

TORUS Concept Machines: Pre-Prototyping Design Assessment for Two Major Topologies

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Abstract – Two different external-rotor-internal-stator TORUS type axial flux PM machines can be derived based on the direction of the flux. In the first type of the TORUS machine, magnet driven flux enters stator and travels circumferentially along the stator core while in the second type the flux enters the stator and travels axially along the machine axis of rotation. The major differences between the two topologies are the direction of the magnet driven flux, the winding arrangement and the thickness of the stator yoke. In this paper, the sizing equations are derived for both types of TORUS machines. Based on the sizing analysis, optimum design is achieved for minimum ripple torque and maximum torque density. Furthermore, Finite Element Analysis (FEA) of both TORUS structures are investigated to get an insight in 3D field distribution, flux directions and paths in different parts of the machines for different load conditions. Minimization of the cogging and ripple torque components of the TORUS concept machines are displayed using 3D FEA for the insight in pulsating torques, ripple torques and cogging torques. Finally the comparison of the TORUS topologies are made in terms of flux densities, cogging and ripple torques and the results are illustrated in the paper.

I. INTRODUCTION

TORUS concept machines are external rotor and internal stator structures. The stator has a slotted structure with strip wound stator steel. Polyphase windings are placed into slots. The two disc shape rotors carry the axially magnetized arch-shaped Neodymium Iron Boron (NdFeB) permanent magnets mounted on the inner surfaces of the rotor discs. Two different TORUS machines, TORUS NN and TORUS NS, can be derived based on the direction of the flux using this structure. In the first type (TORUS NN), magnet driven flux enters the stator and travels circumferentially along the stator core. In the second TORUS type (TORUS NS), the flux enters the stator and travels axially along the machine axis of rotation resulting in theoretically no stator yoke. Moreover, while a back-to-back wrapped winding configuration is used in TORUS NN type machine, short-pitched lap winding configuration is used in TORUS NS type machine in order to produce torque.

Author has introduced torque quality assessment and minimal technology of ripple and cogging torque for the radial and axial flux surface mounted PM machines [1-2], that

used torque ripple factor (TRF), airgap permeance and open slot factor since these are theoretically indicate reducing harmonic effects among the stator winding distribution, the rotor PM skew, the excitation field waveform and the open slot size.

In the paper, both machine structures are clarified. The sizing equations are given for both types of TORUS machines and optimum machine designs for the maximum power density points are accomplished. Based on the above minimal technology of ripple and cogging torque, and sizing analysis, optimum design can be achieved for minimum ripple torque and maximum torque density. Furthermore, 3D Finite Element Analysis of the machines was investigated. Utilizing the techniques mentioned [1-3], the minimization of the cogging torque and ripple torque of the TORUS NN type and NS type machines are displayed using 3D finite element method for the insight in pulsating torques, ripple torques and cogging torques. Finally the comparison and discussion of the TORUS topologies are made in terms of power densities, cogging and ripple torques and the results are illustrated in the paper.

II. TORUS TYPE TOPOLOGY STRUCTURES

The basic TORUS type machine has one stator sandwiched between two disc-shaped rotors. Figures 1a and 1b show the axial flux surface mounted PM slotted TORUS machine NN and NS types. The major differences between the two TORUS topologies are the arrangement of the magnet polarity, the arrangement of the armature winding and the thickness of the stator yoke.

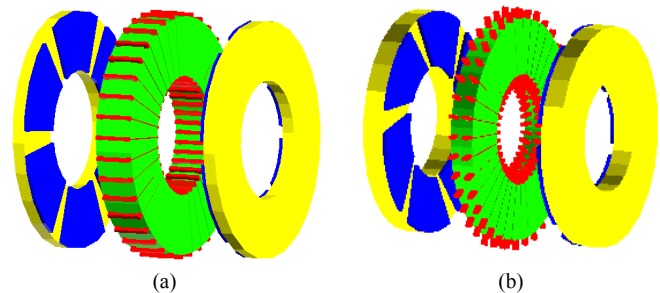


Fig. 1. Slotted TORUS concept machine models (a) NN type, (b) NS type

Surong Huang has been supported by Wisconsin Power Electronics Research Center and National Science Foundation of China (59877014).

