Journal of Energy Technology

JET Volume 12 (2019) p.p. 31-41
Issue 3, November 2019
Type of article 1.04
www.fe.um.si/en/jet.html

INFLUENCE OF ROTOR STRUCTURE ON COGGING TORQUE IN A SURFACE-MOUNTED PM-GENERATOR

VPLIV KONSTRUKCIJE ROTORJA NA SAMODRŽNI VRTILNI MOMENT GENERATORJA S POVRŠINSKO NAMEŠČENIMI TRAJNIMI MAGNETI

Greconici Marian[1], Madescu Gheorghe[2], Milosevici Daniela[3],
Biriescu Marius[4], Mot Martian[4,ℜ]

Keywords: cogging torque, electrical machines, FEM analysis, surface-mounted PM generator

Abstract

This paper deals with the analysis of the cogging torque in a surface-mounted permanent magnet generator in order to determine some techniques to minimize or eliminate the cogging torque. The simulation with finite element method (FEM) was carryout. A four-pole surface-mounted PM generator is investigated in the paper using FEM. The paper analyses the possibilities to reduce this type of torque by producing some asymmetry in the rotor structure. Two types of asymmetry were analysed: the PM pole arc with different widths, and the shifting of the PM. The numerical results obtained in the asymmetrical cases with symmetrical ones were compared and discussed. Finally, some conclusions are highlighted regarding the simulated results.

ℜ Corresponding author: Lecturer dr. ing, Moţ Marţian Tel.: +40-256-40-3454, Mailing address: Timişoara, România, B.dul V. Pârvan nr.2, E-mail address: martian.mot@upt.ro

[1] Politehnica University of Timişoara, Fundamentals of Physics for Engineers Department, Timişoara, Romania, B.dul V. Pârvan nr.2.

[2] Romanian Academy – Timişoara Branch, Timişoara, Romania, B.dul M. Viteazul nr. 24

[3] Faculty of Technical Sciences Cacak, Svetog Save 65, 32102 Cacak, Serbia

[4] Politehnica University of Timişoara, Electrical Engineering Department, Timişoara, Romania, B.dul V. Pârvan nr.2.

Povzetek

Članek obravnava analizo samodržnega vrtilnega momenta generatorja s površinsko nameščenimi trajnimi magneti z namenom določitve konstrukcijskih izboljšav oz. metod za zmanjšanje tovrstnega vrtilnega momenta. Obravnavan je štiri polni generator s površinsko nameščenimi trajnimi magneti pri čemer je analiza izvedena z uporabo metode končnih elementov (MKE). V prispevku so analizirane možnosti za zmanjšanje samodržnega vrtilnega momenta z uvedbo asimetrije na rotorju. Analizirana sta dva tipa asimetrije: spremenjena dolžina obodnega loka trajnih magnetov in zamik trajnih magnetov. Pridobljeni numerični rezultati za asimetrične primere so primerjani z simetričnimi. V zaključku sledi razprava v zvezi s pridobljenimi rezultati numeričnih simulacij.

1 INTRODUCTION

The permanent magnet (PM) generator has many attractive characteristics, such as high efficiency and high torque/power density. Consequently, the use of PM machines has increased significantly in the previous two decades in different industrial applications, mainly due to the diminishing cost of the PMs. The absence of excitation currents and the high power factor make the PM machine a winning solution in many cases. That is why many papers deal with the design and optimization of such electrical machines using analytical and numerical methods, *[1-9]*.

The air gap magnetic field density provides much information about estimating motor performance. Moreover, this magnetic field, as an analytical solution, also allows the calculation of some effects, such as cogging torque, ripple torque, back-EMF shape, etc., *[7, 10, 11, 12]*.

Paper *[13]* compares five analytical models for predicting the cogging torque in surface-mounted permanent magnet machines.

The cogging torque is normally generated due to the presence of stator slots and results from the interaction between the permanent magnet MMF harmonics and the air gap permeance harmonics due to slotting.

Some design parameters have a great influence on the cogging torque. In *[14]*, the authors have introduced a factor that indicates the “goodness” of a slot and pole number combination with regard to cogging torque.

