Goga CVETKOVSKI[1], Lidija PETKOVSKA[1], Paul LEFLEY[2]

Ss. Cyril and Methodius University (1), University of Leicester (2)

Topological modifications in function of cogging torque reduction of permanent magnet synchronous motor

***Abstract**. In this paper the influence of some design parameters on the cogging torque development by a surface mounted permanent magnet motor is investigated. The investigation is focused on the implementation of stator core skewing and dummy slots in the stator teeth and their influence on the cogging torque reduction of the motor. The cogging torque is calculated numerically for the different motor solutions by using finite element method analysis.*

***Streszczenie.** W artykule zaprezentowano badania nad wpływem pewnych parametrów projektowych na rozwój momentów pulsacyjnych powstałych w wyniku zamontowania powierzchniowego magnesu trwałego. Badania skupione są na implementacji rdzenia stojana ze skoszonymi żłobkami i pustymi żłobkami w zębach oraz ich wpływem na redukcję pulsacyjnych momentów w silniku. Moment pulsujący wyznaczany jest numerycznie przy użyciu metody elementów skończonych dla różnych rozwiązań silnika. (**Modyfikacje topologiczne dla redukcji momentu pulsacyjnego w silniku synchronicznym z magnesem trwałym**).*

Keywords: Skewing, dummy slots, cogging torque, PM synchronous motor.
Słowa kluczowe: skos żłobków, puste żłobki, moment pulsacyjny, silnik synchroniczny z magnesem trwałym.

doi:10.12915/pe.2014.12.26

Introduction

The cogging torque results from the interaction between the permanent magnets on the rotor and the stator anisotropy, due to the stator slotting. Many techniques for cogging torque minimisation for PM machines in the literature [1] are documented, 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 teeth, varying the radial shoe depth and graded air gaps.

The investigated object a brushless three phase synchronous permanent magnet Koncar motor type EKM 90M-6 has 36 stator slots and a rotor with 6-skewed $SmCo_5$ surface mounted permanent magnets with B_r=0.95 T. The rated data of the motor are: I=18 A, T=10 Nm and n=1000 rpm @ 50 Hz. The presentation of the permanent magnet synchronous motor (PMSM) is given in Fig. 1. In this paper the investigation of the cogging torque reduction will be realised on this motor by implementation of stator core skewing and dummy slots in the stator teeth, separately.

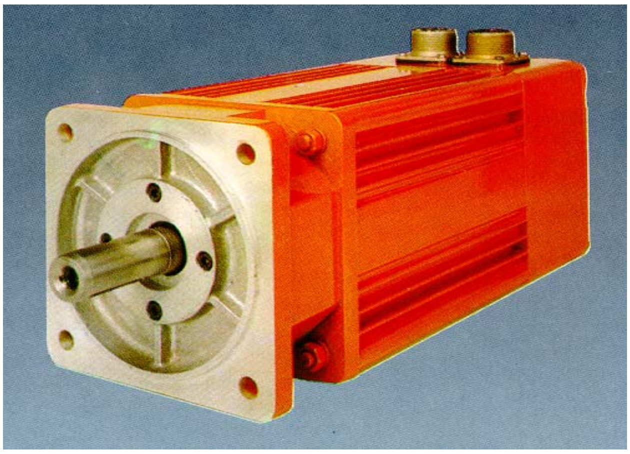

Fig.1. Outer view of the permanent magnet synchronous motor

Cogging Torque Calculation Using FEM

In order to be able to analyse the different PMSM motor models accurately, a calculation of the cogging torque has to be performed for the different motor topologies. The cogging torque, as well as the electromagnetic torque can be determined analytically [2] or numerically by using finite element method. The authors of this paper will use the finite element method approach. The software used for this performance analysis is called Finite Element Method Magnetics-FEMM [3]. This software performs a quasi-two dimensional calculation of the magnetic field in the motor. This means that the magnetic field is calculated in a 2D domain of the motor, but during the calculations it also takes into account the axial length of the motor which is predefined in the pre-processing stage.

