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](image-url)
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).

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.

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).

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];

\[
P_R = \frac{1}{1+K_\phi} \left\{ \frac{m}{m_1} \frac{\pi K_e K_i K_p K_e A f}{p} \left( 1 - \lambda^2 \right)^{\frac{1+\lambda}{2}} \right\} \frac{D_o^2 L_c}{\eta \pi} + \frac{1}{1+K_\phi} \left\{ \frac{m}{m_1} \frac{\pi K_e K_i K_p K_e A f}{p} \left( 1 - \lambda^2 \right)^{\frac{1+\lambda}{2}} \right\} \frac{D_o^3}{\eta \pi}
\]

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 \( K_e \) 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,
- \( \eta \) 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,
- \( K_{dl} = D_o / L_e \) aspect ratio coefficient for the AFM,
- \( \lambda = D_g / D_o \) ratio of the diameter for the AFM.

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

\[
T_{den} = \frac{T_R}{\frac{\pi}{4} D_{out}^2 L_{rot}} = \frac{P_R}{\frac{\pi}{4} D_{out}^2 L_{rot}}
\]

\[
P_{den} = \frac{P_R}{\frac{\pi}{4} D_{out}^2 L_{rot}}
\]

where \( T_R \) is the rated torque of the machine, \( D_{out} \) 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, \(\omega_m\) 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

\[
D_o = \left(\frac{P_R}{m} - \frac{1}{1 + K_p} - m_1 \cdot \frac{m \cdot \pi}{2} \cdot K_e \cdot K_p \cdot \eta \cdot B_g \cdot A \cdot \frac{f}{p} \cdot \frac{L}{\lambda (1 - \lambda)^2} \cdot \frac{1 + \lambda}{2}\right)^{1/3}
\]

The total outer diameter of the machine can be given as

\[
D_{tot} = D_o + 2W_{cu}
\]

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

\[
W_{cu} = \frac{D_o - \sqrt{(D_o^2 - 2A_sD_r) / \alpha_s K_{cu} J_s}}{2}
\]

TORUS NN

\[
\text{TORUS NS}
\]

where \(\alpha_s\) 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

\[
L_c = L_s + 2L_r + 2g
\]

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

\[
L_s = L_{cs} + 2L_{ss}
\]

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

\[
L_{ss} = \frac{D_o - \sqrt{(D_o^2 - 2A_sD_r) / \alpha_s K_{cu} J_s}}{2}
\]

The axial length of the stator core can be derived as

\[
L_{cs} = \frac{B_g \cdot \alpha_p \cdot \pi \cdot D_o \cdot (1 + \lambda)}{B_{cr} \cdot 4 \cdot p} \quad \text{for TORUS NN}
\]

\[
\text{minimal length for TORUS NS}
\]

where \(B_{cr}\) is the flux density in the stator core and \(\alpha_p\) is the ratio of average airgap flux density to peak airgap flux density. The axial length of rotor \(L_r\) becomes

\[
L_r = L_{cr} + L_{PM}
\]

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

\[
L_{PM} = \frac{\mu_r B_g}{B_r - B_g K_f / K_d} (K_e g)
\]

where \(\mu_r\) 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, \(K_e\) 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

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

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

The ratio, \(\lambda\), and airgap flux density are important design parameters effecting the characteristic in axial flux machines. Hence, the ratio \(\lambda\) 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 \(\lambda\) 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.

![Figure 4](https://via.placeholder.com/150)

**Fig. 4.** Power density plot for TORUS NN type machine as a function of air-gap flux density (\(B_g\)) and diameter ratio (\(\lambda\))

\((P_R=200HP, n_R=1200rpm, p=3, A=600A/cm)\)

<table>
<thead>
<tr>
<th>TORUS machine type</th>
<th>NN type</th>
<th>NS type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max power density (MPD) (P_{max} [W/cm^3])</td>
<td>2.56</td>
<td>2.30</td>
</tr>
<tr>
<td>Diameter ratio (\lambda) at MPD point (D_i/D_o)</td>
<td>0.46</td>
<td>0.35</td>
</tr>
<tr>
<td>Airgap flux density at MPD point (B_g [T])</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>Efficiency at MPD point (\eta [%])</td>
<td>94.9</td>
<td>92.2</td>
</tr>
</tbody>
</table>
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.

![Fig. 5. Power density plot for TORUS NS type machine as a function of air-gap flux density (Bg) and diameter ratio (λ)](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Dimensions and Parameters</th>
<th>TORUS NN</th>
<th>TORUS NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Number of poles (2p)</td>
<td>6 poles</td>
<td>6 poles</td>
</tr>
<tr>
<td>Surface current density (A)</td>
<td>600 A/cm</td>
<td>600 A/cm</td>
</tr>
<tr>
<td>Current density (Jc)</td>
<td>9.0 A/mm²</td>
<td>6.6 A/mm²</td>
</tr>
<tr>
<td>Airgap length (g)</td>
<td>0.1 cm</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Pole-arc-ratio (αg)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Outer diameter (Do)</td>
<td>51.96 cm</td>
<td>52.21 cm</td>
</tr>
<tr>
<td>Inner diameter (Di)</td>
<td>25.98 cm</td>
<td>22.84 cm</td>
</tr>
<tr>
<td>Slot depth (d_s)</td>
<td>2.28 cm</td>
<td>2.69 cm</td>
</tr>
<tr>
<td>Axial length of stator core (L_s)</td>
<td>8.91 cm</td>
<td>5.69 cm</td>
</tr>
<tr>
<td>Axial length of rotor core (L_r)</td>
<td>5.06 cm</td>
<td>5.04 cm</td>
</tr>
<tr>
<td>Magnet axial length (L_m)</td>
<td>1.20 cm</td>
<td>0.87 cm</td>
</tr>
</tbody>
</table>

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 at no load. 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](image)

**TABLE III**

<table>
<thead>
<tr>
<th>Flux Density Comparison of TORUS NN Type Machine at No Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
</tr>
<tr>
<td>B_t-max</td>
</tr>
<tr>
<td>FEA</td>
</tr>
<tr>
<td>Sizing A.</td>
</tr>
</tbody>
</table>

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

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 $D_a$

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

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

<table>
<thead>
<tr>
<th></th>
<th>Stator</th>
<th>Airgap</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{stax}$</td>
<td>1.75</td>
<td>1.7</td>
<td>1.05</td>
</tr>
<tr>
<td>$B_{stmax}$</td>
<td>1.8</td>
<td>1.7</td>
<td>0.75</td>
</tr>
<tr>
<td>$B_{rmax}$</td>
<td>1.8</td>
<td>1.7</td>
<td>1.8</td>
</tr>
</tbody>
</table>

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

Fig. 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

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.

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.

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

<table>
<thead>
<tr>
<th>Torque Component</th>
<th>TORUS NN Type</th>
<th>TORUS NS Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogging Torque</td>
<td>0.043 pu</td>
<td>0.043 pu</td>
</tr>
<tr>
<td>Ripple Torque</td>
<td>0.156 pu</td>
<td>0.076 pu</td>
</tr>
<tr>
<td>Cogging Torque</td>
<td>0.0125 pu</td>
<td>0.092 pu</td>
</tr>
<tr>
<td>Ripple Torque</td>
<td>0.075 pu</td>
<td>0.076 pu</td>
</tr>
</tbody>
</table>

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.

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