There are several methods to reduce cogging torque, which may be adopted for rotor structure in surface-mounted PM motors, *[15]*: skewing of the stator slots (or of the PMs), notches in the stator teeth, the width of the PM pole arc, PM pole arc with different widths, shifting of the PMs.

In the present paper, the last two techniques to reduce the cogging torque are analysed and compared using an FEM method.

Some conclusions and discussions are made about these calculated results.

2 GENERATOR TOPOLOGY

A simple four-pole surface-mounted PM generator with the topology illustrated in Figure 1 was used for FEM analysis of cogging torque.

The stator has a classical three-phase winding, star connected, with an integer number of slots per pole per phase (*q*=3) and single layer: six coil series connected per phase with 42 turns per coil. The cross-section area of conductor: 1.1 mm^2.

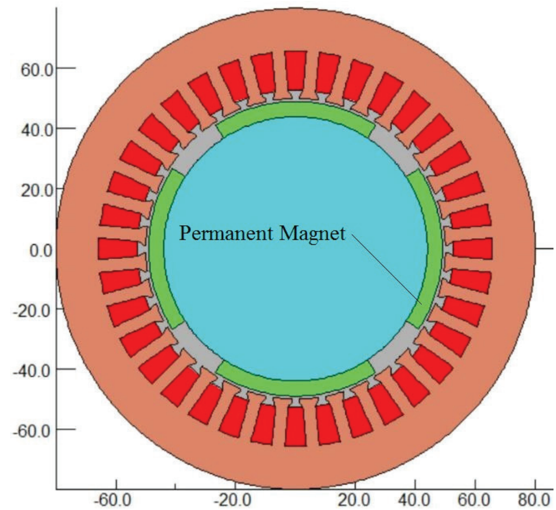

Figure 1: *Cross-section of synchronous surface-mounted PM generator*

The permanent magnets on the rotor surface are mounted. The main specifications of the generator are: power (4 kW); phase number (3); poles number (4); stator slots number (36); stator inner diameter (100 mm); stator length (120 mm); stator outer diameter (160 mm); air-gap thickness (1 mm); permanent magnet thickness (5 mm); Permanent magnet material (NdFeB).

Figure 2 introduces two parameters that are used in the analysis: the width of the PM pole arc (α_m) and the relative position of the magnets (α_{AB}) in the cases of the unsymmetrical arrangement in which the relative positions are different by 90°.

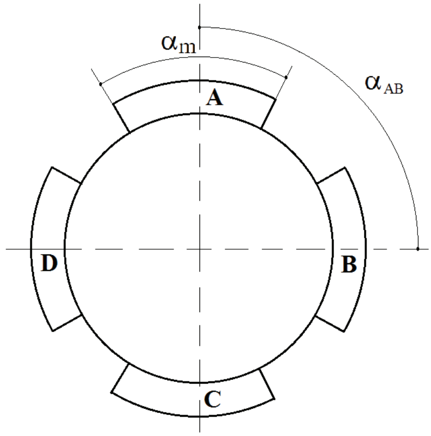

Figure 2: *The width (α_m) and the relative position (α_{AM}) of the magnets*

3 COGGING TORQUE ANALYSIS

The finite element method (OPERA13-Vector Field-software) was used to analyse the cogging torque of a surface-mounted PM generator. Some aspects of these results are presented and discussed.

3.1 Symmetrical rotor structure

In this case, the width of the PM pole arc (α_m) is the same for all the poles (A, B, C, D – Figure 2). Also, the relative position of the magnets present a symmetry, which means α_{AB}= α_{BC}= α_{CD}= α_{DA}=90° (mechanical degree).

In these conditions, Figure 3 shows the air-gap flux density distribution due only to rotor magnets.

The flux density in Figure 3 is provided only by PM with the rotor at standstill (without stator current). It is interesting to note here the same flux density distribution is obtained irrespective of the material placed in the spaces between the PM poles (soft-iron or air). In zone *N* (Figure 3), corresponding to the q-axis, the flux density is zero.