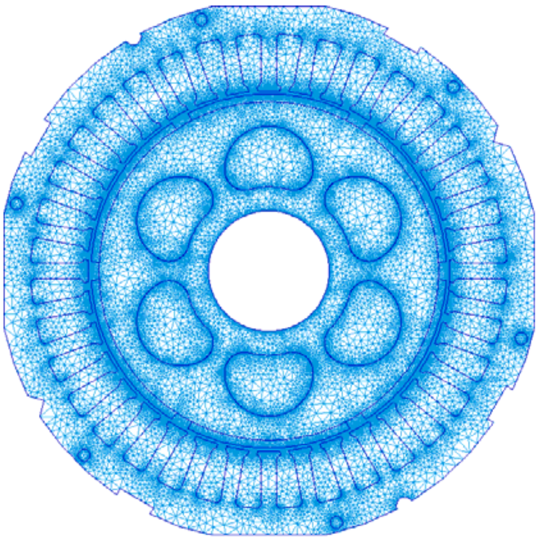

Fig.2. Mesh presentation of PMSM model

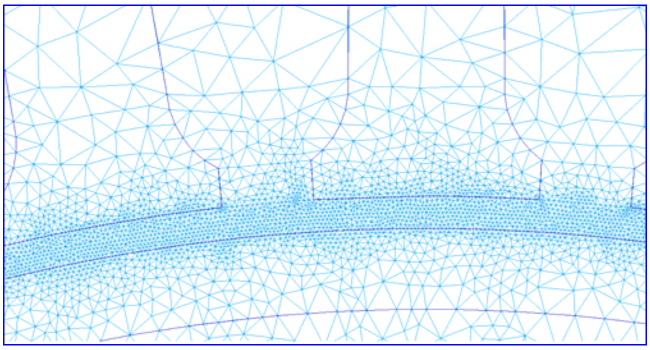

Fig.3. Partial mesh presentation of PMSM model in the air gap

This type of calculation of the magnetic field distribution in the motor is more suitable for this geometry of motor and has a lot of advantages over the three dimensional calculation that is more complicated and also time consuming. The two dimensional presentation of the mesh for the PMSM with reduced number of finite elements for a better view is presented in Fig. 2. In order to have more precise results for the cogging torque, a more dense mesh in the air gap is defined, as presented in Fig. 3.

After the motor has been properly modelled, a 2D FEM magnetic field calculation of the different motor models at no load is performed. The distribution of the magnetic field at no load for the initial motor model is presented in Fig. 4.

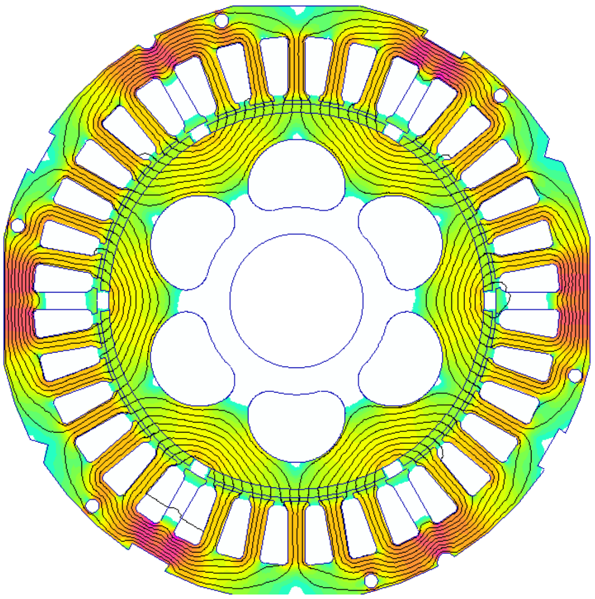

Fig.4. Magnetic field distribution of the initial motor model

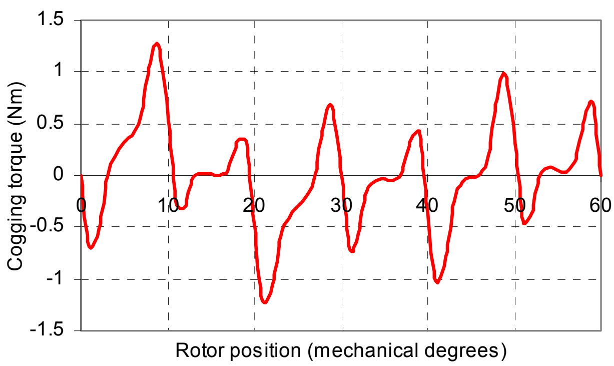

Fig.5. Cogging torque plot for the initial motor model

As it was mentioned before the cogging torque is one of the most important sources of torque pulsating in PM machines. Therefore it is essential to properly determine the cogging torque distribution in relation to the different rotor angular positions. The computation of the cogging torque is performed by using the data from the FEM analysis of the motor at no load.

Cogging torque is determined by calculating the change of the total stored energy in the air gap with respect to the rotor position for one segment and 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 waveform of the calculated cogging torque for the initial PM motor topology is presented in Fig. 5.

