Torque Quality and Comparison of Internal and External Rotor Axial Flux Surface-Magnet Disc Machines

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Abstract **– In this paper, pulsating torque components of PM machines and pulsating torque minimization techniques are discussed for axial flux surface magnet disc type PM machines. The pulsating torque analysis describing general instantaneous electromagnetic torque equation and torque ripple factor (TRF) is briefly given in order to analyze ripple torque of the machines. A detailed Finite Element Analysis (FEA) focusing on the minimization of cogging and ripple torque components using some techniques are also provided. A detailed comparison of the two techniques is also illustrated in the paper.**

I. INTRODUCTION

Torque quality is an important issue in a wide range of motor applications. For example, motors used in submarine propulsions, electric traction drives and electric power steering all require smooth torque operation. In general, the torque quality assessment of different machine types is a challenging task since the assessment does not only consider the torque density and the torque to weight ratio but also consider the pulsating torque. A mathematical approach to torque quality should include a harmonic analysis of the entire electric drive system. The main harmonic sources of the pulsating torque are the effects of slotting the stator that results in producing permeance harmonics and the placement of the windings and PM resulting in producing MMF harmonics.

Axial flux PM disc type non-slotted and slotted internal rotor external stator (AFIR type) and internal stator external rotor (TORUS type) machines have found a growing interest recently for high performance drive applications [1-3]. These machines can be designed for higher torque-to-weight ratio, and higher efficiency and can be considered a significant advantage over conventional PM machines. Torque quality of the axial flux PM machines is an important matter for low noise smooth torque disc machines and directly related to pulsating torque component. Pulsating torque consists of two components: cogging torque and ripple torque. Cogging torque arises from the variation of the magnetic permeance of the stator teeth and the slots above the permanent magnets. Presence of cogging torque is a concern in the design of PM synchronous machines since it adds unwanted harmonics to the pulsating torque. Ripple torque occurs as a result of fluctuations of the field distribution and the armature MMF. At high speeds, ripple torque is usually filtered out by the system inertia. However, at low speeds "torque-ripple" produces noticeable effects that may not be tolerable in smooth torque and low noise applications.

This paper relates to the torque quality of axial flux PM disc machines. The first section discusses the pulsating torque minimization techniques for PM machines. The non-slotted and slotted axial flux disc type PM machine structures are introduced in the second part. Pulsating torque investigation of PM machines using mathematical and finite element approaches utilizing some of the techniques mentioned are presented in the third and fourth sections and special attention is paid to torque ripple minimization of the disc machines. Finally, a detailed comparison of the two approaches and conclusions are illustrated in the last part of the paper.

II. PM MOTOR DESIGN TECHNIQUES FOR PULSATING TORQUE MINIMIZATION

Definitions of the torque components used in this study are given below:

1. Cogging torque: Pulsating torque component produced by the variation of the airgap permeance or reluctance of the stator teeth and slots above the magnets as the rotor rotates. No stator excitation is involved in cogging torque production.
2. Ripple torque: Pulsating torque component generated by the stator MMF and rotor MMF. In surface mounted PM machines, ripple torque is mainly created by interaction between the MMF due to the stator windings and the MMF due to the rotor magnets since there exists no rotor reluctance variation.
3. Pulsating torque: Sum of both cogging and ripple torque components.
4. Total torque: Sum of average torque and pulsating torque components.

Sinusoidal back EMF motors have many similarities with other type of AC motors. For example, if the machine back EMF and current waveform are perfectly sinusoidal it results

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in smooth torque production. The requirement for the sinusoidal machines is that the airgap flux density should vary sinusoidally along the airgap when the stator of the machine is not excited (no load case). The second requirement is that the stator windings of the machine should be distributed sinusoidally around the airgap. Any non-ideal situations such as disturbed stator current waveform arising from the converter and disturbed back EMF waveform arising from the non uniform airgap cause non-sinusoidal current and airgap flux density waveforms resulting in undesired pulsating torque components in the machine. In other words, machine torque is proportional to the square of the flux density in the airgap and if the airgap flux density waveform is disturbed, pulsating torque becomes unavoidable.

There exist many techniques in the literature for the minimization of pulsating torque components of the disc type PM machines [4-8]. In general, these minimization techniques can be classified into two major categories. The first one comprises the techniques for modifying the machine design so that the pulsating torque component is minimized and smooth torque goal is achieved. The second category is based upon control schemes by modifying the stator excitation waveform to obtain smooth torque. In this paper, the focus will be placed on the machine design based techniques to achieve smooth torque operation.