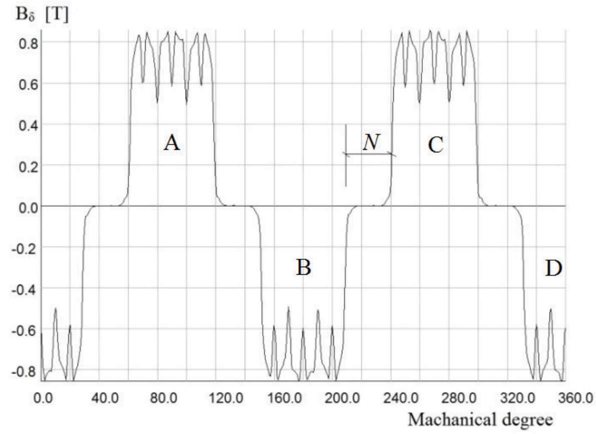

Figure 3: *Air-gap flux density distribution due to rotor magnets*

This air-gap flux density from Figure 3 generates the so-called "cogging torque" component part of the total developed torque. This torque component is due to the presence of stator slots, so that it is zero in slot-less structure. The following expression can be used to calculate this component, *[16]*:

$$T_{cog} = \frac{LR_C^2}{\mu_0} \int_{-\pi}^{\pi} \left(B_{r,PM} \cdot B_{\theta,PM} \right) \cdot \mathrm{d}\theta \tag{3.1}$$

where integration surface is a cylindrical surface in the air-gap with radius R_c and length L (axial length of the stator), and $B_{r,PM}$ and $B_{\theta,PM}$ are, respectively, the radial and tangential components of the air-gap flux density generated by permanent magnets.
Thus, using FEM (in Figure 4) simulated the cogging torque. Again, the same cogging torque waveform as in Figure 4 is obtained in the case with soft-iron pieces placed between the PM poles. The magnitude of cogging torque is about 4% of the working torque.

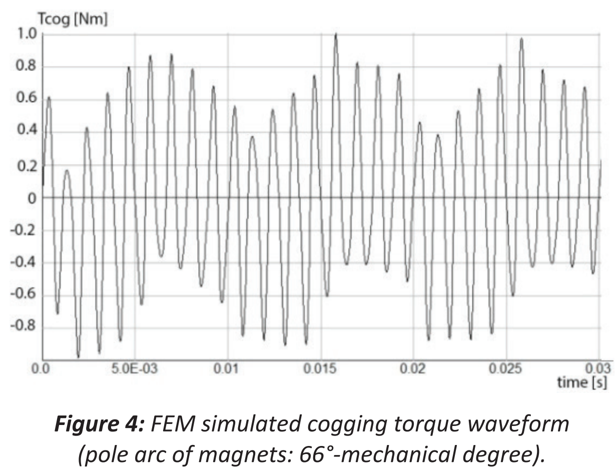

Figure 4: *FEM simulated cogging torque waveform*
(pole arc of magnets: 66°-mechanical degree).

The number of periods of the cogging torque waveforms during a rotation (0.04 s) is 36, equal to the number of teeth (36 teeth).

3.2 PM pole arc with different widths

The PM machine can be designed with PMs of different arc widths (α_m). However, all PM rotors of this kind of structure have the same relative position of the magnets. That means: α_{AB}= α_{BC}= α_{CD}= α_{DA}=90° (mechanical degree).

A little asymmetry of the PM widths along the generator airgap can considerably reduce the cogging torque amplitudes. This asymmetry can be arranged in a different manner.

The first type of arrangement is according to Table 1 and includes the FEM simulated cases.

Table 1: *First type of asymmetry*

Case	α_m mechanical degree			
	A	B	C	D
1	70°	66°	70°	66°
2	74°		74°	
3	78°		78°	
4	82°		82°	
5	86°		86°	

Figure 5 and Figure 6 represent the simulated cogging torque for Cases 1 and 2 of Table 1. One can see the influence of the magnets with different pole widths in these figures.

