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Effect of air gap on torque density for double-sided TORUS and AFIR slotted PM motors

By

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Abstract:

Double-sided axial flux PM motors (AFPM) are the most promising and widely used types. There are two topologies for slotted double-sided AFPM motors. Selecting an AFPM motors with high torque density is an important parameter in applications. So, comparison of torque density between different topologies of double-sided AFPM motors seems to be necessary.

In this paper, the sizing equations of axial flux slotted one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) type PM motors is presented and comparison of the TORUS and AFIR topologies in terms of torque density is illustrated. Finally a high torque double-sided slotted AFPM motor is introduced in the paper.

Keywords:

Axial flux PM motors (AFPM), torque density and electric loading.

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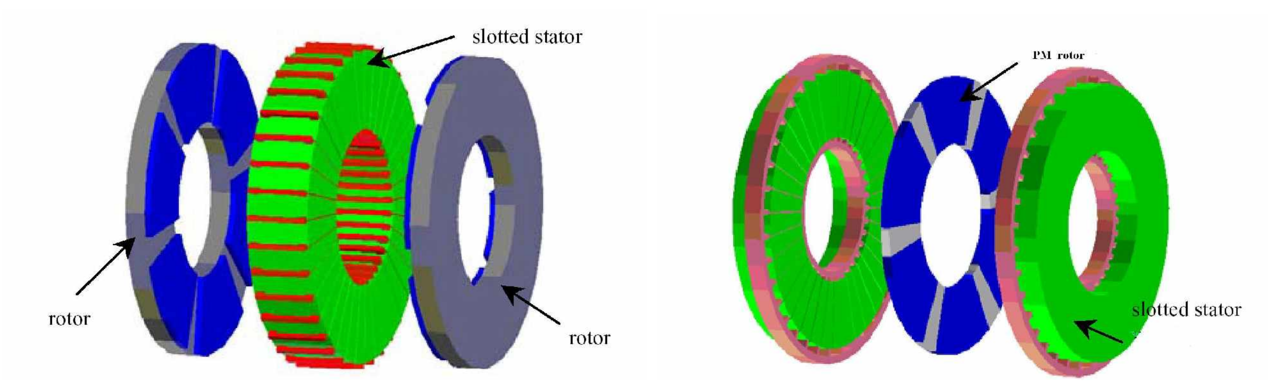
1. Introduction:

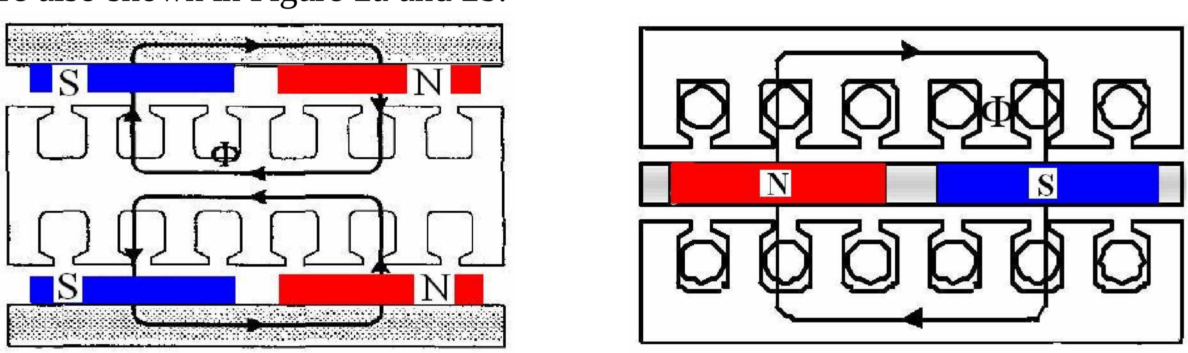
AFPMs (commonly called disc machines) are synchronous machines. In conventional machines, the air gap flux density has normally radial direction; in AFPMs, the air gap flux density presents mainly axial direction. In general, AFPMs exhibit an axial length much smaller than the length of a conventional motor of the same rating [1].
There are two topologies for slotted double-sided AFPM motors. These topologies are axial flux slotted one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) type PM motors. Two AFPM motors and their acronyms are selected TORUS-S (Axial flux slotted external rotor internal stator PM stator) and AFIR-S (Axial flux slotted internal rotor external stator PM motor) for detailed analysis. The stator cores of the machine are formed by tape wound core with a lap and short-pitched polyphase AC winding located in punched stator slots. The rotor structure is formed by the axially magnetized NdFeB magnets [3-4]. The topologies used in the study are illustrated in figure (1).