The most effective way to minimize the torque pulsations lies on proper machine design. Many techniques, such as using appropriate stator winding type, introducing rectangular or pie shaped back-to-back connected (gramme type) stator windings in slotless topologies, skewing either stator slots or rotor magnets are used to achieve this goal from a machine perspective.

Firstly, gramme type back-to-back connected windings are used in slotless machines and it helps reduce the ripple torque component. Replacing the rectangular shaped winding with sector shaped winding help even more to reduce the torque ripple component of the slotless topologies providing better stator utilization. Non-slotted machines with airgap windings have more sinusoidal back EMF distribution than the slotted machines. Secondly, skewing either the stator slots or rotor magnets is one of the effective techniques used in PM machines to reduce the pulsating torque components. However, it has some drawbacks such as giving rise to average loss reduction, complex and expensive rotor construction and an increase in leakage inductance. Thirdly, short-pitched winding can be used to reduce the ripple torque of the machine by reducing the high order harmonics. For instance, a TORUS machine designed with short pitched windings provides better results than TORUS machine designed with back-to-back connected windings in terms of torque quality. Fractional slot windings can also be used for low number of slots per pole per phase. Moreover, cogging torque of a PM machine can be minimized by properly designing pole arc ratio since the cogging torque is produced by the interaction of the magnets and stator teeth. Furthermore, one of the techniques used to reduce the cogging torque is to introduce dummy slots. Introducing dummy slots and dummy teeth help reduce the cogging torque of the machine by increasing the varying frequency of the airgap reluctance with rotor position and reducing the varying amplitude of the airgap reluctance. Besides the techniques mentioned, there exist other methods to minimize the pulsating torque of the PM machines such as increasing the number of phases, increasing the number of pole, reducing the slot openings and placing slot wedge into slots.

III. AXIAL FLUX PM DISC TYPE MOTOR STRUCTURES

Axial flux PM disc machines have either a single stator sandwiched between two disc rotors (TORUS topology) or a single rotor sandwiched between two stators (AFIR topology). The axial flux topologies investigated in this paper are shown in Figures 1a through 1d and the abbreviations are shown in Table I.

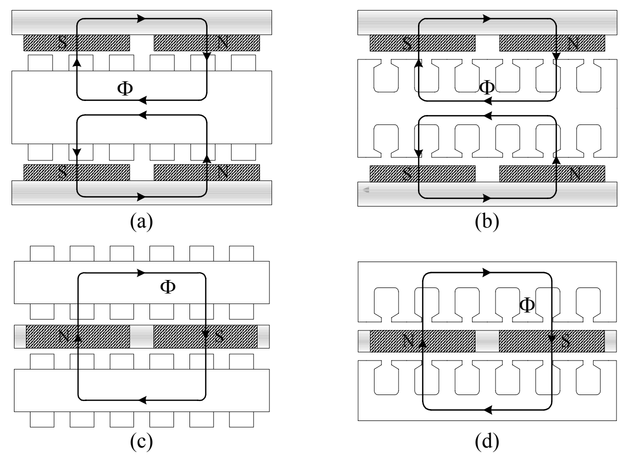


Fig. 1. Axial flux PM disc type motor structures: (a) Slotless TORUS, (b) slotted TORUS, (c) slotless AFIR and (d) slotted AFIR machines

TABLE I
RADIAL AND AXIAL FLUX SURFACE MOUNTED PM MACHINES

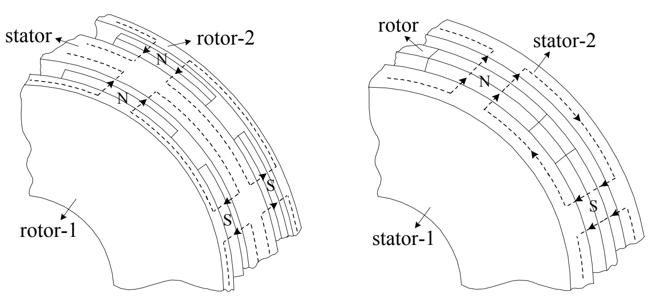
Abbreviation	Radial and Axial Flux Surface Magnet PM Machine Types
RFSM-NS	Radial flux surface mounted PM non-slotted motor
RFSM-S	Radial flux surface mounted PM slotted motor
TORUS-NS	Axial flux external rotor internal stator PM non-slotted motor
TORUS-S	Axial flux external rotor internal stator PM slotted motor
AFIR-NS	Axial flux internal rotor external stator PM non-slotted motor
AFIR-S	Axial flux internal rotor external stator PM slotted motor

Figures 1a and 1b show external-rotor-internal-stator non-slotted and slotted TORUS machine structures. The machines have single stator and two PM rotor discs. The stators of the machines are realized by tape wound core with AC polyphase windings. Airgap windings which are wrapped around the stator core with a back-to-back connection and evenly distributed back-to-back connected windings are used for slotless and slotted TORUS topologies respectively. The rotor structure is formed by fan-shaped surface mounted axially magnetized NdFeB permanent magnets, rotor core and shaft.