The structure of the TORUS NN type machine, winding layout and the flux direction over one pole pair are shown in Figure 2a. The stator current flows in reverse direction in each of the back-to-back stator slots. A back-to-back wrapped winding structure has been used in this topology. The back-to-back wrapped winding is one in which the windings are wrapped around the stator periphery in much the same manner as the winding of a toroid. TORUS NS type machine is the second type of the TORUS machine as mentioned earlier and two-pole section of the machine is illustrated in Figure 2b. The stator current flows in the same direction in each of the back-to-back stator slots in order to create torque. One of the basic differences between the TORUS NN and TORUS NS type machines is the direction and path of the flux. In the TORUS NN type, the N pole of the permanent magnet driven flux enters the stator core through the airgap, travels circumferentially along the stator core, and then goes into the rotor core through the S pole of the permanent magnets as seen in Figure 2 (a).

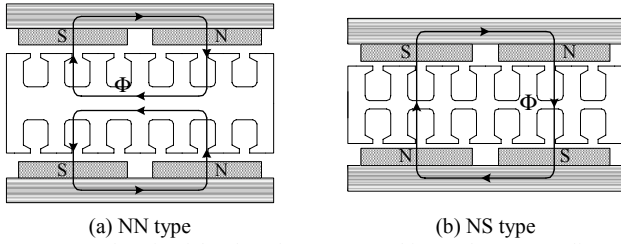


Fig. 2. One pole pair of the slotted TORUS machine at the average diameter and flux directions for both NN type and NS type structures

In the TORUS NS type structure, the N pole of the permanent magnet driven flux enters the stator core through the airgap, travels axially (not circumferentially) along the stator core, enters the second airgap and rotor core through the S pole of the permanent magnets and closes its path through the N pole of the magnets as seen in Figure 2 (b). 3D flux paths of both topologies are also demonstrated in Figures 3a and 3b.

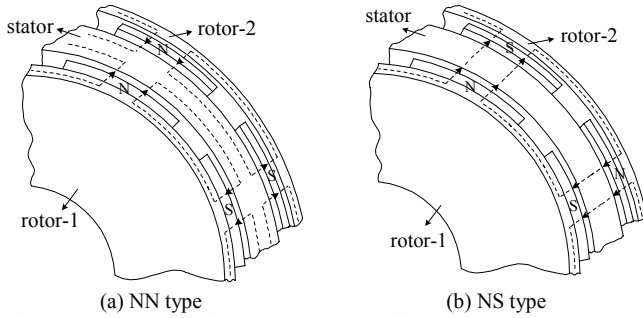


Fig. 3. 3D Flux paths of TORUS NN type and TORUS NS type structures

The physical structures of the stator and rotor of the machines are exactly the same except for the thickness of the stator yoke and winding arrangement. Unlike TORUS NN type, TORUS NS type does not require any stator back iron since the main flux travels axially. This feature implies an increase in power density and efficiency, and a reduction in the stator thickness and iron loss. However, using lap winding in TORUS NS structure results in longer winding length and

end winding, which implies bigger outer diameter, high copper loss and reduced efficiency and power density. Moreover, in order to create the appropriate flux path, the magnets facing each other on each rotor should be N and N poles or S and S poles in TORUS NN type and, N and S or S and N poles in TORUS NS type. Therefore, the direction of armature current must be changed appropriately so as to create torque.

III. SIZING ANALYSIS OF TORUS MACHINES

A. Sizing Equation and Torque Density

The approach for the general purpose sizing equation has been provided in [4] and [5]. The sizing equations have the following form for axial flux machines (AFM) [5];

$$P_R = \begin{cases} \frac{1}{1+K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p K_L \eta B_g A \frac{f}{p} (1-\lambda^2)^{\frac{1+\lambda}{2}} D_o^2 L_e \\ \frac{1}{1+K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} (1-\lambda^2)^{\frac{1+\lambda}{2}} D_o^3 \end{cases} \quad (1)$$

