Global Journal of Pure and Applied Mathematics.
ISSN 0973-1768 Volume 7, Number 2 (2011), pp. 147-156
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http://www.ripublication.com/gjpam.htm

Comparison of Torque Density for Three Phase Double Sided Slot-less AFPM Motors

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Abstract

Selecting an AFPM motors with high torque densities 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 slot-less one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) type PM motors are presented and comparison of the TORUS and AFIR topologies in terms of torque density is illustrated. Finally a high torque slot-less double-sided AFPM motor is introduced in the paper.

Keywords: axial flux PM motors (AFPM), torque density and electrical loading.

List of symbols

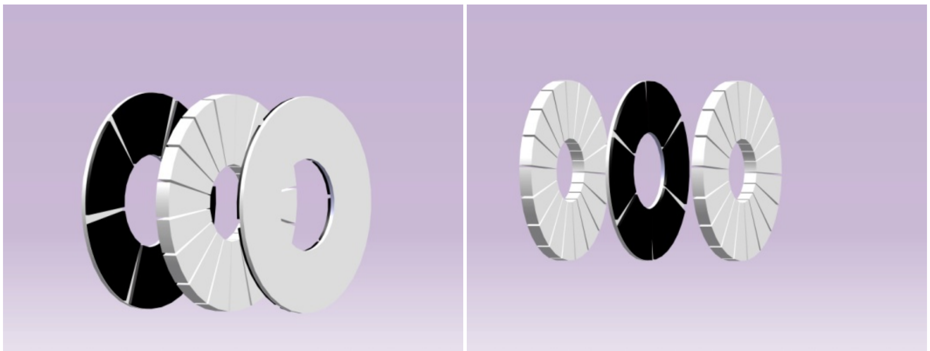
E_{pk}	peak value of air gap EMF
I_{pk}	peak phase current
m	number of phases
T	period of one cycle of the EMF
I_{rms}	rms value of the phase current
K_e	EMF factor
K_w	winding distribution factor
N_{ph}	number of turn per phase
Bg	flux density in the air gap
f	converter frequency
p	machine pole pairs
D_o	diameter of the machine outer surface
D_i	diameter of the machine inner surface

D_{tot}	total machine outer diameter
L_{tot}	total length of the machine
W_{cu}	protrusion of the end winding
L_e,	axial length of the stator
L_{cs}	axial length of the stator core
L_{PM}	PM length

Introduction

Double-sided axial flux PM motors (AFPM) are most promising and widely used types. 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. The stator of the slot-less AFPM machine is realized by slot-less tape wound core with AC polyphase air gap windings and the rotor structure is formed by axially magnetized fan-shaped surface mounted Neodymium Iron Boron (NdFeB) permanent magnets. In general, AFPMs exhibit an axial length much smaller than the length of a conventional motor of the same rating [1,3].

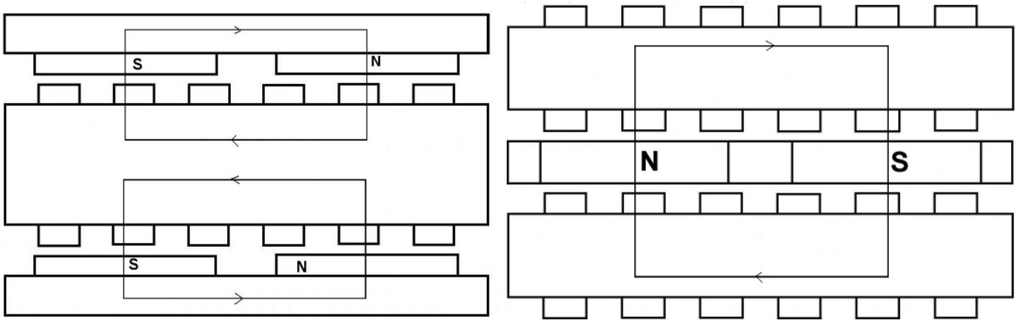
There are two topologies for slot-less double-sided AFPM motors. These topologies are axial flux slot-less one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) type PM motors. Two AFPM motors and their acronyms are selected TORUS-NS (Axial flux slot-less external rotor internal stator PM motor) and AFIR-NS (Axial flux slot-less internal rotor external stator PM motor) for detailed analysis. The stator of the slot-less AFPM motors are realized by slot-less tape wound core with AC polyphase air gap windings that are back-to-back wrapped around the stator core. The rotor structure is formed by axially magnetized surface mounted Neodymium Iron Boron (NdFeB) permanent magnets and shaft. Detailed views of the stator and rotor structures of the TORUS-NS and AFIR-NS motor are given in Fig.1. The portions between the windings are assumed to be filled with epoxy resin as in all slot-less structures in order to increase the robustness of the structure and provide better conductor heat transfer. Moreover, the radial portions of the air gap windings are used for the torque production [2-6].