The AFIR type machines have two stator discs and a single rotor disc as seen in Figures 1c and 1d. The stator of the machine is realized by either slotless or slotted tape wound core with AC polyphase windings. Gramme type windings are wrapped around the stator core for the slotless machine and short-piched lap AC winding for the slotted topology. The winding pitch is designed to be 5/6 so that the airgap harmonics can be minimized. The rotor structures of the AFIR machines are formed by the axially magnetized surface magnets and a shaft. It should be mentioned that the portions between the windings in non-slotted topologies are filled with epoxy resin so as to form a solid rotor structure, increase the robustness of the structure and provide better heat transfer.

Since the windings in the airgap of the TORUS-NS machine are used for the torque production, the end windings are quite short compared to slotted TORUS machine. In addition, slotted AFIR machine end windings are much longer than its slotless counterpart, which results in less copper loss and higher efficiency. Also, slotless axial flux machines have the advantage of providing easier conductor heat transfer because the airgap windings are on the stator surface.

The basic flux paths of the TORUS and AFIR topologies are shown in Figures 2a and 2b respectively. As can be seen in Figure 2a (for the TORUS machines) the N magnets drive flux into the stator core through the airgaps. The flux then travels circumferentially along the stator core, returns across the airgaps and then enters the rotor core through the opposite polarity of the PMs. In the AFIR type machines seen in Figure 2b, the magnets with the polarity of N drive flux across the upper airgap into the upper stator core. The flux then travels circumferentially along the upper stator core, returns to the upper airgap, then enters the lower stator core through the S pole of the magnets and closes its path.



(a) (b)

Fig 2. 3D Flux paths of the (a) TORUS and (b) AFIR type topologies

III. PULSATING TORQUE ASSESSMENT OF AXIAL FLUX MACHINES USING MATHEMATICAL APPROACH

In general, if stator leakage inductance and resistance are neglected, the general instantaneous electromagnetic torque for any electrical machine can be expressed as

$$T_{em}(t) = \frac{1}{\omega_m} \sum_{j=1}^{m} e_j(t)\, i_j(t) \qquad (1)$$

where j is the order of machine phase, m is the number of machine phases, $e_j(t)$ and $i_j(t)$ are the back-EMF and current respectively in phase j, and ω_m is the rotor angular speed.

In the electromagnetic and ripple torque analyses, it was assumed that the motor is unsaturated, armature reaction is neglected and the fundamental components of the currents and the corresponding back-EMF's are maintained in phase. For the Y-connected three-phase stator winding, the back-EMF in phase a can be written as

$$e_a = E_1 \sin \omega t + E_3 \sin 3\omega t + E_5 \sin 5\omega t + E_7 \sin 7\omega t + \ldots \qquad (2)$$

and the current in phase a can be written as

$$i_a = I_1 \sin \omega t + I_5 \sin 5\omega t + I_7 \sin 7\omega t + I_{11} \sin 11\omega t + \ldots \qquad (3)$$

where E_n is the n^{th} time harmonic peak value of the back EMF, which is produced by n^{th} space harmonic of the airgap magnetic flux density B_{gn} and I_n is the n^{th} time harmonic peak value of armature current which depends on the armature current waveform. Moreover, it should be noted that there is no neutral connection used in the winding so that the harmonics of multiple of three do not exist. The product $e_a i_a$ is composed of an average component and even-order harmonics for phase a. The total instantaneous torque contributed by each machine phase is proportional to the product of back EMF and phase current of each phase. The sum ($e_a\, i_a + e_b\, i_c + e_c\, i_c$) will contain an average component and harmonics of the order of six and the other harmonics are eliminated. The final instantaneous electromagnetic torque equation becomes

$$T_{em}(t) = T_0 + T_6 \cos 6\omega t + T_{12} \cos 12\omega t + T_{18} \cos 18\omega t + \ldots$$

$$= T_0 + \sum_{n=1}^{\infty} T_{6n} \cos n6\omega t \qquad (4)$$

where T_0 is the average torque, T_{6n} is harmonic torque components and n = 1,2,3…. The fundamental and first three harmonic torque components are given from (5) through (8).