where

- P_R rated output power of the machine,
- $K_\phi = A_r/A_s$ ratio of electrical loading on rotor and stator (without a rotor winding, $K_\phi=0$),
- m number of machine phases,
- m_1 number of phases of each stator,
- K_e EMF factor incorporating winding distribution factor K_w and the per unit portion of the total airgap area spanned by salient poles of the machine (if any),
- K_i current waveform factor,
- K_p electrical power waveform factor,
- η machine efficiency,
- B_g air gap flux density,
- A total electrical loading,
- f converter frequency
- p machine pole pairs
- L_e effective stack length of the machine,
- D_o, D_g, D_i machine diameters at outer surface, air-gap surface and inner surface,
- $K_L = D_o/L_e$ aspect ratio coefficient for the AFM,
- $\lambda = D_i/D_o$ ratio of the diameter for the AFM.

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

$$T_{den.} = \frac{T_R}{\frac{\pi}{4} D_{tot}^2 L_{tot}} = \frac{P_R}{\omega_m \frac{\pi}{4} D_{tot}^2 L_{tot}} \quad (2)$$

$$P_{den.} = \frac{P_R}{\frac{\pi}{4} D_{tot}^2 L_{tot}} \quad (3)$$

where T_R is the rated torque of the machine, D_{tot} is the total outer diameter of the machine 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, ω_m is the rotor angular speed.

B. Sizing Analysis for Surface Mounted PM Slotted TORUS Type Machines

From (1), outer surface diameter D_o can be determined as

$$D_o = (P_R / \frac{1}{1+K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} \lambda (1-\lambda^2) \frac{1+\lambda}{2})^{1/3} \quad (4)$$

The total outer diameter of the machine can be given as

$$D_{tot} = D_o + 2W_{cu} \quad (5)$$

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

$$W_{cu} = \begin{cases} \frac{D_i - \sqrt{(D_i^2 - 2A_s D_g) / \alpha_s K_{cu} J_s}}{2} & \text{TORUS NN} \\ \frac{(0.46 \sim 0.62) D_o}{p} & \text{TORUS NS} \end{cases} \quad (6)$$

where α_s is the ratio of stator teeth portion to the stator pole pitch portion, K_{cu} is the slot fill factor of the stator winding and J_s is the current density of the stator winding. The axial length of the machine is

$$L_e = L_s + 2L_r + 2g \quad (7)$$

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

$$L_s = L_{cs} + 2L_{ss} \quad (8)$$

where L_{cs} is the axial length of the stator core, and the axial length of the stator slot can be written as

$$L_{ss} = \frac{D_i - \sqrt{(D_i^2 - 2A_s D_g) / \alpha_s K_{cu} J_s}}{2} \quad (9)$$

The axial length of the stator core can be derived as

$$L_{cs} = \begin{cases} \frac{B_g \alpha_p \pi D_o (1 + \lambda)}{B_{cs} 4p} & \text{for TORUS NN} \\ \text{minimal length for} & \text{for TORUS NS} \\ \text{mechanic strength} & \end{cases} \quad (10)$$

where B_{cs} is the flux density in the stator core and α_p is the ratio of average airgap flux density to peak airgap flux density. The axial length of rotor L_r becomes

$$L_r = L_{cr} + L_{PM} \quad (11)$$

where L_{cr} is the axial core length of rotor disc core, the PM length can be calculated as

$$L_{PM} = \frac{\mu_r B_g}{B_r - B_g K_f / K_d} (K_c g) \quad (12)$$

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 for stator slot, K_f is the peak value corrected factor of air-gap flux density in radial direction of the disc motor.

The axial core length of rotor disc core is

$$L_{cr} = \frac{K_f B_g \pi D_o (1 + \lambda)}{K_d B_{cr} 8p} \quad (13)$$

where B_{cr} is the flux density in the rotor disc core.

The ratio, λ , and airgap flux density are important design parameters effecting the characteristic in axial flux machines. Hence, the ratio λ and the airgap flux density must be chosen carefully to optimize the axial flux machine performance. Figure 4 shows power density plot as a function of airgap flux density and the ratio λ for TORUS NN type machine. From this plot, the maximum power density (or torque density), which is found as 2.56 W/cm³, occurs at an airgap flux density of 0.91 T and the diameter ratio of $\lambda=0.460$. For that maximum point, the motor efficiency is 94.9%. Likewise, maximum power density point can be obtained for TORUS NS type machine and shown in Figure 5. The optimization results for both machines are tabulated in Table I.

