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Cogging Torque Minimisation of PM Disc Motor by Inserting Stator Slot Closure and Magnet Skewing

***Abstract**. A variety of techniques exist for reducing the cogging torque of conventional radial flux PM machines. This paper presents an application of two cogging torque minimization techniques in which the permanent magnets are skewed in a conventional manner and the stator slots are closed with soft magnetic composite material. The comparative analysis of the different motor designs regarding the cogging torque is performed by using data from a quasi 3DFEM calculation of the adequately FEM modelled motor solutions.*

***Streszczenie.** Istnieją różnorodne sposoby redukcji momentu uzębienia w konwencjonalnych maszynach z magnesem trwałym ze strumieniem promieniowym. Artykuł przedstawia zastosowanie dwóch sposobów minimalizacji momentu uzębienia, w których magnesy trwałe są skoszone w sposób konwencjonalny a żłobki stojana są zamknięte miękkim kompozytowym materiałem magnetycznym. Analiza porównawcza różnych projektów silnika co do momentu uzębienia przedstawiono za pomocą danych z obliczeń quasi-3D metodą elementów skończonych. (**Minimalizacja momentu uzębienia silników dyskowych z magnesami trwałymi poprzez zamknięcie żłobków stojana i skoszenie magnesów trwałych**)*

Keywords: cogging torque minimisation, PM disc motor, permanent magnet skewing, stator slot closure.
Słowa kluczowe: minimalizacja momentu uzębienia, silnik dyskowy z magnesem trwałym, skoszenie magnesu trwałego, zamknięcie żłobków stojana.

Introduction

Torque quality is very decisive issue for variable speed drive applications. There exist two undesired pulsating torque components in PM machines which affect the machine performance; one is ripple torque arising from harmonic content of the machine voltage and current waveforms, and the other is cogging torque caused by the attraction between the rotor magnetic field and angular variations of the stator reluctance. These components not only affect the self-starting ability of the motor, but also produce noise and mechanical vibrations.

Many techniques for cogging torque minimisation are documented in the literature for PM machines, due to the high demand on PM machines for high performance applications. These techniques include magnet pole shape, skewing stator tooth or rotor magnets, magnet or pole shifting, pole-arc ratio and stator slot design, dummy slots on the stator tooth, varying the radial shoe depth and graded air gaps. Most of the techniques mentioned can be also applied to axial flux machines. In this paper the cogging torque will be minimised by applying a conventional permanent magnet skewing, as well as novel stator slots closing technique using soft magnetic composite (SMC) material.

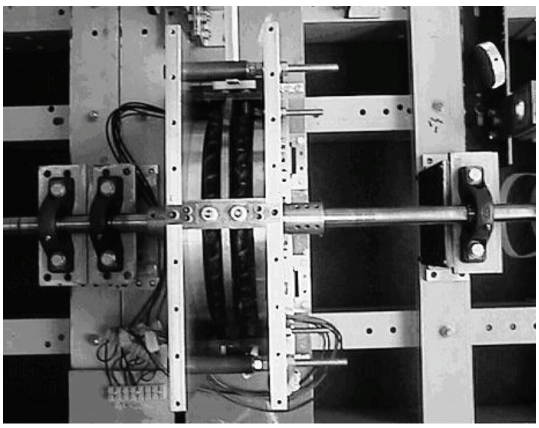


Fig.1. PMDM presentation-view from above

Motor description and presentation

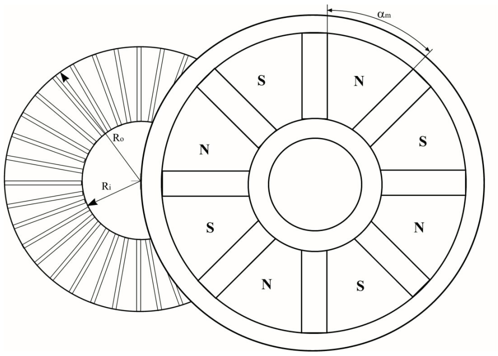
The motor used for this cogging torque analysis is a prototype brushless three phase synchronous permanent magnet disc motor (PMDM) fed by a PWM inverter connected to a rechargeable battery supply or a fuel cell. This motor is a double-sided axial field motor with two laminated stators having 36 slots and a centred rotor with 8 neodymium-iron-boron permanent magnets. In this type of motor the slots become progressively farther apart as the laminations occupy a greater diameter. Torque is very important parameter in variable speed drive applications, especially when they are applied in electric vehicles as in this case. The rated data are: I=8.7 A, T=54 Nm and n=750 rpm @ 50 Hz. The presentation of the permanent magnet disc motor is given in Fig. 1.