$$T_0 = \frac{3}{2\omega_m} [E_1 I_1 + E_5 I_5 + E_7 I_7 + E_{11} I_{11} + E_{13} I_{13} + \ldots] \qquad (5)$$

$$T_6 = \frac{3}{2\omega_m} [I_1 (E_7 - E_5) + I_5 (E_{11} - E_1) + I_7 (E_1 + E_{13}) + I_{11}(E_5 + E_7) + \ldots] \qquad (6)$$

$$T_{12} = \frac{3}{2\omega_m} [I_1(E_{13} - E_{11}) + I_5(E_{17} - E_7) + I_7(E_{19} - E_5) + I_{11}(E_{23} - E_1) + \ldots] \qquad (7)$$

$$T_{18} = \frac{3}{2\omega_m} [I_1(E_{19} - E_{17}) + I_5(E_{23} - E_{13}) + I_7(E_{25} - E_{11}) + I_{11}(E_{29} - E_7) + \ldots] \qquad (8)$$

In the ideal case, if the back-EMF's and the armature currents are sinusoidal, the electromagnetic torque is constant and no ripple torque exists, which is illustrated in Figure 3a. The same quantities are plotted for sinusoidal armature current and square back EMF waveforms. The resultant plots including torque pulsations are shown in Figure 3b.

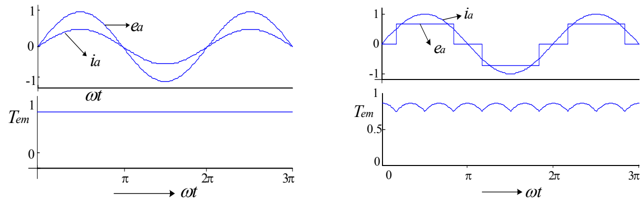


Fig. 3. Torque ripple for (a) sinusoidal and (b) square wave current cases

Since almost all-practical stator windings and PM field distributions have significant winding harmonics and flux density harmonics, induced back-EMF's are not sinusoidal and contain high-order harmonics. As a result, ripple torque exists even with a sinusoidal armature current source.

The torque-ripple factor (TRF) can be defined as the ratio of peak-to-peak ripple torque to average torque:

$$\text{TRF} = \frac{T_{pp}}{T_0} = \frac{2\sqrt{T_6^2 + T_{12}^2 + T_{18}^2 + ...}}{T_0} \tag{9}$$

where T_{pp} is the peak-to-peak ripple torque. For the sinusoidal current case, the torque-ripple factor expression becomes

$$\text{TRF}=2\frac{\sqrt{(K_{h7}-K_{h5})^2+(K_{h13}-K_{h11})^2+(K_{h19}-K_{h17})^2+...}}{K_{h1}} \tag{10}$$

where

$$\frac{E_n}{E_1} = \frac{K_{wn}\cdot K_{sn}\cdot K_{fn}\cdot K_{osn}}{K_{w1}\cdot K_{s1}\cdot K_{f1}\cdot K_{os1}} = \frac{K_{hn}}{K_{h1}} \tag{11}$$

and $K_{hn} = K_{wn}\ K_{sn}\ K_{fn}\ K_{osn}$ is n^{th} harmonic factor, K_{wn} is n^{th} harmonic winding factor, K_{fn} is n^{th} PM field harmonic form factor, K_{sn} is n^{th} harmonic rotor PM skew factor and K_{osn} is n^{th} harmonic open slot factor.

The analysis procedure summarized here can be applied to any of the surface mounted permanent magnet machines. The slotless TORUS machine is given as an example machine in the following pulsating torque analysis. First, a back-to-back connected gramme type rectangular shaped AC winding is used in the design and the TRF is investigated for different rotor skew angles and pole arc ratios of the PM. The winding structure is then replaced with pie shaped winding to smooth the torque ripple of the slotless TORUS machine. Optimum design point can be obtained for minimum TRF after this procedure.

Figure 4 shows the TRF plot as a function of magnet pole arc ratio and magnet skew angle for rectangular shaped back-to-back connected stator winding case. It is clear from the figure that the TRF is a minimum near the pole arc ratio of 0.8 and a skew angle of 31 degrees.

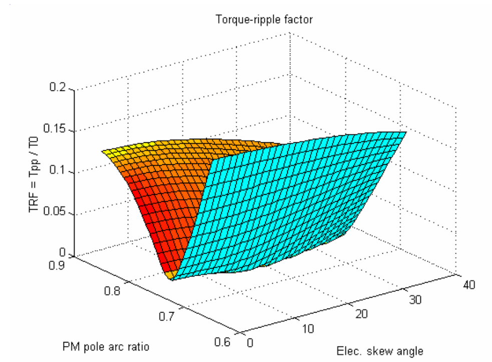


Fig. 4. Torque Ripple Factor of the slotless TORUS machine with rectangular shaped winding as a function of pole arc and magnet skew angle

When the stator AC winding structure is replaced with pie shaped back-to-back connected winding, which provides better stator utilization compared to rectangular shaped winding, the torque ripple of the machine becomes smaller as seen in Figure 5. The TRF is minimum at a pole arc ratio of 0.81 and skew angle of 31 degrees. The optimum skew angle and pole arc ratio can also be seen clearly in Figures 6a and 6b for this case.