Stator Core Skewing

A well known method to reduce the cogging torque is the skewing of the stator slots, or alternatively, of the permanent magnets, with the same result. In order to minimise the cogging torque to great extend the skewing angle θ_{sk} has to be equal to:

(2) $$\theta_{sk} = \frac{1}{N_p} \cdot \frac{2\pi}{N_{slots}}$$

where: N_{slots} number of stator slots and N_p is the number of periods per one stator slot, and can be calculated by using the following equation

(3) $$N_p = \frac{2\pi}{HCF(N_{slots}, 2p)}$$

where: HCF is the highest common factor. In this case the skewing angle should be $\theta_{sk} = 10^\circ$, as it is presented in Fig. 6.

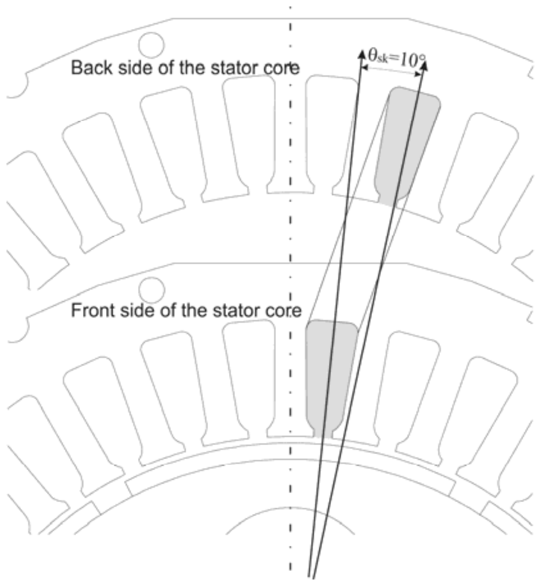

Fig.6. Stator core skewing

In order to model the skewing of the motor the axial length of the motor was divided into 6 equal segments. The calculation of the magnetic field and the cogging torque is performed for all six segments for different rotor positions.

The total cogging torque T_{cog} produced by the machine is obtained from the following equation

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

where n is the number of segments. The cogging torque waveforms for all segments are shown in Fig. 7 and the total cogging torque compared with the initial one is presented in Fig. 8.

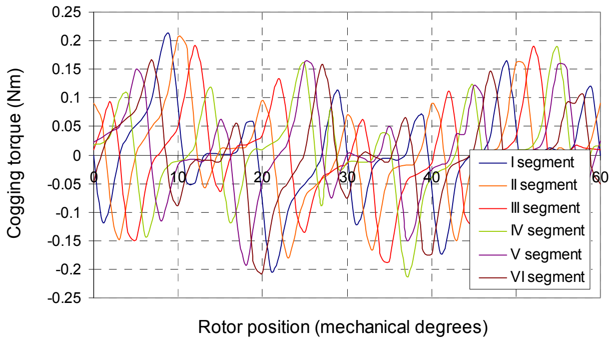

Fig.7. Cogging torque waveforms for all six skewing segments

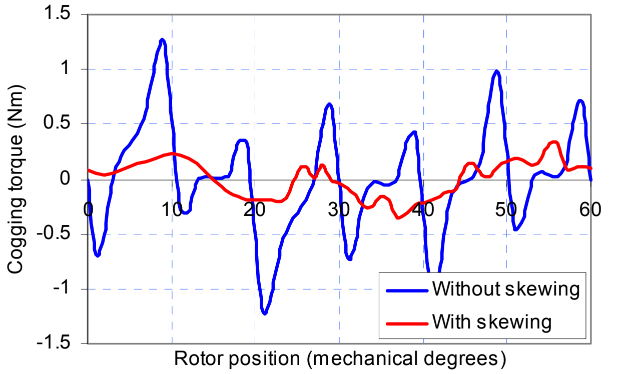

Fig.8. Cogging torque comparative plot for the initial motor and the motor model with skewing