(a) (b)

Figure (1): Axial flux slotted (a) one-stator-two-rotor TORUS-S type [4] (b) two-stator-one-rotor AFIR-S type [3]

Flux directions of both AFIR and TORUS slotted topologies at the average diameter in 2D are also shown in Figure 2a and 2b.



(a) (b)

Figure (2): One pole pair of the (a) TORUS-S [4] (b) AFIR-S [3]

Selecting a double-sided AFPM motors with high torque density is an important parameter, especially in electrical vehicle applications. So, comparison of torque density between different topologies of double-sided AFPM motors seems to be necessary.
Increasing the air gap length, maximum torque density will change in AFPM motors. These changes are not the same in different topologies. Maximum torque density of TORUS-S is higher than AFIR-S in large air gap length.
In Section2, the generalized sizing approach for TORUS-S and AFIR-S types PM motors is briefly discussed. Then, some results of comparisons of the TORUS-S and AFIR-S topologies in terms of torque density are illustrated in Section3. The conclusions are given in Section 4.

2. Sizing equations of AFPM motors:

and the per unit portion of the total air gap area spanned by the salient poles of the machine (if any), N_{ph} is the number of turn per phase, Bg is the flux density in the air gap, f is the converter frequency, p is the machine pole pairs, λ is the diameter ratio for AFPM defined as D_i / D_o, D_o is the diameter of the machine outer surface, D_i is the diameter of the machine inner surface. The peak phase current in (1) is given by:

$$I_{pk} = A \pi K_i \frac{1+\lambda}{2} . \frac{D_o}{2 m_1 N_{ph}} \quad (5)$$

Where, m_1 is number of phases of each stator and A is the electrical loading. Combining (1) through (5), the general purpose sizing equations take the following form for AFPM.

$$P_{out} = \frac{m}{m_1} \frac{\pi}{2} K_e K_p K_i A B_g \eta \frac{f}{p} (1-\lambda^2)(\frac{1+\lambda}{2}) D_o^3 \quad (6)$$

The machine power density for the total volume can be defined as

$$P_{den} = \frac{P_{out}}{\frac{\pi}{4} D_{tot}^2 L_{tot}} \quad (7)$$

Where, D_{tot} is the total machine outer diameter including the stack outer diameter and the protrusion of the end winding from the iron stack in the radial direction, L_{tot} is the total length of the machine including the stack length and the protrusion of the end winding from the iron stack in the axial direction [2-4].

2.1. Sizing equations for the TORUS-NS:

The generalized sizing equation approach can easily be applied to axial flux permanent magnet TORUS type motor [4]. The outer surface diameter D_o can be written as

$$D_o = \left(P_{out} \Big/ \frac{\pi m}{2 m_1} K_e K_p K_i A B_g \eta \frac{f}{p} (1-\lambda^2)(\frac{1+\lambda}{2}) \right)^{1/3} \quad (8)$$

The machine total outer diameter D_{tot} for the TORUS-S motor is given by

$$D_{tot} = D_o + 2 W_{cu} \quad (9)$$

Where, W_{cu} is the protrusion of the end winding from the iron stack in the radial direction. For the back-to-back wrapped winding, protrusions exist toward the axis of the machine as well as towards the outsides and can be calculated as

$$W_{cu} = \frac{D_i - \sqrt{D_i^2 - \left(2 A D_g \big/ K_{cu} J_s \right)}}{2} \quad (10)$$

Where, Dg is the average diameter of the machine, J_s is the current density and K_{cu} is the copper fill factor.