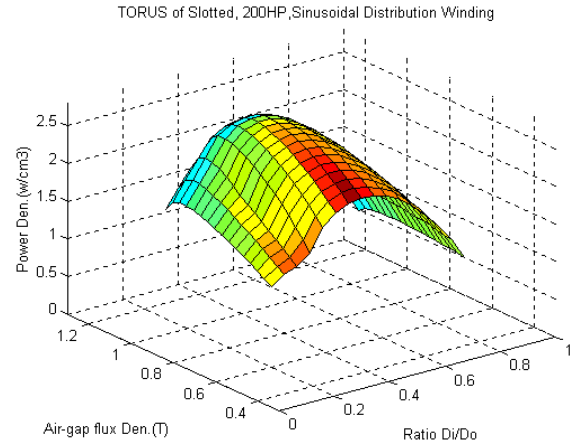


Fig. 4. Power density plot for TORUS NN type machine as a function of air-gap flux density (B_g) and diameter ratio (λ) ($P_R=200$ HP, $n_s=1200$ rpm, $p=3$, $A=600$ A/cm)

TABLE I
OPTIMIZATION OF TORUS NN TYPE AND NS TYPE MACHINES FOR MAXIMUM POWER DENSITY POINT

TORUS machine type	NN type	NS type
Max power density (MPD) P_{dmax} [W/cm ³]	2.56	2.30
Diameter ratio λ at MPD point D_i/D_o	0.46	0.35
Airgap flux density at MPD point B_g [T]	0.91	0.90
Efficiency at MPD point η [%]	94.9	92.2

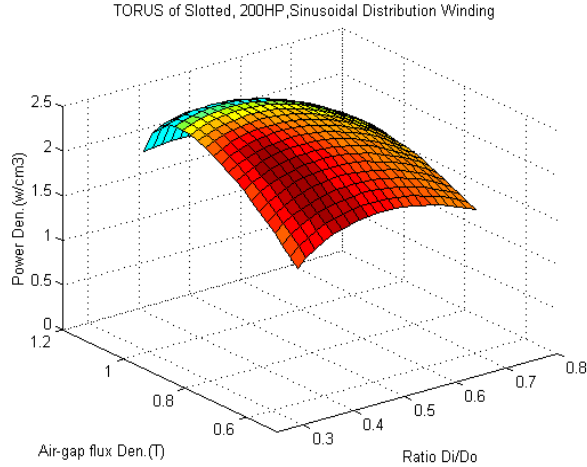


Fig. 5. Power density plot for TORUS NS type machine as a function of air-gap flux density (B_g) and diameter ratio (λ) ($P_R=200\text{HP}$, $n_s=1200\text{rpm}$, $p=3$, $A=600\text{A/cm}$)

IV. FINITE ELEMENT ANALYSIS OF TORUS CONCEPT MACHINES

A. FEA of TORUS NN Type Machine

To analyze the magnetic circuit and torque pulsations, 3D Finite Element Analysis was used for both TORUS concept machines. The purpose of the analysis is to get the overall picture of the saturation levels in various parts of the machine, to compare the values of the flux density obtained from FEA and sizing analysis, and to investigate and minimize the cogging and ripple torques of the machines. The 200HP, 1200rpm TORUS NN and NS type machines are used for the 3D field analysis. The machine dimensions obtained from the generalized sizing equations and parameters for both topologies are given in Table II.