Cogging torque minimisation techniques

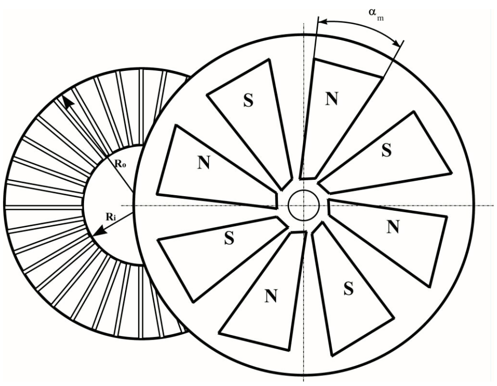
Cogging torque minimisation is becoming necessary since the motor is finding its application in torque-ripple-sensitive drives such as electric power steering, robotics, electric vehicles, and indeed, any application where minimizing torque ripple, vibration, and noise is an essential requirement. Ideally, the desired torque-ripple minimisation scheme should not only minimise the torque ripple due to cogging torque, but also minimise the other sources of torque ripple without sacrificing the average torque value. Hence, proper engineering judgment should be exercised when a particular scheme has been chosen for accomplishing the objective for either a trapezoidal or a sinusoidal back electromotive force (EMF). The interaction between the stator teeth and the permanent magnets yields the cogging torque. Several methods have been reported in the literature [1-2] to reduce the cogging torque. The magnet pole arc design, skewing of rotor magnets or stator slots, step skew of the magnets, dummy slots, PM shifting, etc., are well-known and effective techniques for reducing the cogging torque. In this paper one of this techniques will be incorporated such as permanent magnet skewing, and a novel one will be introduced where the stator slots will be closed with SMC material. Thus, four motor topologies are possible: PMDM with standard permanent magnets and open slots, PMDM with standard permanent magnets and closed slots, PMDM with skewed permanent magnets and open slots, and PMDM with skewed permanent magnets and closed stator slots. In the paper, all configurations will be analysed.

Permanent magnet skewing technique

The first technique that will be applied in the design of the motor is the magnet skewing, as an effective and simple approach to cogging torque minimisation , used frequently in PM machines. Its application is even easier in axial flux machines than in radial flux machines, due to their flat magnet surface and simpler magnet geometry. Both stator slot and magnet skewing add complexity and cost to the overall drive system. Stator skewing complicates automatic winding of the coils. Hence, for mass-production rotor magnet skewing is more popular than stator skewing. As known from theory, the permanent magnet skewing is done by one stator slot pitch. A series of cogging torque simulations using quasi-3D FEA are performed, for both models with unskewed and skewed permanent magnets. The geometry of these models is shown in Fig. 2.



a) PMDM with unskewed PMs and open slots

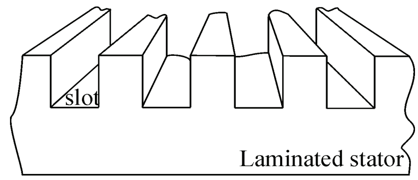


b) PMDM with skewed PMs and open slots

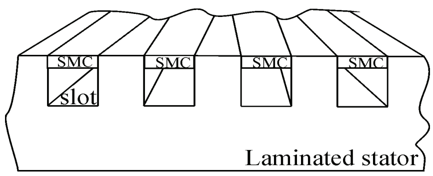
Fig.2 Presentation of the two PMDM models with open slots

Soft magnetic composite material for stator slot closure

The second technique applied in the design procedure of the motor by inserting soft magnetic composite material as stator slot closure [3] is performed. The basis for the material whose utilisation is the subject of this paper is bonded iron powder. The powder is coated, and then pressed into solid material using a die and finally heat treated to anneal and cure the bond. This material at high frequencies has relatively high permeability and lower loss values. This property together with the isotropic characteristics of the material along all three axes provides significant cost and performance advantages over other materials. Although the SMC materials have low permeability and high specific iron loss at low frequencies in the recent years they became very attractive for use as magnetic core parts or for manufacturing the stator cores of permanent magnet motors in general. The low value of the SMC material permeability (≤800) in PM motor application does not affect the overall performance of the motor as it does in induction and reluctance motor applications. Other very important favourable property of the SMC material is their isotropy and rather good iron loss at high frequencies, which are usually generated by the inverter performance. All disadvantages mentioned above can be annulled by the most important feature of the SMC material; can be shaped in complex forms, and the surface can later be finished very smoothly. This property makes the SMC material very attractive for producing a stator slot closure or complex shaped stator, as it is the disc stator of the PMDM. The very fast development of new soft magnetic composite materials with improved magnetic properties goes in favour of the application of this material for producing also stator cores. The analysed motor is with laminated stators made of grain oriented silicon steel strip with thickness of 0.3 mm (Telmag), while the SMC material stator slots closures are made of SOMALOY^{TM}500 (Höganas). A series of cogging torque simulations using quasi-3D FEA are performed, for both models with unskewed and skewed permanent magnets and with SMC material used as stator slot closure. Partial and full presentation of these models is shown in Fig. 3 and Fig. 4, respectively.