The axial length of the machine L_e is given by

$$L_e = L_s + 2L_r + 2g \qquad (11)$$

Where, L_s is axial length of the stator, L_r is axial length of the rotor and g is the air gap length. The axial length of the stator L_s *is*

$$L_s = L_{cs} + 2W_{cu} \qquad (12)$$

The axial length of the stator core L_{cs} can be written as

$$L_{cs} = \frac{B_g \pi \alpha_p D_o (1+\lambda)}{4pB_{cs}} \qquad (13)$$

Where, B_{cs} is the flux density in the stator core and α_p is the ratio of average air gap flux density to peak air gap flux density. Since there is no rotor core in rotor PM topologies, the axial length of rotor Lr is

$$L_r = L_{PM} \qquad (14)$$

Also, the axial length of the rotor core L_{cr} is

$$L_{cr} = \frac{B_u \pi D_o (1+\lambda)}{8pB_{cr}} \qquad (15)$$

Where, B_{cr} is the flux density in the rotor disc core, and B_u is the attainable flux density on the surface of the PM. The PM length L_{PM} can be calculated as

$$L_{PM} = \frac{\mu_r B_g}{B_r - \left(\frac{K_f}{K_d} B_g\right)} (g + W_{cu}) \qquad (16)$$

Where, μ_r is the recoil relative permeability of the magnet, B_r is the residual flux density of the PM material, K_d is the leakage flux factor, K_c is the carter factor, $K_f = B_{gpk}/B_g$ is the peak value corrected factor of air gap flux density in radial direction of the AFPM motor. These factors can be obtained using FEM analysis [4].

2.2. Sizing equations for the AFIR-NS:

The concept of Double-sided Axial Flux two-stator-one-rotor (AFIR) type PM motors was presented in [2-3]. The outer surface diameter D_o is obtained from (6).

$$D_o = \left(2P_{out} \Big/ \frac{\pi m}{2m_1} K_e K_p K_i A B_g \eta \frac{f}{p} (1-\lambda^2)(\frac{1+\lambda}{2}) \right)^{1/3} \qquad (17)$$

The machine total outer diameter D_{tot} for the AFIR type machines is given as

$$D_{tot} = D_o + 2W_{cu} \qquad (18)$$

Where, W_{cu} is the protrusion of the end winding from the iron stack in the radial direction and can be calculated as

$$W_{cu} = \frac{D_i - \sqrt{D_i^2 - \left({}^{A D_g}\!/\!{}_{K_{cu} J_s} \right)}}{2} \quad (19)$$

The axial length of the machine L_e is

$$L_e = L_r + 2L_s + 2g \quad (20)$$

Where, Ls is axial length of the stator, L_r is axial length of the rotor and g is the air gap length. The axial length of a stator L_s is

$$L_s = L_{cs} + 2W_{cu} \quad (21)$$

Where, L_{cs} is the axial length of the stator core. The axial length of the stator core L_{cs} *can* be written as

$$L_{cs} = \frac{B_g \pi \alpha_p D_o (1+\lambda)}{8p B_{cr}} \quad (22)$$

Since there is no rotor core in rotor PM topologies, the axial length of rotor Lr is

$$L_r = L_{PM} \quad (23)$$

The PM length L_{PM} can be calculated as

$$L_{PM} = \frac{2\mu_r B_g}{B_r - \left(\frac{K_f}{K_d} B_g \right)} (g + W_{cu}) \quad (24)$$

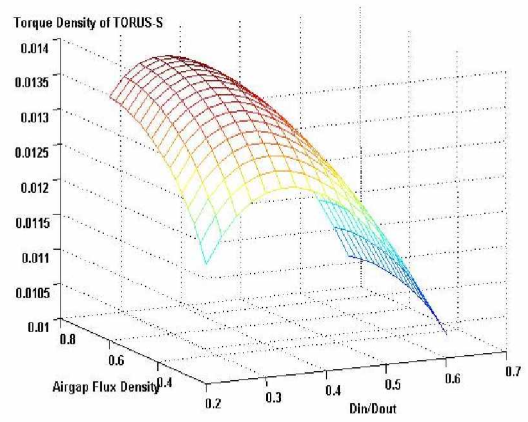
3. Comparison of TORUS-S and AFIR-S

Comparison of two different Double-sided axial flux slotted PM motors in terms of torque density is accomplished for 10KW output power, 4 poles and 60Hz drive. In this comparison, other constant parameters of motors are tabulated in table1.