TABLE II
PARAMETERS AND MACHINE DIMENSIONS FOR TORUS NN AND TORUS NS TYPE MACHINES

Dimensions and Parameters	TORUS NN	TORUS NS
Frequency (f)	60 Hz	60 Hz
Number of poles ($2p$)	6 poles	6 poles
Surface current density (A)	600 A/cm	600 A/cm
Current density (J_s)	9.0 A/mm ²	6.6 A/mm ²
Airgap length (g)	0.1 cm	0.1 cm
Pole-arc-ratio (α_i)	0.8	0.8
Outer diameter (D_o)	51.96 cm	52.21 cm
Inner diameter (D_i)	25.98 cm	22.84 cm
Slot depth (d_{ss})	2.28 cm	2.69 cm
Axial length of stator core (L_{cs})	8.91 cm	5.69 cm
Axial length of rotor core (L_{cr})	5.06 cm	5.04 cm
Magnet axial length (L_{pm})	1.20 cm	0.87 cm

Finite Element Analysis of the TORUS concept machines was realized for both no load and rated load cases. Figure 6 shows the airgap flux density of the TORUS NN type machine for the no load case. It can be seen from these plots

that the maximum airgap flux density is roughly 1.0 T and the average airgap flux density was determined to be 0.75 T. The flux directions in the middle of the stator core and airgaps as well as the magnetization directions are also illustrated in Figure 7. A comparison of the flux densities between the FEA results and sizing analysis results for different parts of the machine at no load is tabulated in Table III. From the no load flux density plots, it is seen that the results are consistent with the results obtained from the sizing analysis.

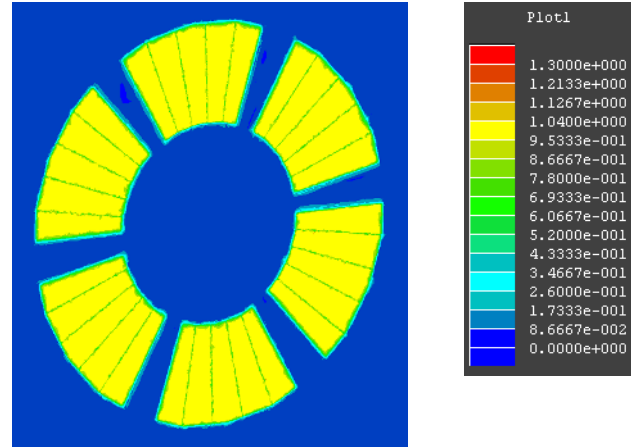


Fig. 6. Airgap flux density of the TORUS NN type machine at no load

TABLE III
FLUX DENSITY COMPARISON OF TORUS NN TYPE MACHINE AT NO LOAD

	Stator		Airgap		Rotor
	B_{fs-max}	B_{cs-max}	B_{g-max}	B_{g-avg}	B_{cr-max}
FEA	1.75	1.7	1.0	0.75	1.8
Sizing A.	1.8	1.7	1.02	0.76	1.8

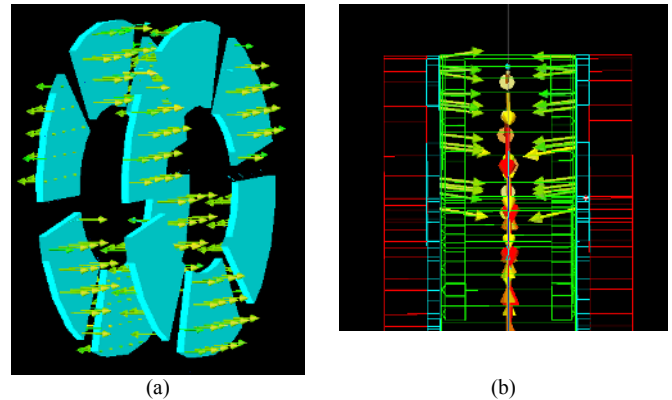


Fig. 7. (a) Magnetization direction of the PMs and (b) flux directions in the airgap and stator core for no load condition

The airgap flux density at the average diameter D_g over one pole using FEA was obtained and is shown in Figure 8. This plot shows that there are gaps in the airgap flux density right above the stator slots arising from the fact that there is a sudden change of the airgap permeance because of the slots. Magnetic wedges could be used to help to reduce these gaps, eliminate peaks and result in more smooth airgap flux density waveform. Figure 9 shows how the airgap flux density changes over one pole as the airgap diameter varies from inner D_i to outer D_o .