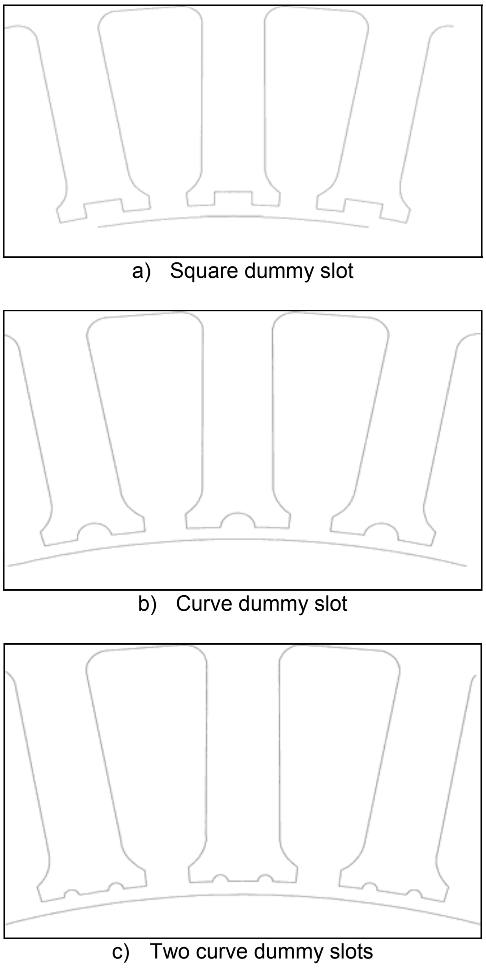

Fig.9. Dummy slots in stator teeth

Dummy Slots in Stator Teeth

Another technique that is applied in order to reduce the cogging torque is the implementation of dummy slots in the stator teeth [4]. Usually they are equally spaced and as wide as the opening of the actual slots. In this paper the influence on the cogging torque by implementation of different shapes and number of dummy slots is investigated. A presentation of the different dummy slots is shown in Fig. 9. The investigated dummy slot shapes on the stator teeth are: rectangular dummy slot with the same size as the stator slot opening, single curve dummy slot and two smaller curve dummy slots. In these investigations the skewing of the stator is not taken into account.

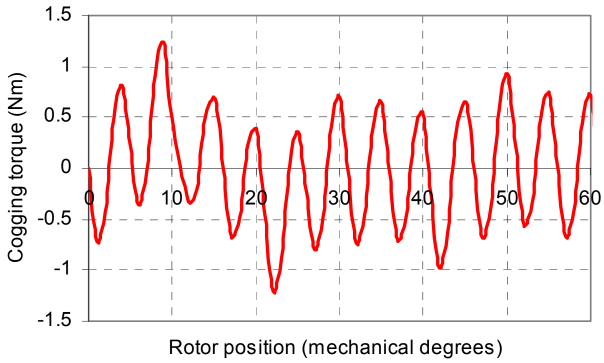

Fig.10. Cogging torque plot for the motor model with squared dummy slots on stator teeth

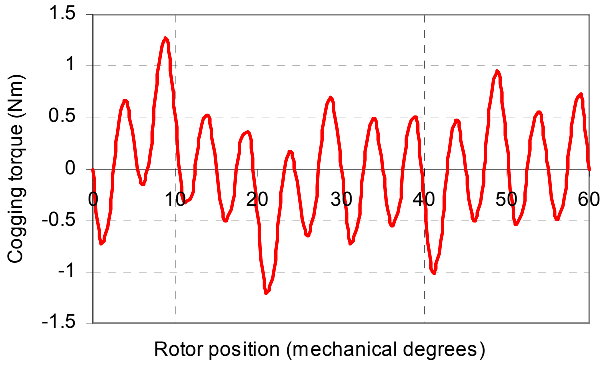

Fig.11. Cogging torque plot for the motor model with one curve dummy slot on stator teeth

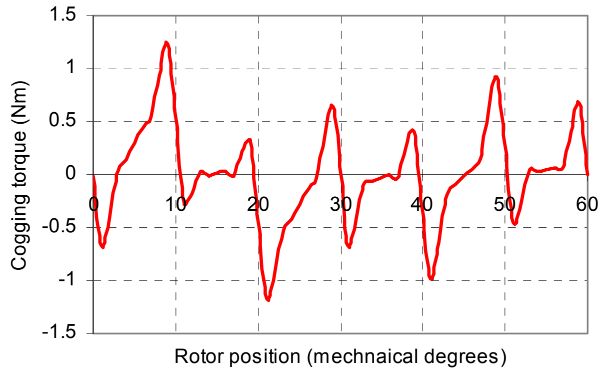

Fig.12. Cogging torque plot for the motor model with two curve dummy slots on stator teeth

The cogging torque for all the solutions with different dummy slots, as it has been done previously, is determined by using finite element method based computer programme called FEMM. The cogging torque distribution for different rotor positions for the proposed three solutions with different dummy slots shapes are presented in Fig. 10, Fig. 11 and

Fig. 12. The effective reduction of cogging torque includes reduction of the amplitude and increase of the number of cycles per mechanical revolution [5]. In the presented cogging torque techniques in this paper only a partial improvement was realised. By skewing of the stator core a significant reduction of the amplitude was realised. On the other hand by adding dummy slots to the stator teeth an incensement of the number of cycles per mechanical revolution was realised by unfortunately only a very small cogging torque amplitude reduction was realised. This suggests that a combination of stator skewing and implementation of dummy slots in the stator teeth might give a much better result, and the authors will take this as a future task. Also a reduction of the cogging torque amplitude can be realised by inserting soft magnetic composite (SMC) material in the stator slots openings that was analysed in some previous authors' works [6, 7].