(a) (b)

Figure 1: Axial flux slot-less (a) one-stator-two-rotor TORUS-NS type (b) two-stator-one-rotor AFIR-NS type.

Flux directions of both AFIR and TORUS slot-less topologies at the average diameter in 2D are also shown in Fig.2a and 2b.



(a) (b)

Figure 2: One pole pair of the (a) TORUS-NS (b) AFIR-NS.

Sizing equations of AFPM Motors

In general, if stator leakage inductance and resistance are neglected, the output power for axial flux permanent magnet motor can be expressed as

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

Where, m_1 is number of phases of each stator, m is number of phases of the machine, K_p is termed the electrical power waveform factor, K_e is the EMF factor which incorporates the winding distribution factor K_w and the per unit portion of the total air gap area spanned by the salient poles of the machine (if any), K_i is the current waveform factor, A is the electrical loading, η is machine efficiency, N_{ph} is the number of turn per phase, B_g 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 AFPG 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[1,3-6].

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

$$P_{den} = \frac{P_{out}}{\frac{\pi}{4} D_{tot}^2 L_{tot}} \tag{2}$$

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 [9-13].

Sizing equations for the TORUS-NS

The generalized sizing equation approach can easily be applied to axial flux permanent magnet TORUS type motor [3].

The outer surface diameter D_o can be written as

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

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

$$D_{tot} = D_o + 2W_{cu} \tag{4}$$

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

$$W_{cu} = \frac{D_i - \sqrt{D_i^2 - \left(2AD_g \Big/ K_{cu} J_s \right)}}{2} \tag{5}$$

where D_g 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

$$L_e = L_s + 2L_r + 2g \tag{6}$$

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*

$$L_s = L_{cs} + 2W_{cu} \tag{7}$$

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

$$L_{cs} = \frac{B_g \pi \alpha_p D_o (1+\lambda)}{4p B_{cs}} \tag{8}$$

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

$$L_r = L_{PM} \tag{9}$$

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

$$L_{cr} = \frac{B_u \pi D_o (1+\lambda)}{8p B_{cr}} \tag{10}$$

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

$$L_{PM} = \frac{\mu_r \, B_g}{B_r - \left(\frac{K_f}{K_d} B_g \right)} (g + W_{cu}) \tag{11}$$

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 [1, 3].

Sizing equations for the AFIR-NS

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

$$D_o = \left(2P_{out} \Big/ \frac{\pi \, m}{2m_1} K_e \, K_p K_i A B_g \, \eta \frac{f}{p} (1 - \lambda^2)(\frac{1+\lambda}{2}) \right)^{1/3} \tag{12}$$

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

$$D_{tot} = D_o + 2W_{cu} \tag{13}$$

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

$$W_{cu} = \frac{D_i - \sqrt{D_i^2 - \left(AD_g \Big/ K_{cu} \, J_s \right)}}{2} \tag{14}$$

The axial length of the machine L_e is

$$L_e = L_r + 2L_s + 2g \tag{15}$$

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 a stator L_s is

$$L_s = L_{cs} + 2W_{cu} \tag{16}$$

where L_{cs} is the axial length of the stator core.