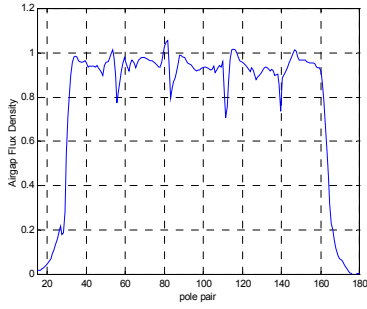


Fig. 8. Airgap flux density for TORUS NN type machine obtained from FEA at average diameter D_g

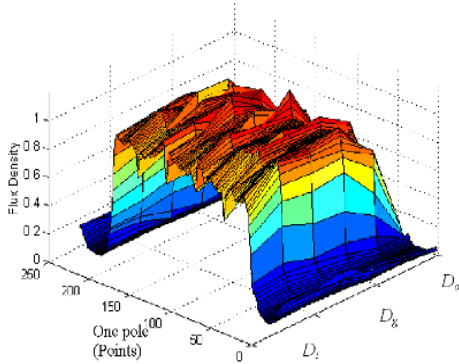


Fig. 9. 3D Airgap flux density for TORUS NN type machine obtained from 3D FEA

B. FEA of TORUS NS Type Machine

The results of the FEA were given for the final machine model (skewed rotor magnets) of TORUS NS type structure. The machine was first analyzed at no load. Figures 10, 11 and 12 show the flux density, directions in the airgap as well as inside the stator and magnetization directions of the skewed magnets. As can be seen from the figures, the direction of the magnet flux is as described earlier. The magnets facing each other have the opposite polarity. From these plots it is seen that maximum airgap flux density is roughly 1.05 T and the average airgap flux density was determined to be 0.75 T.

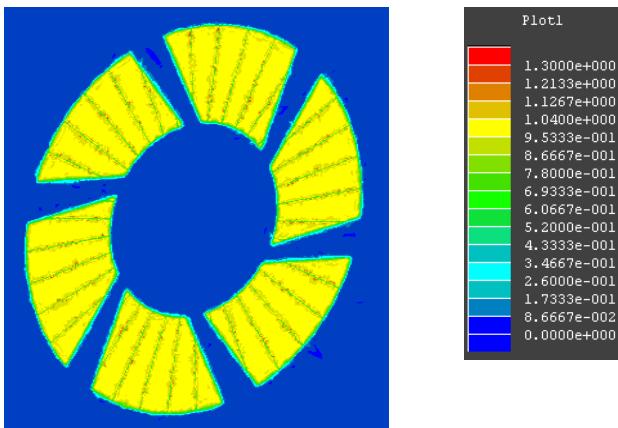


Fig. 10. Airgap flux density for TORUS NS type machine at no load

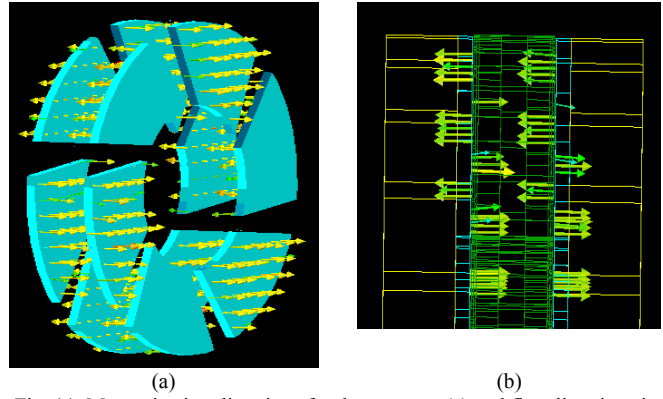


Fig. 11. Magnetization directions for the magnets (a) and flux directions in the airgap and stator core (b) for TORUS NS type machine at no load

A comparison of the values of the flux density between the FEA results and sizing analysis results on different parts of the machine at no load is tabulated in Table IV. From the no load airgap flux density plots and the table, it is seen that the results agree well.

