. Power of an AFPM machine is directly proportional to its diameter, which makes cogging torque a sensitive design parameter. Cogging torque is proportional to the square flux and change in reluctance, with respect to its position to the stator. This paper paper explores various cogging torque reduction techniques.

***Keywords:*** Cogging torque, axial flux permanent magnet machine, torque ripples reduction.

## I. Introduction

Cogging torque is often called no-load torque. It is caused by the attraction between rotor magnets and stator teeth. Cogging torque is undesirable and an important parameter to be considered in machine designing. Although it has no net value but degrades the performance of machines [1].

There are numerous methods available and investigated for cogging torque reduction in axial flux machines. Broadly these techniques can be divided into two categories. Rotor side modification technique and stator side modification technique [2]. Stator side modification techniques are slot skewing, teeth notching [4], and slot opening variation. The rotor side cogging torque reduction techniques include pole skewing, magnet shaping [5], pole arc to pole pitch ratio, and pole arc offset [7]. The cogging torque can also be modified with changing airgap length.

## II. Rotor Side Modification

In axial flux machines, it is convenient to modify rotor poles. It is possible to shape magnets for reducing cogging torque. In [2] different skewing techniques are used and investigated its effect on cogging torque. The rotor side modification is elaborated in the following sections.

### *A. Pole arc to pole pitch ratio*

Pole arc to pole pitch ratio is an important design parameter, its effect on cogging torque is very prominent [7]. This research investigated different pole arc to pole pitch ratios and reached to the conclusion that at the ratio of 0.68 the cogging torque is minimum. At 0.55 and 0.77 the cogging torque has the maximum value the results can be summarized as in the table below.

Table 1 table below shows the change in cogging torque with the change in pole arc [2, 7].

| **Pole arc** | 0.444 | 0.555 | 0.666 | 0.68 | 0.778 | 0.88 |
|---|---|---|---|---|---|---|
| **Cogging torque (Nm)** | 7.9 | 8 | 3.1 | 0.8 | 8 | 7.5 |

Table 1 shows the effect of pole arc on cogging torque.Using a suitable pole arc to pole pitch ratio is an easy, simple, and effective way to reduce cogging torque. The equation used to find the optimum value of pole arc to pole pitch ratio is as below [2].

$$\alpha_{p=}\frac{N-k}{N} \qquad (1)$$

Where αp is pole arc to pole pitch ratio, N= Ns/2p, Ns is the number of slots and 2p is the number of poles. [7], [8]. k= 1, 2, 3 ….N-, however, due to the fringing effect pole arc value is slightly more than that calculated in (1). To represent this increase, another factor k2 is added to (1)

$$\alpha_{p=}\frac{N-k1}{N} + k2 \qquad (2)$$

In (2) k2 represents the effect of fringing, its value is from 0.01-0.03. [8]

### *B. Pole skewing*

Pole skewing is another effective method to reduce cogging torque. The cogging torque is because of changing reluctance. The optimum value of skewing can be cited from [2][5].

$$\text{Maximum skew angle} = \frac{2\pi}{Nc} \qquad (3)$$

Where Nc is the least common multiple of stator slots and pole number. Different skewing techniques are possible [2][7]

[8]. However, skew angel is not the same as in (3) but slightly larger than that, in axial flux permanent machines. Magnet skewing is very easy to implement. M Aydin et al in [7] investigated different types of the skewing techniques, like triangular skew, double skew, parallel side skew, and trapezoidal skew that effectively reduced cogging torque. In [5] the research proposed the combination of short pitching and skewing of the magnetic poles, the result show that the combination of both short pitching and skewing is more effective than skewing alone.

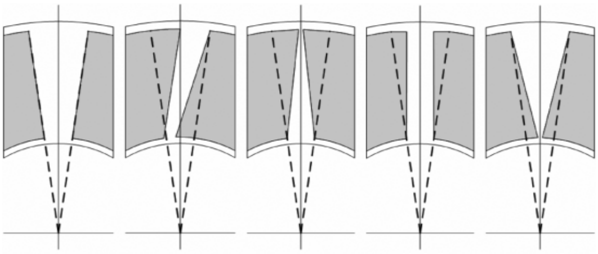


Figure 1: (a) Un skew (b) Conventional skew (c) Triangular skew (d) Parallel side magnet (e) Trapezoidal skew [9]
Figure 1 summary of the available skewing technique.