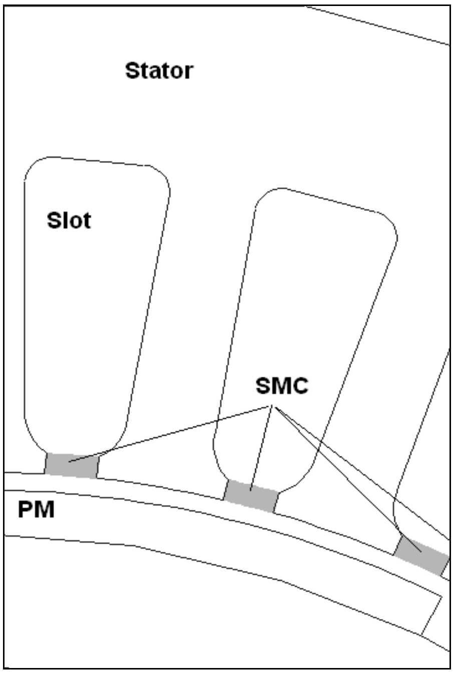

Fig.13. Soft magnetic composite material as stator slots closure for cogging torque reduction

Finally it can be summarised that a valuable reduction of the cogging torque in a PMSM can be realised by a combination of some of the techniques mentioned in this papers, as well as with some of the previously mentioned and investigated techniques. Such an investigation will be in the focus of the near future research work of the authors.

Conclusion

Various techniques for minimising cogging torque of a PMSM have been presented and examined. The aim of the paper is to give a unified description of the effects by each technique on the cogging torque of PMSM and determine the most suitable one for the motor. Different cogging torque reduction techniques such as stator skewing and implementation of different number and shape of stator teeth dummy slots have been investigated. Finite element method software has been used for determination of the cogging torque for the different solutions. The results are graphically presented and number of suggestions for cogging torque reduction and future work are given.

REFERENCES

[1] Zhu Z. Q., Howe D., Influence of Design Parameters on Cogging Torque in Permanent Magnet Machines, *IEEE Transactions on Energy Conversion*, 15 (2000), No. 4, 407-412.
[2] Virtič P., Pišek P., Hadžiselimović M., Marčič T., Štumberger B., Torque analysis of an axial flux permanent magnet synchronous machine by using analytical magnetic field calculation, *IEEE Transactions on Magnetics,* 45 (2009), 1036-1039.
[3] Meeker D. FEMM-Finite Element Method Magnetics Software", *User's Manual,* 2002, 155.
[4] Bianchi N., Bolognani S. Design Techniques for Reducing the Cogging torque in Surface-Mounted PM Motors, *IEEE Transactions on Industry Applications*, 38 (2002), No, 5, 1259-1265.
[5] Islam M., Mir S., Sebastian T., Issues in Reduction of Cogging Torque of Mass-Produced Permanent-Magnet Brushless DC Motor, *IEEE Transactions on Industry Applications*, 40 (2004), No, 3, 813-820.
[6] Cvetkovski G., Petkovska L., Performance Improvement of PM Synchronous Motor by Using Soft Magnetic Composite Material, I*EEE Transactions on Magnetics,* 44 (2008), No.11, 3812-3815.
[7] Petkovska L., Cvetkovski G., Lefley P. Design Consideration of Permanent Magnet Motor for Cogging Torque Reduction, *Proceedings of ISEF'2013*, PS1-250_1-8.

***Authors**: prof. dr Goga Cvetkovski, Ss. Cyril and Methodius University, Faculty of Electrical Engineering and Information Technologies, Rugjer Boskovic bb, P.O. Box 574, 1000 Skopje, Republic of Macedonia, E-mail: gogacvet@feit.ukim.edu.mk; prof. dr Lidija Petkovska, Ss. Cyril and Methodius University, Faculty of Electrical Engineering and Information Technologies, Rugjer Boskovic bb, P.O. Box 574, 1000 Skopje, Macedonia, E-mail: lidijap@feit.ukim.edu.mk; prof. dr Paul Lefley, University of Leicester, Department of Engineering, University Road, Leicester LE1 7RH, UK, E-mail: pwl3@le.ac.uk.*