TABLE IV
FLUX DENSITY COMPARISON OF TORUS NS TYPE MACHINE AT NO LOAD

	Stator		Airgap		Rotor
	B_{fs-max}	B_{cs-max}	B_g-max	B_g-avg	B_{cr-max}
FEA	1.75	1.7	1.05	0.75	1.8
Sizing A.	1.8	1.7	1.02	0.76	1.8

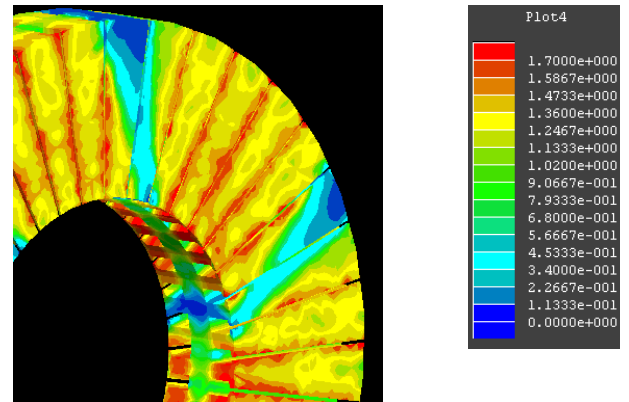


Fig. 12. Flux densities on the stator core and surface for TORUS NS type machine at no load condition

C. Torque Analysis of TORUS Concept Machines

One important advantage of using FEA in machine design is the ability to calculate the torque variations such as cogging torque, ripple torque and total torque with changes in rotor position. The main purpose of this analysis is to find out and minimize the ripple torque of the TORUS concept machines analyzed here. 3D FEA calculations were carried out for non-skewed and skewed magnet cases in order to obtain the total torque behavior of the TORUS concept machines.

Pulsating torque component of TORUS concept machines is consist of both cogging and ripple torque components. Figures 13a and 13b show the resultant cogging torque plots obtained from FEA calculations without and with skewed rotor magnet cases respectively. FE calculations reveal that

the peak-to-peak cogging torque for the TORUS topology without skewing the magnets is 0.043 pu. When the rotor magnets were skewed by the optimum skew angle, the peak-to-peak cogging torque became 0.013 pu. Hence, skewing the rotor PMs reduced the cogging torque of the slotted TORUS machine by nearly 69.8%. Since the slot opening of both NN and NS type topologies are kept the same, this cogging torque analysis represents both PM machines.

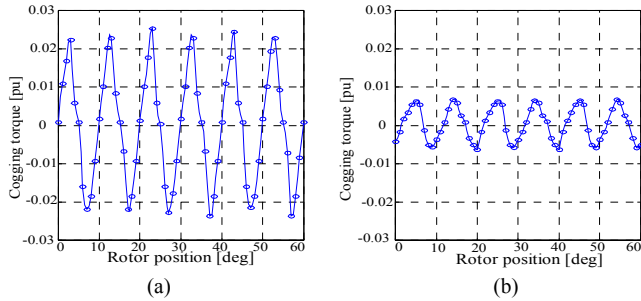


Fig. 13. Cogging torque of the TORUS concept machines (a) without and (b) with skewed rotor magnets

The total torque behavior of the TORUS NN type machine is illustrated in Figure 14a and 14b. The ripple torque of the NN type machine was found to be 0.156 pu peak-to-peak for the non-skewed rotor magnet case and 0.076 pu peak-to-peak for the skewed rotor magnet case. This results in a ripple torque reduction of 51.3% by simply skewing the PMs.

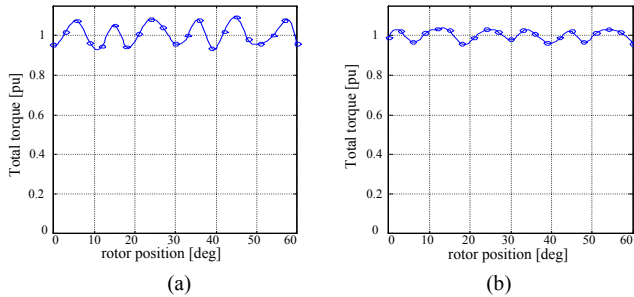


Fig. 14. Total torque of the TORUS NS type machine with back-to-back type winding and (a) without skewed magnets, (b) with skewed rotor magnets