### *C. Magnetic Pole shaping*

Magnetic pole shaping is used by [3], to reduce cogging torque. In axial flux machines usually trapezoidal shapes are used, in that case the whole edge of rotor pole interact with edge of rotor teeth and produce high cogging torque. The torque can be reduced with managing the shape of magnetic pole in such a way that both the edges (stator teeth edge and rotor pole edge) do not interact with each other as a whole at the same time. With magnetic pole shaping it became possible to reduce this interaction.

Three magnetic pole edge and face shaping techniques are investigated by [3].

- Rounded edges of magnetic poles figure 2.
- Magnetic pole with concave face figure 3.
- Magnetic pole convex face figure 4.

Rounded edges pole as in the figure one, machine was analyzed by [3] for different values of radius r for rounding the edge. The rounding of edge makes the interaction between stator and rotor gradually and hence reduces the cogging torque. The cogging torque reduction is 63% (maximum) when the rounding length r is equal to slot opening width wsw.

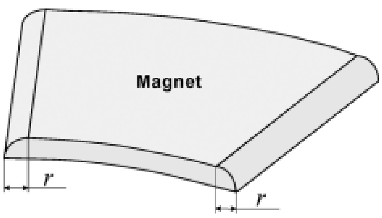


Figure 2: Magnetic pole with rounded edges.

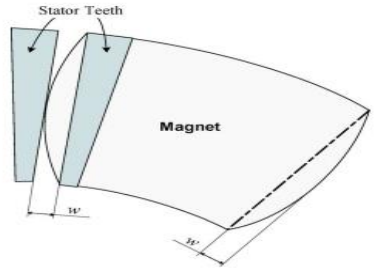


Figure 3: Magnetic pole with concave face.

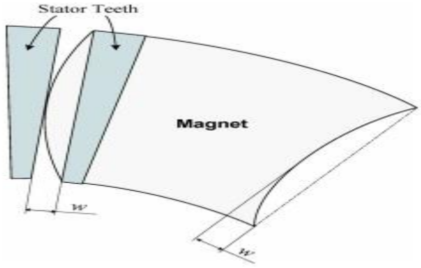


Figure 4: Magnetic pole with convex face.

The concave and convex face are shown in figure 2 and figure 3, both have similar effect on the cogging torque reduction, it makes the interaction between rotor and stator gradual, and hence reduces the cogging torque . The cogging torque is maximum when the rounded face length is equal to the slot opening width the reduction in cogging torque for concave face is 40%, and for convex face is 60%.

### *D. Double layer magnetic pole design for cogging torque reduction*

Double layer magnetic pole is investigated by [10], the investigation used double rotor single stator machine. Every rotor has 8 pole total 16 poles, and 48 slots at stator. Ring type winding and NN type rotor facing were considered for the design. In the analyses volume of magnet is kept constant, first the reference model was investigated and then the double layer was simulated with finite element method software.

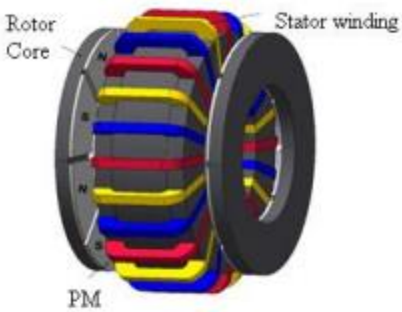


Figure 5: Double rotor single stator design of axial flux machine [10].

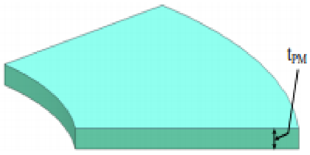

Figure 6: Conventional magnetic pole design with thickness tpm [10].

Figure 5 show axial flux machine design, while figure 6 show conventional model of magnetic pole.

