Evaluation of Power Density for Three Phase Double-Sided Axial Flux Slotted PM Generator

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ABSTRACT

There are two topologies for slotted double-sided axial flux permanent magnet generator (AFPG). Choosing an AFPG with high power density is an important parameter in applications. Hence, power density Evaluation between double-sided AFPM generators topologies is necessary. In this paper, the sizing equations of axial flux slotted one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) type PM generators is presented and comparison of the TORUS and AFIR topologies in terms of power density is illustrated. Finally a high power double-sided AFPG is introduced in the paper.

KEYWORDS

Axial flux, Generator, Power density, PM

1. INTRODUCTION

The BLDC generator is a kind of permanent-magnet (PM) generator that has permanent magnets inside the machine. In conventional machines, the air gap flux density has normally radial direction; in AFPGs, the air gap flux density presents mainly axial direction. In general, AFPGs exhibit an axial length much smaller than the length of a conventional generator of the same rating [1-4].

Two topologies of slotted double-sided AFPGs are axial flux slotted one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR). Two AFPGs 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 generator) for detailed analysis [5-7].

The stator cores of the machine are formed by tape wound core with a lap and short-pitched poly phase AC winding located in punched stator slots. The rotor structure is formed by the axially magnetized NdFeB magnets [1,6, 10-13].

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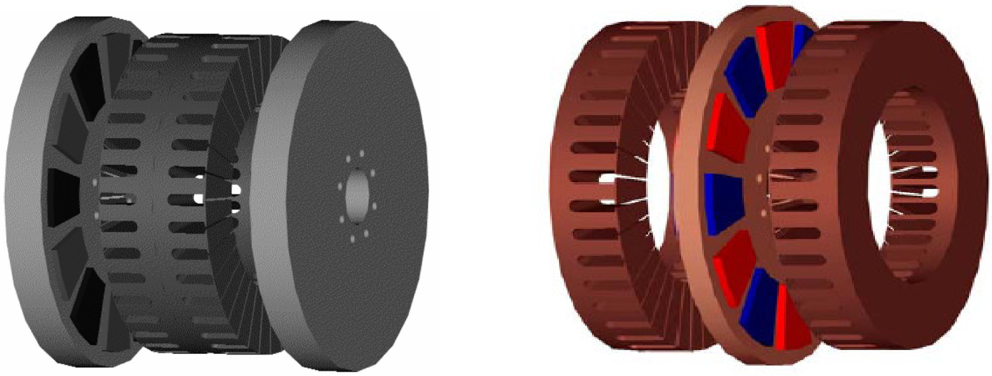
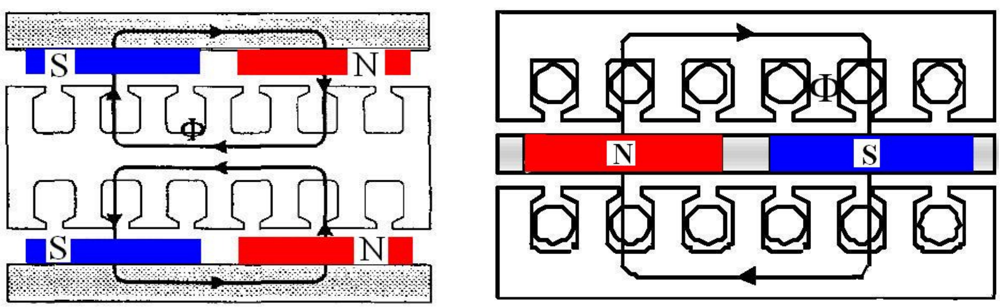


(a) (b)

Figure1. Axial flux slotted (a) one-stator-two-rotor TORUS-S type (b) two-stator-one-rotor AFIR-S type

Figure1 are illustrated the topologies used in this article. Figure2 is also illustrated Flux directions of AFIR and TORUS slotted topologies.



(a) (b)

Figure2. One pole pair of the (a) TORUS-S [6] (b) AFIR-S [5]

Selecting double-sided AFPGs with high power density is an important parameter. So, comparison of power density between different topologies of double-sided AFPGs seems to be necessary [1, 3, 6-8].