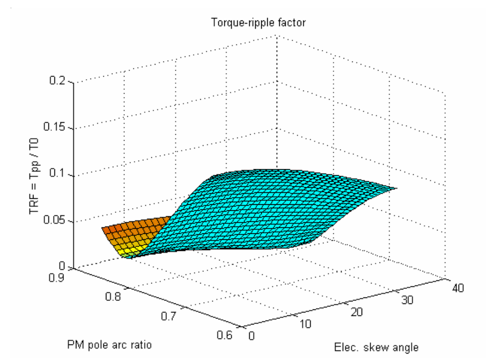


Fig. 5. Torque Ripple Factor of the slotless TORUS machine with pie shaped winding as a function of pole arc and magnet skew angle

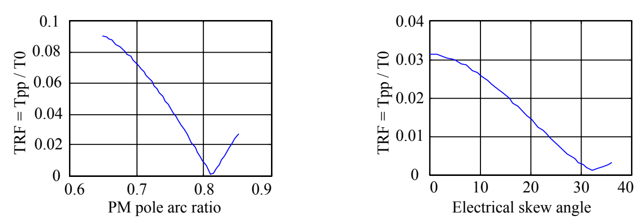


Fig. 6. TRF of the slotless TORUS machine with pie shaped winding as a function of (a) pole arc and (b) magnet skew angle

The same analysis has been completed for all the radial and axial flux PM machines. A summary of the results with rectangular and pie shaped windings for different skew angles and PM pole arc ratios are provided in Tables II and III for TORUS and AFIR topologies respectively. The TRFs for different PM arc ratios and skews angles as well as non-skewed case around the minimum TRF are illustrated in the Tables. It can be observed from the tables that precision of skew angle and PM arc ratio is very important for high torque quality PM motors. In other words, ripple torque is very sensitive to PM arc ratio and skew angle.

TABLE II
TORQUE RIPPLE FACTOR FOR TORUS-NS AND TORUS-S MACHINES

	α_i	**0.79**	**0.80**	**0.81**	**0.82**
TORUS-NS rectang. type	$\theta_{skew} = 0$	0.102	0.113	0.121	0.129
	$\theta_{skew} = 30$	0.046	0.057	0.067	0.077
	$\theta_{skew} = 31$	0.043	0.054	0.064	0.074
	$\theta_{skew} = 32$	0.040	0.051	0.062	0.071
TORUS-NS pie shaped	$\theta_{skew} = 0$	0.043	0.037	0.032	0.029
	$\theta_{skew} = 30$	0.021	0.014	0.007	0.001
	$\theta_{skew} = 31$	0.020	0.013	0.006	0.001
	$\theta_{skew} = 32$	0.019	0.012	0.006	0.002
TORUS-S	$\theta_{skew} = 0$	0.337	0.346	0.330	0.360
	$\theta_{skew} = 30$	0.048	0.041	0.036	0.033
	$\theta_{skew} = 31$	0.042	0.034	0.028	0.024
	$\theta_{skew} = 32$	0.039	0.030	0.022	0.018

TABLE III
TORQUE RIPPLE FACTOR FOR AFIR-NS AND AFIR-S MACHINES

	α_i	**0.79**	**0.80**	**0.81**	**0.82**
AFIR-NS rectang. type	$\theta_{skew} = 0$	0.100	0.111	0.120	0.127
	$\theta_{skew} = 30$	0.045	0.056	0.066	0.076
	$\theta_{skew} = 31$	0.042	0.053	0.064	0.073
	$\theta_{skew} = 32$	0.040	0.051	0.061	0.070
AFIR-NS pie shaped	$\theta_{skew} = 0$	0.043	0.037	0.032	0.029
	$\theta_{skew} = 30$	0.021	0.014	0.007	0.001
	$\theta_{skew} = 31$	0.020	0.013	0.006	0.001
	$\theta_{skew} = 32$	0.019	0.012	0.006	0.002
AFIR-S	$\theta_{skew} = 0$	0.317	0.331	0.317	0.349
	$\theta_{skew} = 30$	0.027	0.030	0.032	0.033
	$\theta_{skew} = 31$	0.019	0.022	0.023	0.024
	$\theta_{skew} = 32$	0.015	0.017	0.017	0.019