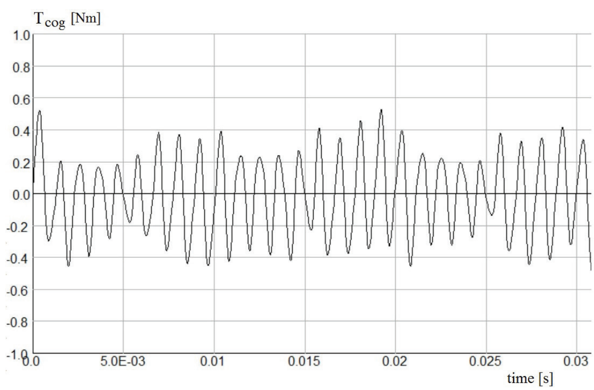

Figure 5: *FEM simulated cogging torque waveform (case1, Table I)*

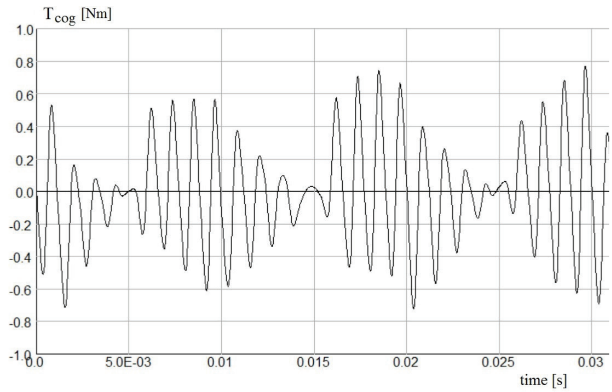

Figure 6: *FEM simulated cogging torque waveform (case2, Table I)*

In Figure 5, it is evident that a small increase in width of the magnets A and C (only 4° mechanical degree) reduces the cogging torque about 50% compared with symmetrical case in Figure 4.

Also, from Figure 6, it can be seen that an additional increase in width of the both A and C magnets does not provide a further decrease of the cogging torque.

Another type of asymmetry is presented in Table 2.

Table 2: *Second type of asymmetry*

Case	α_m mechanical degree			
	A	B	C	D
1	70°	70°	66°	66°
2	74°	74°		
3	78°	78°		
4	82°	82°		
5	86°	86°		

Figure 7 and Figure 8 show the cogging torque simulations in Cases 1 and 2 of Table 2. From this figure it comes out again that a small asymmetry in PM pole widths (around 4°) for two PM poles (magnets A and B) can reduce the cogging torque by 45% compared with the symmetrical case.

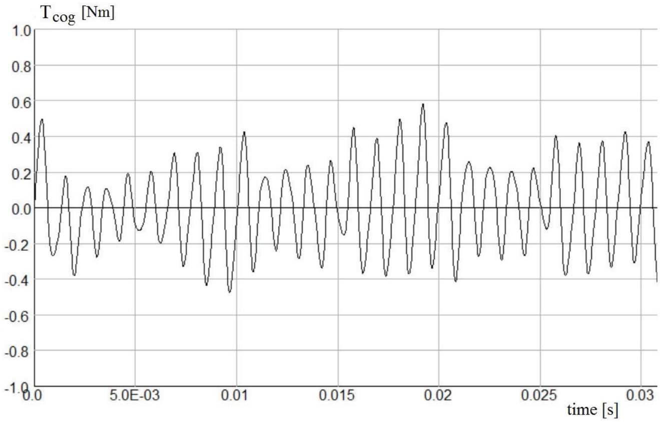

Figure 7: *FEM simulated cogging torque waveform (case1, Table II)*

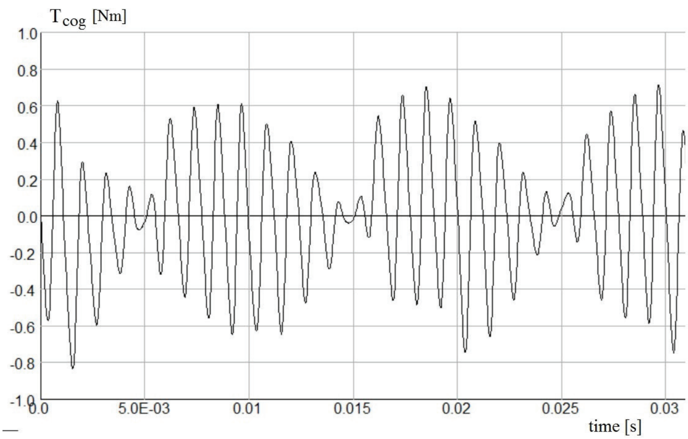

Figure 8: *FEM simulated cogging torque waveform (case2, Table II)*

Consequently, this effect is obtained with a little increase of two PM poles arc (anyone of them), as can be seen in Figure 5 compared with Figure 7.