Increasing the air gap length, maximum power density will change in AFPGs. In Section2, the generalized sizing approach for TORUS-S and AFIR-S types PM generators is briefly discussed. The power density comparisons and some results of TORUS-S and AFIR-S topologies are presented in Section 4.

2. SIZING EQUATION of AFPGs

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

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

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

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

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].

2.1. Sizing equations for the TORUS-S

Sizing equation of axial flux permanent magnet TORUS type generator can easily be calculated according to above equations [1, 6, and 11]. The outer surface diameter D_o can be written as

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

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

$$D_{tot} = D_o + 2W_{cu} \qquad (4)$$

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

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

Where, D_g is the average diameter of the machine, J_s is the current density and K_{cu} is the copper fill factor. Note for the slotted topology machines the depth of the stator slot for slotted generators is L_{ss}=W_{cu}.

The axial length of the machine L_e is given by

$$L_e = L_s + 2L_r + 2g \qquad (6)$$

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*

$$L_s = L_{cs} + 2L_{ss} \qquad (7)$$

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

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

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.

The axial length of rotor L_r becomes

$$L_r = L_{cr} + L_{PM} \quad (9)$$

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

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

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

$$L_{PM} = \frac{\mu_r B_g}{B_r - \left(\frac{K_f}{K_d} B_g \right)} K_c g \quad (11)$$

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 AFPG *generator*. These factors can be obtained using FEM analysis [1], [6-10].

2.2. Sizing equations for the AFIR-S

Also, sizing equation of axial flux permanent magnet two-stator-one-rotor (AFIR) type generator can easily be calculated according to above equations [1, 6, and 11].
The outer surface diameter D_o is obtained from (1).

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

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

$$D_{tot} = D_o + 2W_{cu} \quad (13)$$

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

$$W_{cu} = \frac{(0.46-0.62)D_o}{p} \quad (14)$$

The axial length of the machine L_e is

$$L_e = L_r + 2L_s + 2g \quad (15)$$

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 stator L_s is

$$L_s = L_{cs} + d_{ss} \quad (16)$$

Where, L_{cs} is the axial length of the stator core, and the depth of the stator slot for slotted machines d_{ss} is

$$d_{ss} = \frac{D_i - \sqrt{D_i^2 - \left(2 A D_g \Big/ \alpha_s K_{cu} J_s \right)}}{2} \quad (17)$$

Where, α_s is the ratio of stator teeth portion to the stator pole.
The axial length of the stator core L_{cs} can be written as

$$L_{cs} = \frac{B_g \pi \alpha_p D_o (1+\lambda)}{8p B_{cr}} \quad (18)$$

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

$$L_r = L_{PM} \quad (19)$$

The PM length L_{PM} can be calculated as

$$L_{PM} = \frac{2\mu_r B_g}{B_r - \left(\frac{K_f}{K_d} B_g \right)} K_c g \quad (20)$$

3. COMPAROSON of TORUS-S and AFIR-S

Comparison of two different Double-sided axial flux slotted PM generators in terms of power density is accomplished for 14 Hp output power, 4 poles and 60Hz drive. In this comparison, other constant parameters of generators are tabulated in table1.

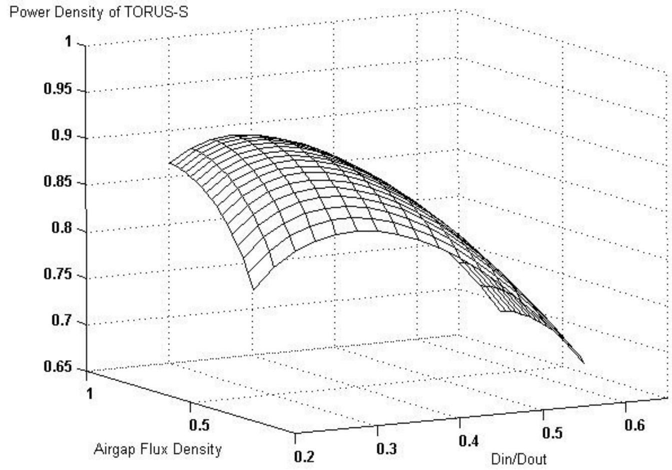
In AFPG generators, the air gap flux density and diameter ratio are the two important design parameters which have significant effect on the generator characteristics. Therefore, in order to optimize the generator performance, the diameter ratio and the air gap flux density must be chosen carefully.