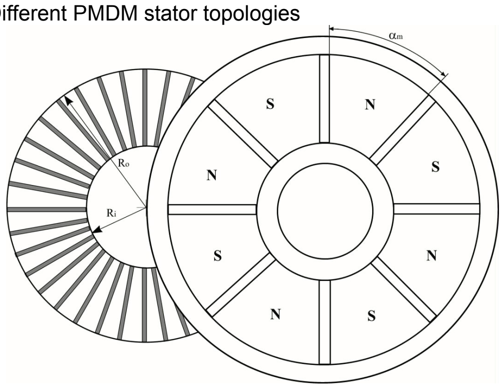


a) Open slot model

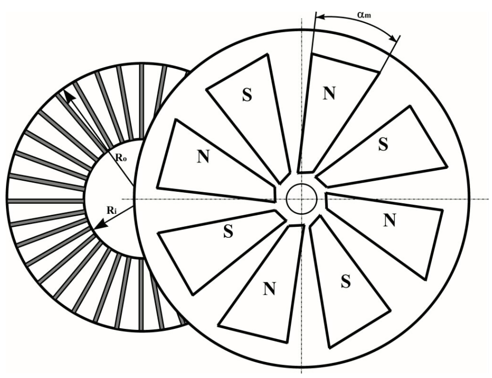


b) Closed stator slot model with SMC material

Fig.3 Different PMDM stator topologies



a) PMDM with unskewed PMs and SMC slot closure

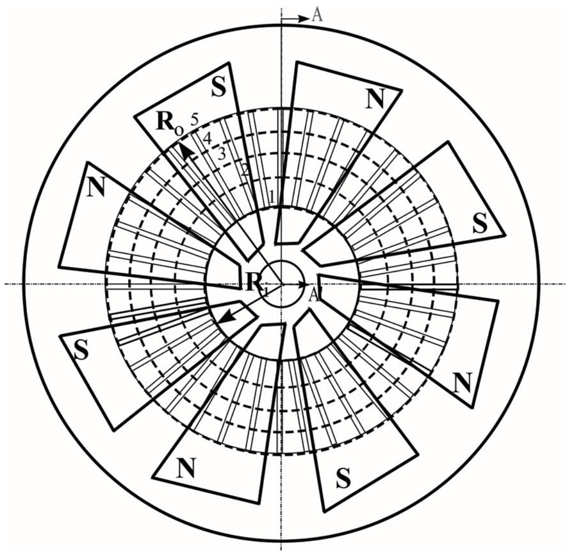


b) PMDM with skewed PMs and SMC slot closure

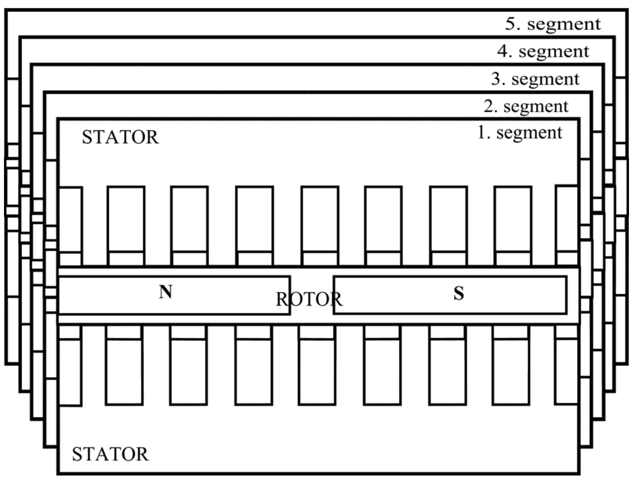
Fig.4 Presentation of the two PMDM models with SMC slot closure

Structural modelling of the PMDM for FEM analysis

In order to be able to analyse the four models of the PMDM with different topologies accurately, a calculation of the magnetic field has to be performed for all models. The quasi-3D method which is adopted for this analysis consists of a 2D FEM calculation of the magnetic field in a three dimensional radial domain of the axial field motor. For this purpose, a notional radial cut through the two stators and one rotor of the disc motor is performed and then opened out into linear form, as shown in Fig.5. By using this linear quasi three-dimensional model of the disc motor, which is divided into five segments, it is possible to model the skewing of the magnets and also to simulate the vertical displacement and rotation of the rotor.