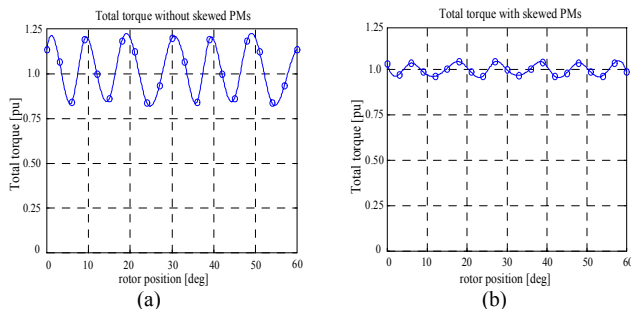


Fig. 15. Total torque of the TORUS NS type machine with lap winding and (a) without skewed magnets, (b) with skewed rotor magnets

The pulsating torque and ripple torque analysis for the skewed magnet case was also investigated for the TORUS NS type machine. The resultant plot is shown in Figure 15. The peak-to-peak ripple torque of the TORUS NS structure was reduced by 76.7% by simply skewing the magnets from 0.395pu to 0.092pu. Moreover, the machines are compared in

terms of torque quality and the results obtained from 3D FEA are illustrated in Table V.

TABLE V
RIPPLE TORQUE MINIMIZATION USING FEA FOR TORUS CONCEPT MACHINES

	TORUS NN Type		TORUS NS Type	
	Cogging Torque	Ripple Torque	Cogging Torque	Ripple Torque
w/o skewed rotor	0.043 pu	0.156 pu	0.043 pu	0.395 pu
w/ skewed rotor	0.0125 pu	0.076 pu	0.0125 pu	0.092 pu

V. COMPARISON AND CONCLUSIONS

The main focus of this paper was the analytical sizing, optimized machine design and torque quality of the axial flux surface mounted permanent magnet TORUS concept machines, namely TORUS NN type and TORUS NS type structures. One of the key points of the design of TORUS concept machines is that the diameter ratio, axial length and airgap flux density values must be chosen carefully to optimize the machine power density and efficiency. Furthermore, magnet pole arc, skew angle and winding shape have to be chosen carefully in order to minimize the pulsating torque component of the TORUS concept machines.

Finite element analysis of the TORUS NN type and NS type machines provides an idea about the torque quality and help achieve minimization of pulsating torque component of both structures. It was found that the peak-to-peak cogging torque of the TORUS concept machines was reduced from 4.3% to 1.3% of the rated torque by simply skewing the rotor magnets. The cogging torque reduction obtained was 69.8% for both structures. Besides, the peak-to-peak ripple torque of the TORUS NN type machine was reduced from 15.6% to 7.6%. The ripple torque reduction by basically skewing the rotor PMs was found to be 51.3%. The peak-to-peak ripple torque of the TORUS NS type machine was reduced from 39.5% to 9.2% using the same technique and the ripple torque reduction was found to be 76.7%.

Finally, this paper has revealed the following design aspects of the TORUS NN type and NS type machines:

- The TORUS NS type machine eliminates the stator back core which reduces the machine axial length and iron losses. It also implies increased power density and efficiency of the TORUS NS type machine.
- Lap windings have to be used in a TORUS NS type structure in order to produce torque and the stator currents in back-to-back stator slots have to flow in the same directions.
- Since the lap winding has a longer length and a bigger protrusion of the end winding, high copper loss, increased total outer diameter and reduced the space between the inner surface of stator pole and the outer surface must be expected. This results in reduced power density and efficiency of the TORUS NS type machine.
- The TORUS NN type machine has to have the stator back core large enough to handle the main flux coming

from both rotors. This reduces the power density and efficiency of the TORUS NN type machine.

- The TORUS NN type machine uses the back-to-back connected gramme type windings and the stator current flows in reverse direction in each of two back-to back stator slots.
- The back-to back wrapped windings greatly reduce the length and the protrusion of the end windings, which increases power density and efficiency of the TORUS NN type machine.

ACKNOWLEDGMENT

The authors are grateful to the Naval Surface Warfare Center for their financial support (Grant Number: N00014-98-1-0807).

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