Variation of power density as a function of air gap flux density and the diameter ratio for the AFIR-S and TORUS-S generators are shown in Figure3.

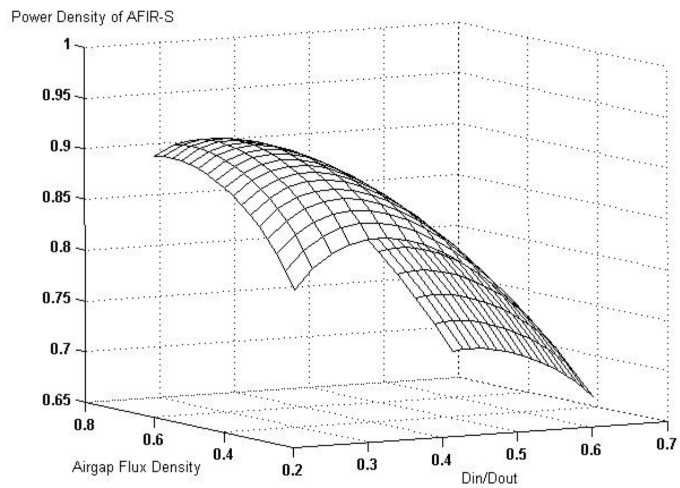
Table1. Constant parameters of *generators* in comparison

Number of phases	3
Slot fill factor	0.80
Pole arc ratio	0.75
flux density in stator	1.55 T
flux density in rotor	1.55 T
Efficiency	90%
Residual flux density of	1.2 T

As can be seen from Figure3b, the maximum power density occurs at Bg=0.528 (T) and $\lambda = 0.261$. In various air gap length, the maximum power density occurs in different Bg and λ. Table2 shows maximum power density with corresponding Bg and λ.



(a)



(b)

Figure3. Power density vs. air-gap flux density and diameter ratio for A=20000 (A/m), g=1 (mm), J_s=6000000 (A/m^2) a) TORUS-S b) AFIR-S

Table2. Maximum power density with corresponding Bg and λ

Type	g (mm)	*Bg*	λ	Maximum power
TORUS-S	1	0.585	0.29	0.92
	1.5	0.569	0.271	0.91
	2	0.565	0.271	0.89
	2.5	0.569	0.271	0.878
AFIR-S	1	0.528	0.261	0.925
	1.5	0.518	0.261	0.902
	2	0.507	0.26	0.884
	2.5	0.518	0.251	0.87

The maximum power density is changed by variation of air gap length. These variations are shown for the AFIR-S and TORUS-S generators for A=20000 (A/m), Js=6000000 (A/m2) in figure4.

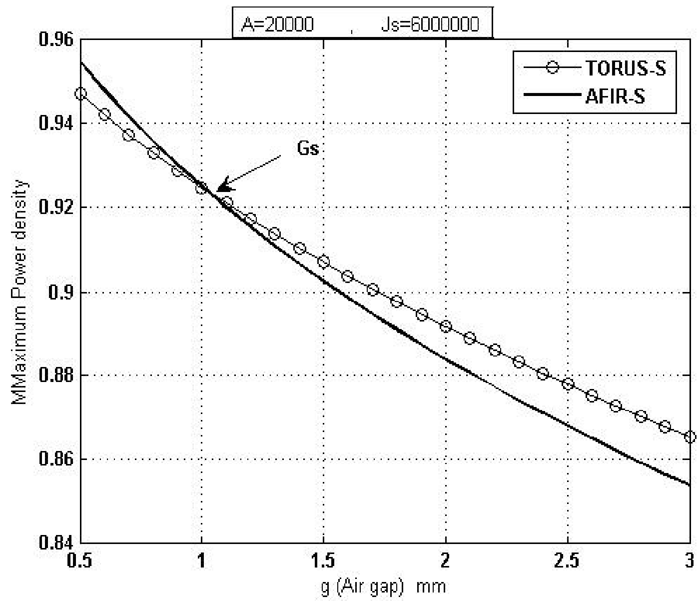


Figure4. Maximum power density AFIR-S and TORUS-S vs. air gap length

Maximum power density of two types of generators will be the same In special air gap length (Gs). According to presentation in Figure4, TORUS type of this generator has high power density in large air gap length. Should be noted that the value of Gs will change when the electrical loading 'A' and current density 'Js' change.