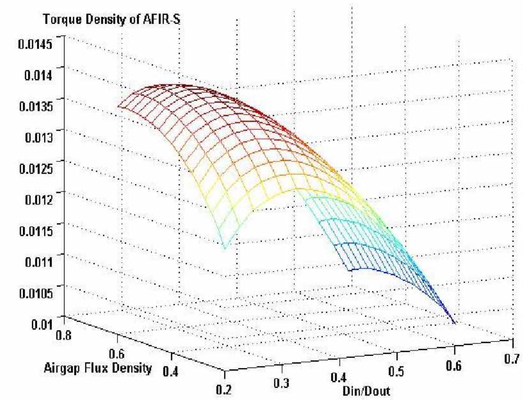
Table (1): Constant parameters of motors in comparison

Number of phases	3
Slot fill factor	0.8
Pole arc ratio	0.75
Slot per Pole per Phase	1
flux density in stator	1.5 T
flux density in rotor	1.5 T
Efficiency	90%
Residual flux density of PM	1.1 T

In AFPM motors, the air gap flux density and diameter ratio are the two important design parameters which have significant effect on the motor characteristics. Therefore, in order to optimize the motor performance, the diameter ratio and the air gap flux density must be chosen carefully. Figure (3) shows the torque density variation as a function of air gap flux density and the diameter ratio for the AFIR-S and TORUS-S motors.



(a)



(b)

Figure (3): Torque density vs. air gap flux density and diameter ratio for A=30000 (A/m), g=1 (mm) , J_s=9000000 (A/m^2) a) TORUS-S b) AFIR-S

As can be seen from figure (3b), the maximum torque density occurs at Bg=0.51 (T) and $\lambda = 0.27$. In various air gap length, the maximum torque density occurs in different *Bg* and λ. Table (2) shows maximum torque density with corresponding *Bg* and λ.

Table (2): Maximum torque density with corresponding Bg and λ

Type	g (mm)	*Bg* (T)	λ	Maximum torque density (N.m/cm^3)
TORUS-S	1	0.56	0.3	0.014
	1.5	0.57	0.3	0.0137
	2	0.58	0.27	0.0134
AFIR-S	1	0.51	0.27	0.014
	1.5	0.52	0.27	0.0136
	2	0.53	0.28	0.0133

Figure (4) shows the maximum torque density variation as a function of air gap length for the AFIR-S and TORUS-S motors for A=30000 (A/m), Js=9000000 (A/m^2).

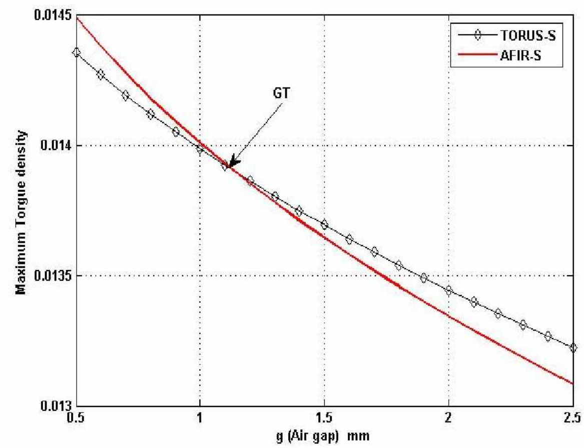


Figure (4): Maximum power density AFIR-S and TORUS-S vs. air gap length

In special air gap length (this air gap length is called G_T) maximum torque density of AFIR-S and TORUS-S motors will be the same. Considering figure (4), it can be concluded that in large air gap length, slotted TORUS motor has high power density.