IV. PULSATING TORQUE ASSESSMENT OF RADIAL AND AXIAL FLUX MACHINES USING FEA

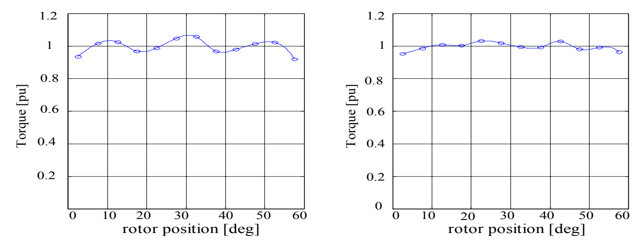
Finite Element Analysis (FEA) can accurately analyze the models involving permanent magnets of any shape and material. There is no need to calculate the reluctances and inductances using circuit type analytical methods since these values can simply be extracted from the finite element analysis. One important advantage of using FEA 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 radial and axial flux machines using some of the techniques mentioned earlier.

A. RFSM Type Topologies

The FE calculations of the 200HP, 6poles and 1200rpm machine were carried out using Maxwell 2D and 3D software without and with skewed rotor magnet cases for different rotor positions. The peak-to-peak torque ripple for slotless RFSM machine was found to be 0.063 pu without skewed PMs and 0.035 pu with skewed PMs. The same analysis was carried out for conventional radial flux slotted PM machine which is used as a reference machine in the comparison. The cogging and ripple torque analyses were performed for different cases such as modified slot, with slot wedge in the slot openings, with and without skewed rotor magnets and pulsating torque was tried to be minimized. In the final design, the peak-to-peak ripple torque was found to be 5.9%.

B. TORUS Type Topologies

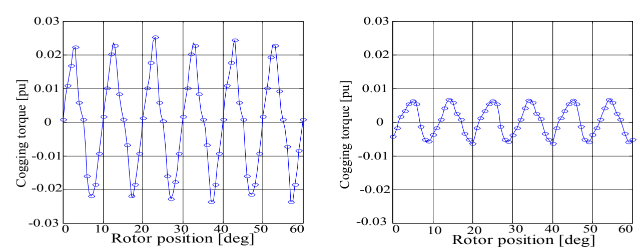
Since no slots exist in the slotless TORUS topology, the cogging torque is negligible and the pulsating torque component of the machine is equal to the ripple torque component. FEA calculations were carried out for different rotor positions over one pole for the same 200HP, 6pole, 1200rpm machine without and with skewed rotor magnets. The total torque of the machine at rated power with rectangular shaped back-to-back connected stator winding and without skewed rotor PMs was plotted over one pole and is shown in Figure 7a. The peak-to-peak torque ripple was found to be 0.12 pu. As a second step of the analysis, the winding structure was changed to a pie shaped back-to-back structure to reduce the ripple torque by obtaining better stator utilization and the ripple torque was reduced to 0.046 pu. In the third part, the rotor magnets are skewed by the optimum skew angle with the pie shaped winding structure and it was found that the ripple torque was reduced to 0.033 pu. The resultant ripple torque plot is shown in Figure 7b. The total ripple torque reduction from step-1 to step-3 becomes 72.5% for this machine.



(a) (b)

Fig. 7. Total torque of the TORUS-NS machine (a) with rectangular shaped back-to-back connected winding and without skewed magnets, (b) with pie shaped back-to-back connected winding and skewed rotor magnets

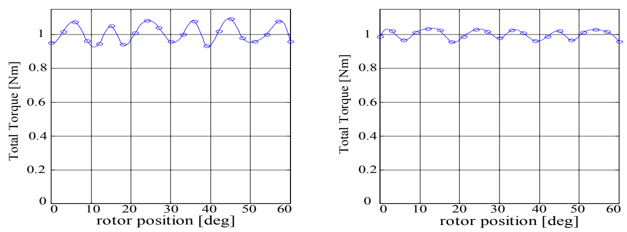
In the TORUS-S machine, pulsating torque comprises both cogging and ripple torque components unlike slotless TORUS topology. Figures 8a and 8b show the resultant cogging torque plots without and with skewed rotor magnet cases. FE calculations reveal that the peak-to-peak cogging torque for the TORUS-S topology without skewing the magnets is 0.043 pu. When the rotor magnets were skewed by the optimum skew angle, the cogging torque became 0.0125 pu. Hence, skewing the rotor PMs reduced the cogging torque of the slotted TORUS machine by nearly 79.0%.