Figure5 shows the variation of the maximum power density as a function of air gap length in A=25000 (A/m), J_s=6000000 (A/m^2) for the AFIR-S and TORUS-S generators. Figure6 shows the variation of the maximum power density as a function of air gap length in A=20000 (A/m), J_s=7000000 (A/m^2) for the AFIR-S and TORUS-S generators also.

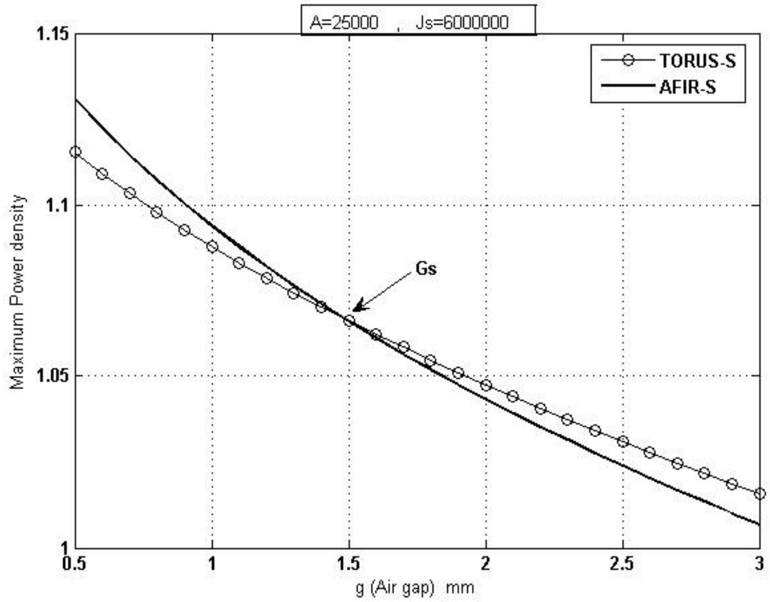


Figure5. Maximum power density AFIR-S and TORUS-S
Vs. air gap length

Figure5 shown that the point (Gs) is shifted to larger air gaps for AFIR-S type generator and this means that AFIR-S generator has higher maximum power density in smaller air gaps. Also, Figure6 shown that the point Gs is shifted to smaller air gaps for TORUS-S type generator and this means that TORUS-S generator has higher maximum power density in higher air gaps.

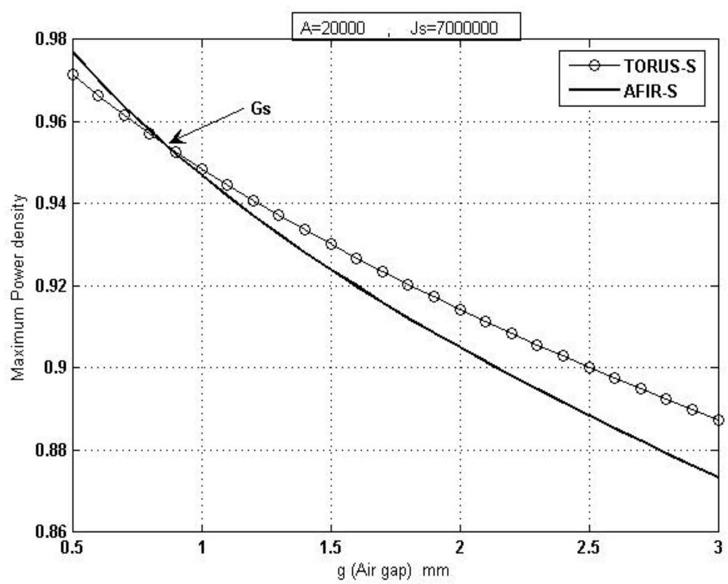


Figure6. Maximum power density
AFIR-S and TORUS-S vs. air gap length

4. CONCLUSIONS

The main goal of this paper has been introducing to double-Sided Axial Flux Slotted PM generators with maximum power density. There are two topologies for slotted double-sided AFPG generators.

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

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