a) Motor

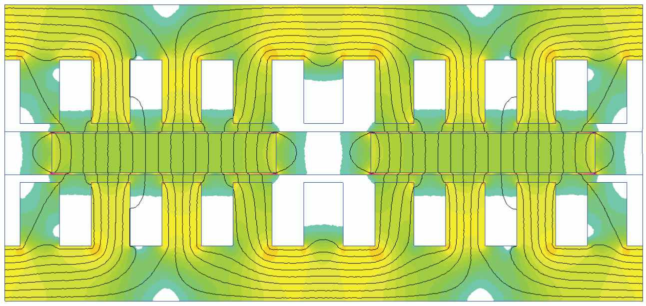


b) segments

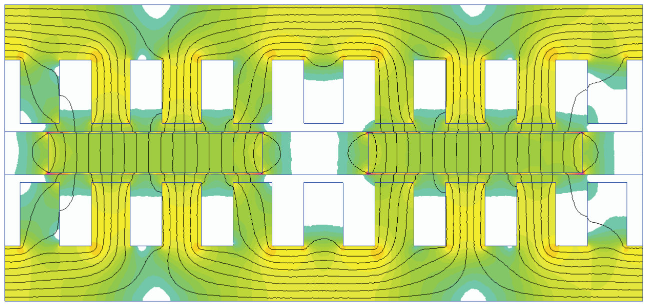
Fig.5 Radial division of the motor into 5 segments

Magnetic field analysis

After the motor has been modelled, a 2D FEM magnetic field calculation of the four motor models at no load and for different rotor positions is performed. The distribution of the magnetic field only for the middle (third) segment at no load for the open slot models with unskewed and skewed PMs, as well as for the SMC closed slots models with unskewed and skewed permanent magnets are presented in Fig. 6, and Fig. 7, respectively.

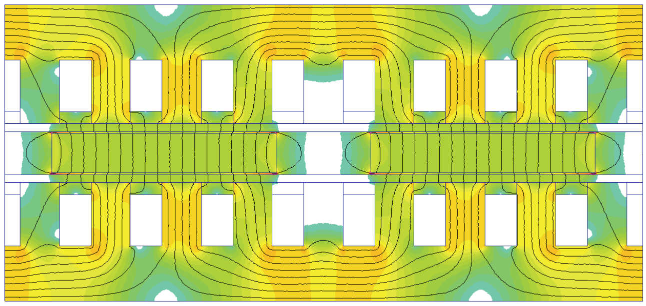


a) PMDM with unskewed PMs and open slots

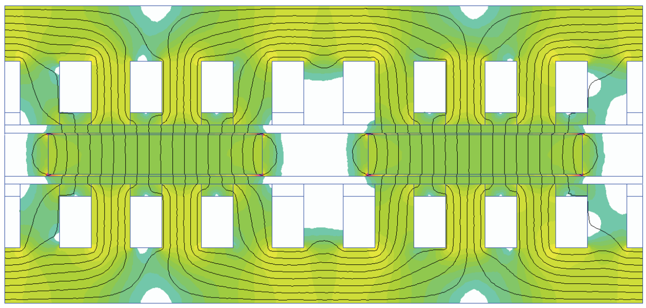


b) PMDM with skewed PMs and open slots

Fig.6 Magnetic field distribution for the middle segment



a) PMDM with unskewed PMs and SMC closed slots



b) PMDM with skewed PMs and SMC closed slots

Fig.7 Magnetic field distribution for the middle segment

Cogging torque analysis

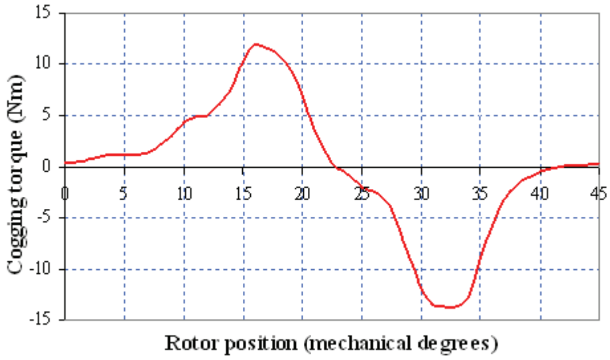
As mentioned before, the cogging torque is one of the most important sources of torque pulsating in PM machines. The cogging torque is caused by the attraction between the rotor magnetic field and the angular variations of the stator reluctance. By definition, no excitation current is involved in cogging torque production. Therefore it is essential to properly determine the cogging torque distribution in relation to the different rotor angular position. The computation of the cogging torque is performed by using the data from the FEM analysis of the motor at no load. The waveform of the cogging torque calculated for all four PMDM topologies is presented in Fig. 8 and Fig. 9. Cogging torque is determined by calculating the change of reluctance in the air gap with respect to the rotor position for one segment; hence, it can be expressed as:

(1) $$T_{cog,i}(\theta_r) = -\frac{1}{2}\Phi_g^2 \frac{dR}{d\theta_r}$$

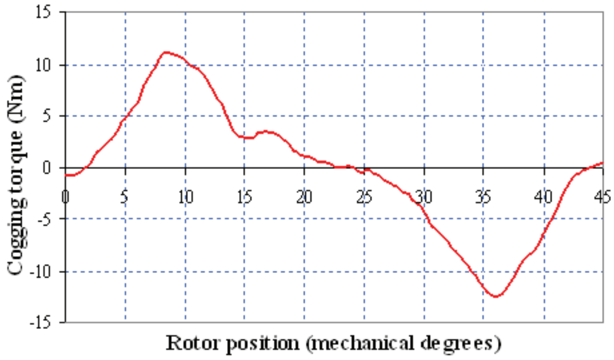
where Φ_g is the air gap flux, R is the air gap reluctance and θ_r is the angular rotor position. The total cogging torque T_{cog} produced by the machine is obtained from the following equation

(2) $$T_{cog}(\theta_r) = \sum_{i=1}^{n} T_{cog,i}(\theta_r)$$

where n is the number of segments.



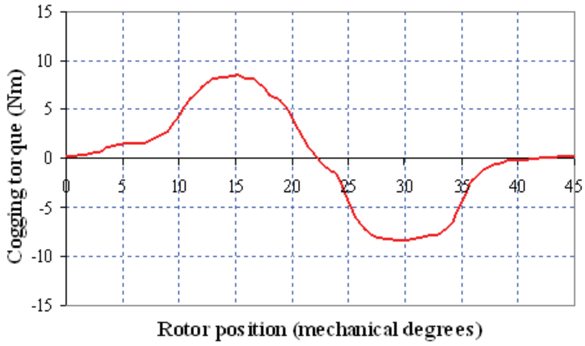
a) PMDM with unskewed PMs and open slots



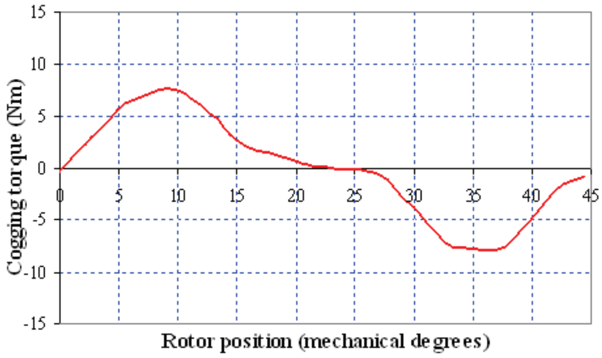
b) PMDM with skewed PMs and open slots

Fig.8 Cogging torque distribution

From the presented cogging torque distribution it can be concluded that two solutions with stator slot closures have a significant decrease of the maximum cogging torque value, compared to the maximum cogging torque with open slot solutions. On the other hand, for the analysed type of motor the skewing of the permanent magnets for one slot pitch did not show a significant decrease of the peak cogging torque value. For that reason in future an investigation can be performed for determination the optimal skewing angle. Since the permanent magnet disc motor solution with skewed permanent magnets and soft magnetic composite material closed slots had the best performance results regarding the cogging torque it was decided to be constructed, and further investigated.



a) PMDM with unskewed PMs and SMC closed slots



b) PMDM with skewed PMs and SMC closed slots

Fig.9 Cogging torque distribution

Conclusion

In this paper, two different cogging torque minimisation techniques, such as PMs skewing and SMC material stator slot closure, for PMDM have been studied. The investigated topologies of the PMDM are with standard PMs and both open slots and closed slots, as well as with skewed PMs and both open and closed slots. The effectiveness of the applied techniques, and the gained results for all four PMDM models has been examined by quasi-3D finite element analysis and the cogging torque distributions are compared. The technique in which SMC material has been inserted as stator slot closure showed much better results in the attempt to reduce the cogging torque of the PMDM in relation to the skewing of the permanent magnets. It is important to emphasise that the application of slot closures is easier and more efficient applied, than permanent magnet skewing.

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