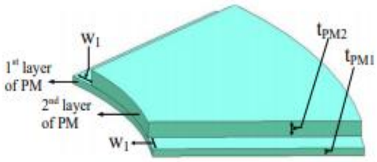

Figure 7: double layer magnetic pole [10].

Double layer pole shown in figure 7 the thickness and offset can be found with the following formula.

$$t_{pm2} = \frac{1 - x\, t_{sp}\left(t_{pm} - t_{pm1}\right)}{1 - x\left(t_{sp} - 2w_{1}\right)} \qquad (4)$$

$$x = \frac{P}{\pi\left(R_{o} + R_{i}\right)} \qquad (5)$$

Where $R_0$ outer diameter of stator and rotor core while $R_i$ is inner diameter. Thickness of layer 1 is $t_{pm1}$ and layer 2 is $t_{pm2}$, $W_1$ is offset between two layers. The finite element method result show that the cogging torque is reduced from 10.6 Nm of conventional design to 2.2 Nm of modified design, with less performance degradation.

### E. *Segmented magnetic pole skewing*

Segmented skewing is a low cost skewing technique investigated in [6]. Segmentation is techniques that also reduces eddy current losses in PM. The research used two segment magnetic pole and three segments magnetic pole and reached to result that regardless of pieces of magnet, this approach reduced the cogging torque significantly without effecting load ability of machine [6].

## III. STATOR SIDE MODIFICATION

It is also possible to modify stator of machine to reduce cogging torque. However, this method is avoided by designers because of the manufacturing complication [2]. Stator modification techniques to reduce cogging torque is further elaborated in the following sections.

### A. *Stator teeth displacement*

Stator displacement technique used by [1] for double rotor single stator axial flux machine to reduce cogging torque. The stator is sandwiched between two rotors, and stator have winding on both faces.

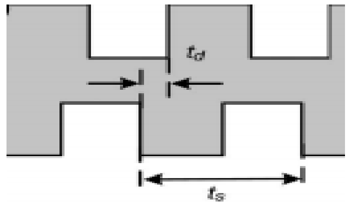

Figure 8: Stator slot displacement.

Figure 8 shows displacement of slots, ts is slot pitch td slot displacement. The author of [1] used a ratio kd = td / ts and investigated the stator for kd 0.13 0.46, and 0.86 the investigation concluded that cogging torque reduced 50% at kd 0.5.

### B. *Slot opening*

P. Kumar and R. K. Srivastava in [4] used different type of slot opening and reduced the cogging torque effectively. The research used a reference machine with parallel opening slot machine and then modified the opening. The author of the paper used trapezoidal opening, parallel opening, and skewed opening (conventional skew, double skew, consecutive opposite skew) that reduced the cogging torque as compared to open slot machines as shown in figure 9 (a), (b) and figure 10.

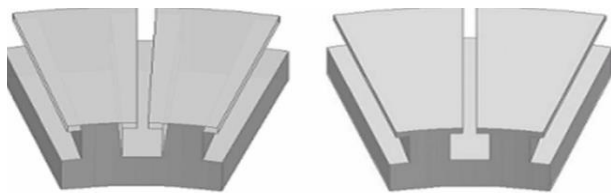
Figure 9: (a)Trapezoidal (b) Parallel l slot opening

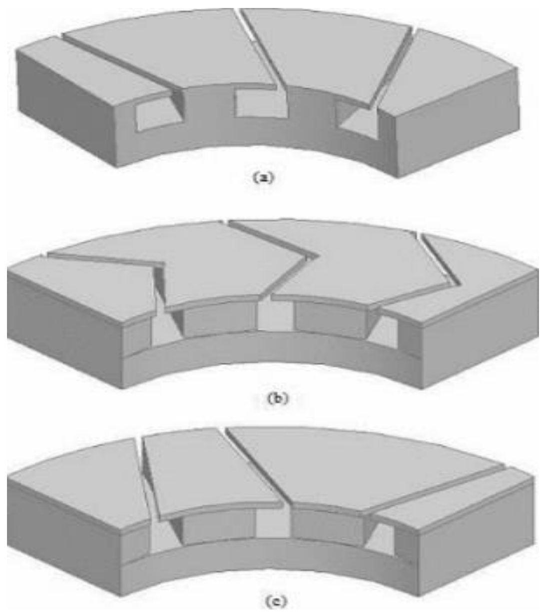

Figure 10: Slot opening modification (a) conventional skew (b) double skew (c) consecutive opposite skew