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

$$L_{cs} = \frac{B_g \, \pi \alpha_p \, D_o (1 + \lambda)}{8p \, B_{cr}} \tag{17}$$

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

$$L_r = L_{PM} \tag{18}$$

The PM length L_{PM} can be calculated as

$$L_{PM} = \frac{2\mu_r B_g}{B_r - \left(\frac{K_f}{K_d} B_g \right)} (g + W_{cu}) \tag{19}$$

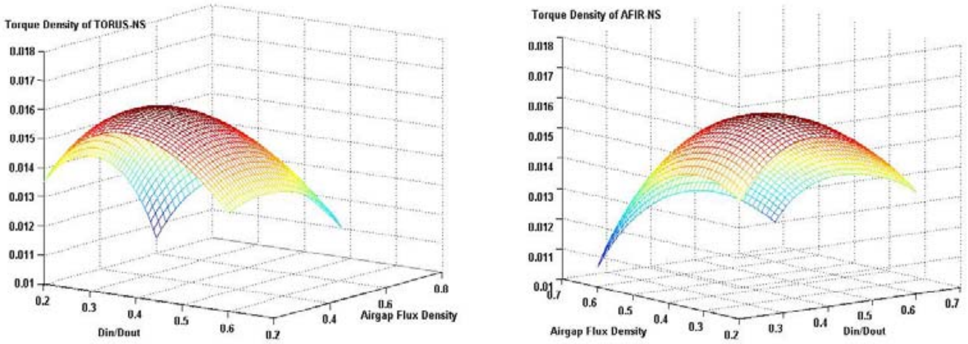
Comparisons of TORUS-NS and AFIR-NS

Comparison of two different Double-sided axial flux slot-less PM motors in terms of torque density is accomplished for 10 Kw output power, 6 poles and 60Hz drive. In this comparison, other constant parameters of motors are tabulated in table1.

Table1: Constant parameters of motors.

Number of phases	3
Slot fill factor	0.85
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%
PM Residual flux density	1.1 T

In AFPM motors, the air gap flux density, Bg and diameter ratio, λ and 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. Fig.3 shows the torque density variation as a function of air gap flux density and the diameter ratio for the AFIR-NS and TORUS-NS 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-NS b) AFIR-NS.

As can be seen from Fig3b, the maximum torque density occurs at Bg=0.312 T and $\lambda = 0.34\tilde{3}$. Varying air gap length, maximum torque density occurs in different Bg and λ. Table2 shows maximum torque density with corresponding Bg and λ.

Table2: Maximum torque density with corresponding Bg and λ.

Type	*g (mm)*	*Bg (T)*	λ	*Maximum torque density (N.m/cm^3)*
TORUS-NS	1	0.32	0.36	0.0161
	1.5	0.32	0.365	0.0155
	2	0.32	0.37	0.0151
AFIR-NS	1	0.31	0.34	0.0161
	1.5	0.3	0.35	0.0152
	2	0.3	0.35	0.0149

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

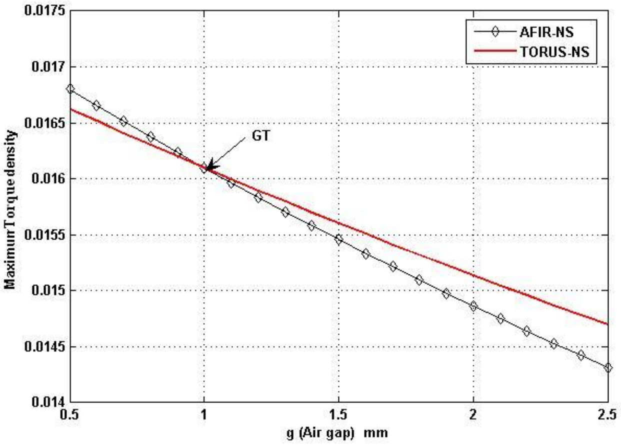


Figure 4: maximum torque density AFIR-S and TORUS-NS vs. air-gap length.