(a) (b)

Fig. 8. Cogging torque of the TORUS-S machine (a) without and (b) with skewed rotor magnets

The total torque behavior of the slotted TORUS machine is displayed in Figure 9a and 9b. The ripple torque of the machine was found to be 0.156 pu peak-to-peak for the non-skewed rotor magnet case and 0.075 pu peak-to-peak for the skewed magnet case. This results in a ripple torque reduction of 51.3% by simply skewing the PMs.

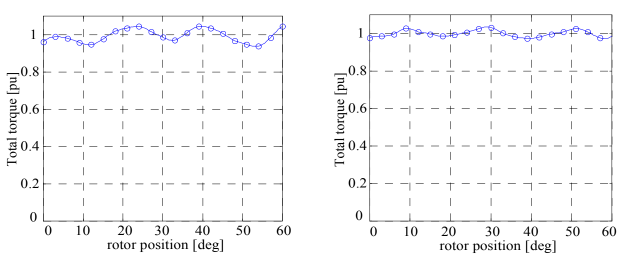


(a) (b)

Fig. 9. Total torque of the TORUS-S machine (a) with rectangular gramme type winding and without skewed magnets, (b) with pie shaped winding and without skewed rotor magnets

C. AFIR Type Topologies

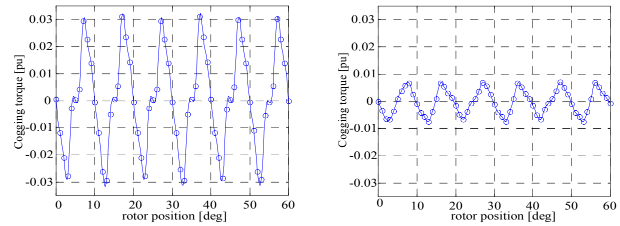
3D FEA is again used for the internal rotor external stator PM (AFIR) disc machines to investigate the torque quality for the same ratings. The same ripple torque analysis was carried out for slotless AFIR topology for gramme type winding with a non-skewed magnet and a pie shaped winding with a skewed magnet cases. The torque ripple with rectangular gramme type winding was 0.105 pu while the same quantity was calculated to be 0.055 pu with pie shaped winding and without skewed magnet as seen in Figures 10a and 10b. Thus, a torque ripple reduction from case 1 to case 2 was found to be 52%.



(a) (b)

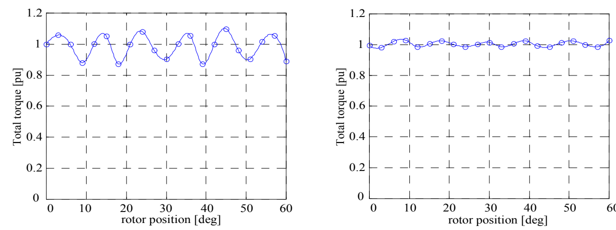
Fig. 10. Total torque of the non-slotted internal rotor type machine (a) without and (b) with skewed rotor magnets

Torque quality of the slotted AFIR machine was also examined by analyzing cogging and ripple torque components for the same machine ratings. As can be seen from Figures 11a and 11b, the peak-to-peak cogging torques for the AFIR-S topology were found to be 0.062pu and 0.013pu without and with skewing magnets. Again the optimum skew angle was used in the FEA models. The effect of skewing in slotted AFIR topology is again clearly seen in Figures 12a and 12b. It can be observed that the torque ripple has a peak-to-peak value of 0.383 pu for non-skewed magnet case and 0.081 pu for skewed magnet case. This leads to a ripple torque reduction of 78.8% for this machine.



(a) (b)

Fig. 11. Cogging torque of the non-slotted internal rotor type machine (a) without and (b) with skewed rotor magnets



(a) (b)

Fig. 12. Total torque of the AFIR-S machine at rated load (a) without and (b) with skewed rotor magnets

V. COMPARISON OF TORQUE QUAILITY USING BOTH MATHEMATICAL AND FINITE ELEMENT APPROACHES

The summary of the torque analysis using FEA is shown in Tables IV and V. Figures 13a and 13b show the peak-to-peak values of cogging and ripple torque comparison obtained from FEA for both non-slotted and slotted topologies respectively.