The paper also investigated 2mm, 3mm, and 5mm opening and compared the results, reached to the conclusion that the reduced slot opening also reduces cogging torque. . The results can be summarized as below.

- Parallel and trapezoidal shape opening have 90% and 91% reduction in torque.
- 2mm slot opening have 96.42 % reduction in cogging torque.
- Conventional skew has 97.75% reduction in cogging torque.
- Dual skew has 98.44% reduction in cogging torque.
- Consecutive opening opposite skew has 98.71 % reduction in cogging torque.

The consecutive opening opposite skew has maximum cogging torque reduction that is 98.71 % [4]. This is very significant reduction in the cogging torque.

### C. *Teeth notching*

Impact of teeth notching in flux switching axial flux machine was investigated in [9] and reached to the conclusion, that in flux switching permanent magnet machines teeth notching is effective to reduce cogging torque. The author investigated there different notching techniques as in figure with finite element method. Slot one S1 and slot two S2 dimension are as give in the table 2.

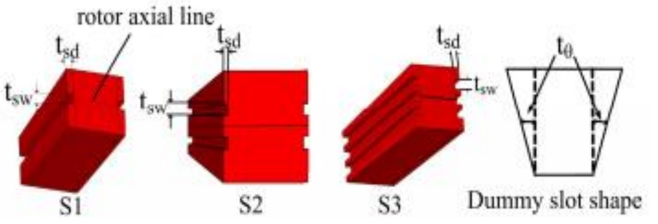


Figure 11: Show slot notch design slot 1 have one notch, slot 2 has two notches, slot 3 has three notches.[9]

Table 2: Result of optimum slot notches and comparison between slot 1 and slot 2 [9].

| Slot notching | No dummy slot | Slot 1 (S1) | Slot 2 (S2) |
|---|---|---|---|
| **slot width (tsw)** | -- | $3.96^0$ | $3^0$ |
| **Slot depth (tsd)** | -- | 1.01mm | 1.79mm |
| **Slot shape ($t_0$)** | -- | $0.53^0$ | $1.62^0$ |
| **Cogging torque** | 1.06Nm | 0.8264 Nm | 0.6087Nm |
| **Output torque** | 8.505 | 8.06Nm | 8.263Nm |

The finite element results for the dimensions given in the table 2 are, that cogging torque is reduced upto 22% by S1, and 43% by S2. The reduction in produced torque is 5.22% and 2.8% respectively [9] as shown in figure 11.

### D. *Slot opening displacement*

Slot opening displacement is a simple method to reduce cogging torque. The research [4] investigated the slot displacement of 1.8750 and 3.750 with 3D finite element method (FEM) the resultant cogging torque was 96% less than that of conventional machine [4].

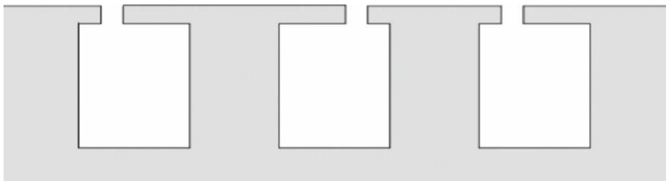

Figure 12: slot opening displacement of stator.

Figure 12 shows displacement of slot opening, slot opening can be away or toward each other, both will be having the same effect on cogging torque.

## CONCLUSION

Rotor side modification is the preferred technique for cogging reduction in AFPM. The rotor side modification is simple and effective compared to stator side modification. Skewing of rotor pole is very effective. The same technique can be used on stator side but it increases manufacturing complexity. Axial and radial slicing of poles can also be implemented on rotor side of AFPM machines.

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