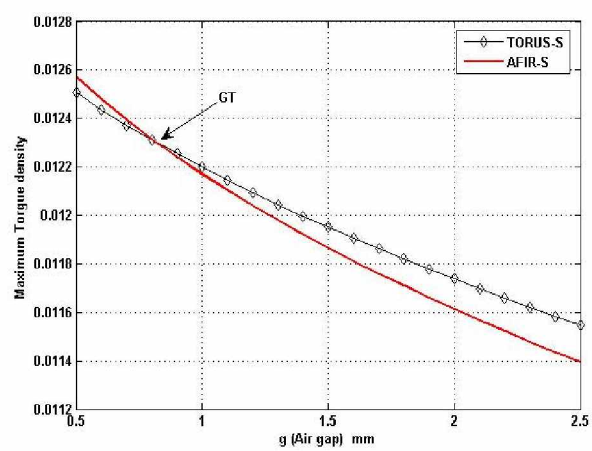


Figure (5): Maximum torque density AFIR-S and TORUS-S vs. air gap length

The considerable point is that the value of G_T will vary when the electrical loading *'A'* changes.

Figure (5) shows the variation of the maximum torque density as a function of air gap length in A=25000 (A/m) for the AFIR-S and TORUS-S motors.

Figure (6) shows the variation of the maximum torque density as a function of air gap length in A=35000 (A/m) for the AFIR-S and TORUS-S motors also.

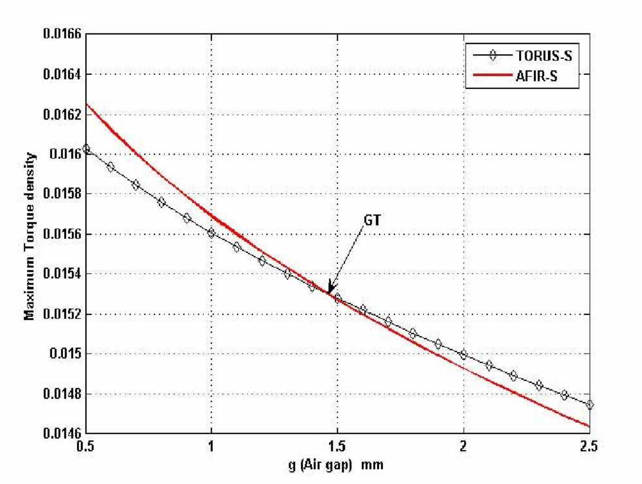


Figure (6): Maximum torque density
AFIR-S and TORUS-S vs. air gap length

According to figure (6) it can be concluded that point G_T is shifted to larger air gaps and this means that in smaller air gaps AFIR-S motor has higher maximum torque density.

According to figure 5 it can be concluded that point G_T is shifted to smaller air gaps and this means that in higher air gaps TORUS-S motor has higher maximum torque density. Other value of G_T for various A is tabulated in table (3).

Table (3): Other value of GT
for Various A

A *(A/m)*	G_T *(mm)*
15000	0.43
20000	0.58
25000	0.81
30000	1.12
35000	1.46
40000	1.93

4. Conclusions:

Selecting an AFPM motors with higher torque density is an important parameter in applications. The main goal of this paper has been introduce to double-Sided Axial Flux Slotted PM Motors with maximum torque density. There are two topologies for slotted double-sided AFPM motors.
The maximum torque density is changed by different value of the air gap and electrical

loading. TORUS-S topology has high torque density in low electrical loading. But, AFIR-S topology has high torque density in high electrical loading.

References:

S. Huang, J. Luo, F. Leonardi, and T. A. Lipo, “A General Approach to Sizing and Power Density Equations for Comparison of Electrical Machines,” IEEE Trans. On Energy Conversion, IA-34, No.1, pp.92-97, 1998.

S. Huang, J. Luo, F. Leonardi and T. A. Lipo, “A Comparison of Power Density for Axial Flux Machines Based on the General Purpose Sizing Equation”, IEEE Trans. on Energy Conversion, Vol.14, No.2 June 1999, pp. 185-192.

Aydin, M.; Huang, S.; Lipo, T.A.; “Optimum design and 3D finite element analysis of nonslotted and slotted internal rotor type axial flux PM disc Machines”, Power Engineering Society Summer Meeting, 2001. IEEE Volume 3, 15-19 July 2001 Page(s):1409 - 1416 vol.3.

Aydin, M.; Surong Huang; Lipo, T.A.; “Design and 3D electromagnetic field analysis of non-slotted and slotted TORUS type axial flux surface mounted permanent magnet disc machines”, Electric Machines and Drives Conference, 2001. IEMDC 2001. IEEE International2001 Page(s):645 – 651.