TABLE IV
COGGING TORQUE COMPARISON OF RADIAL AND AXIAL FLUX MACHINES USING FINITE ELEMENT APPROACH

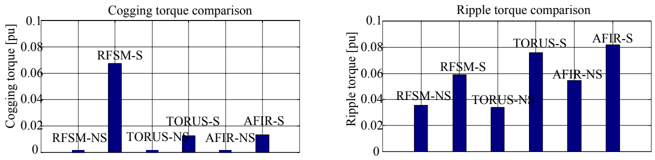
	Without skewed rotor PMs [pu]	With skewed rotor PMs [pu]
RFSM-NS	0	0
RFSM-S	0.26 / 0.067*	0.088
TORUS-NS	0	0
TORUS-S	0.043	0.0125
AFIR-NS	0	0
AFIR-S	0.062	0.013

TABLE V
RIPPLE TORQUE COMPARISON OF RADIAL AND AXIAL FLUX MACHINES USING FINITE ELEMENT APPROACH

	with rectangular shaped winding	with pie shaped winding	with skewed PMs
RFSM-NS	0.063	---	0.035
RFSM-S	0.429 / 0.101*	---	0.059
TORUS-NS	0.120	0.046	0.033
TORUS-S	0.156	---	0.075
AFIR-NS	0.105	0.055	---
AFIR-S	0.383	---	0.081

* Slot wedge is used

It can be observed from the tables and figures that in general, non-slotted topologies have negligible cogging torque while the cogging torque is the highest for the conventional PM machine (RFSM-S). In general, non-slotted machines have less ripple torque than slotted topologies. As for the non-slotted axial flux machines, slotless TORUS machine has the lowest ripple torque compared to the other topologies and slotless RFSM machine has the highest ripple torque component compared to the other non-slotted machines.



(a) (b)

Fig. 13. Cogging torque (a) and ripple torque (b) comparison for radial and axial flux surface magnet PM machines

Table VI shows a summary of the results obtained from mathematical TRF analysis. The table shows the ripple torque in pu for different machines with and without skewed PMs. As can be seen from the comparison between the two approaches, results obtained from mathematical approach agrees well with the finite element approach for slotless topologies since the armature reaction of non-slotted topology machines is quite small. However, the armature reaction of slotted topologies strongly interferes with airgap flux field which results in stronger harmonic components. Therefore, ripple torque by mathematical approach is slightly less than that by FEA approach. Besides, it was assumed that the motor is unsaturated and armature reaction is neglected in the mathematical analysis. Since the effect of armature reaction is significant in slotted machines, a small discrepancy between the TRF and FEA approaches can be expected for slotted axial flux machines. Torque ripple sensitivity (TRS) to skew angle is also illustrated in the table. It shows that peak-to-peak ripple torque in slotless topologies is less sensitive to skew angle change than that in slotted topologies because of the armature reaction effect.

TABLE VI
RIPPLE TORQUE COMPARISON OF RADIAL AND AXIAL FLUX MACHINES USING MATHEMATICAL APPROACH

	Non-slotted with rectangular shaped winding or slotted with double layer lap winding			Non-slotted with pie shaped winding or slotted with back to back connected winding		
	without skewed PM	with skewed PM	TRS factor*	without skewed PM	with skewed PM	TRS factor*
RFSM-NS	0.037	0.014	2.64	---	---	---
RFSM-S	0.37	0.031	11.9	---	---	---
TORUS-NS	0.11	0.057	1.93	0.037	0.014	2.64
TORUS-S	0.33	0.030	11.0	0.35	0.041	8.53
AFIR-NS	0.11	0.056	1.96	0.037	0.014	2.64
AFIR-S	0.33	0.029	11.3	---	---	---

*Torque ripple sensitivity (TRS)=Ripple torque at non-skewed PM/Ripple torque at skewed PM

VI. CONCLUSIONS

In this paper, a study of pulsating torque analysis using mathematical approach was described. A detailed 2D and 3D Finite Element Analysis for axial flux machines to predict both cogging and ripple torque behavior was illustrated. Both approaches were compared. The following conclusions can be obtained from both mathematical approach and finite element approach:

- Skewing the PMs with optimum skew angle is an important tool in minimizing the pulsating torque component.
- In axial flux surface-magnet disc motors, replacing the gramme type rectangular shaped winding with the pie shaped winding helps reduce the torque ripple component of the slotless topologies by providing a better stator utilization.
- Ripple torque is sensitive to the change of skew angle and pole-arc ratio. Using this principle, a ripple torque minimization technique was developed using skewing and choosing the PM arc ratio.
- Ripple torque sensitivity ratio for PM motors implies that the ripple torque performance of the PM motors will fluctuates due to small change of the skew angle and PM arc ratio.
- Precise design and manufacture of the skew angle and PM arc ratio is very important for high torque quality PM motors even though it increases the manufacturing cost.
- Non-slotted PM motors are less sensitive to ripple torque than slotted type PM motors, which implies that non-slotted topologies are better than the slotted topologies in terms of ripple torque stability.

VI. ACKNOWLEDGMENTS

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