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

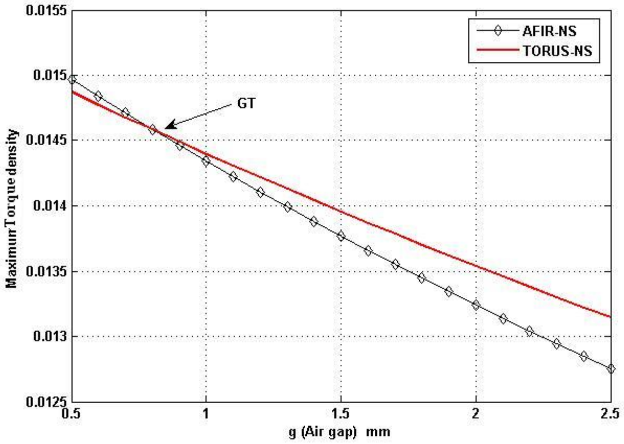


Figure 5: maximum torque density AFIR-NS and TORUS-NS vs. air-gap length.

The considerable point is that the value of G_T will vary when the electrical loading 'A' and current density 'Js' changes. Fig.5 shows the maximum torque density variation as a function of air gap length in A=25000 (A/m) for the AFIR-NS and TORUS-NS motors. Fig.6 shows the maximum torque density variation as a function of air gap length in A=35000 (A/m) for the AFIR-NS and TORUS-NS motors also.

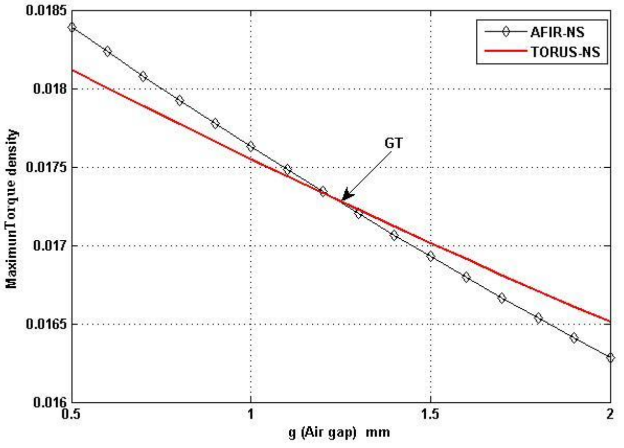


Figure 6: maximum torque density AFIR-NS and TORUS-NS vs. air-gap length.

According to Fig.5 it can be concluded that point G_T is shifted to larger air gaps and this means that in smaller air gaps AFIR-NS motor has higher maximum torque density. According to Fig.6 it can be concluded that point G_T is shifted to smaller air gaps and this means that in higher air gaps TORUS-NS motor has higher maximum torque density. Other value of G_T for various A is tabulated in table 3.

Table 3: Other value of G_T for Various A.

A (KA/m)	*G_T (mm)*
15	0.45
20	0.62
27	0.85
30	1
37	1.3
45	1.6

Conclusion

Selecting an AFPM motors with higher torque density is an important parameter in applications. The main goal of this paper has been introducing to double-Sided Axial Flux slot-less PM Motors with maximum torque density. There are two topologies for slot-less double-sided AFPM motors.

The maximum torque density is changed by different value of the air gap and electrical loading TORUS-NS topology has high torque density in low electrical loading. But, AFIR-NS topology has high torque density in high electrical loading

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IEEE TRANSACTIONS ON MAGNETICS, VOL. 42, NO. 10, OCTOBER 2006.

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