3.3 Shifting of the PM

The PM generator can be also designed with the same pole arc widths (α_m) and different relative position of the magnets along the airgap. Table 3 includes five cases of this asymmetry type analysed with the FEM method.

Table 3: *Third type of asymmetry*

Case	Pole arc width (α_m)				Position of the magnets			
	A	B	C	D	α_{AB}	α_{BC}	α_{CD}	α_{DA}
1	68	68	68	68	88	92	88	92
2	70	70	70	70	86	94	86	94
3	72	72	72	72	84	96	84	96
4	74	74	74	74	82	98	82	98
5	76	76	76	76	80	100	80	100

Figure 9 shows the simulated cogging torque in Case 1 of Table III. A small asymmetry by shifting of the PM by 2° produces a decrease of the cogging torque by 52% compared with the symmetrical case. A greater shifting in the PM poles distribution along the airgap cannot provide further a smaller cogging torque.

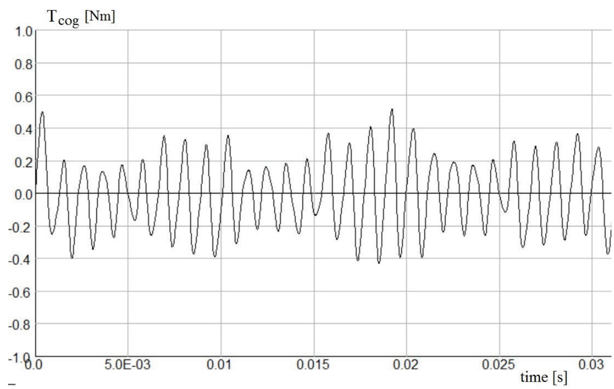

Figure 9: *FEM simulated cogging torque waveform (case1, Table III)*

4 CONCLUSIONS

A four-pole surface-mounted PM generator is investigated in the paper, using FEM. Two methods for minimizing the cogging torque have been analysed. The simulated results show that a small asymmetry in PM pole arc between 4-5% for half of the number of PM poles (anyone of them) is enough to reduce the cogging torque by around 50%. Furthermore, a small asymmetry by shifting of the PM by 2° (mechanical degree) can produce a decrease of the cogging torque by 48%-53%. These two techniques for reducing the cogging torque in a surface-mounted PM generator a very simple and easy to apply.

References

[1] Yao Duan, D. M. Ionel, "A review of recent developments in electrical machine design optimization methods with a permanent magnet synchronous motor benchmark study," *IEEE Transactions on Industry Applications*, 2013, Volume: 49, Issue 3, pp. 1268-1275, DOI: 10.1109/TIA.2013.2252597

[2] S. V. A. Simion, L. Livadaru, N.D. Irimia, F. Lazăr, "FEM analysis of a low speed permanent magnet synchronous machine with external rotor for a wind generator," *Proceedings of OPTIM 2012*, 24-26 May 2012, pp. 624-629, DOI: 10.1109/OPTIM.2012.6231940

[3] M. Pinilla, S. Martinez, "Selection of Main Design Variables for Low-Speed Permanent Magnet Machines Devoted to Renewable Energy Conversion," *IEEE Transactions on Energy Conversion* 2011, Volume: 26, Issue: 3, pp. 940-945, DOI: 10.1109/TEC.2011.2157161

[4] R. Missoum, N. Bernard, M.E. Zaim, J. Bonnefous, "Influence of magnetic materials on maximum power limits of permanent-magnet synchronous machines", *Proceedings of ICEM 2006* paper 696, sept. 4-7, 2006, Chania, Greece

[5] Claudia da Silva, Z. Makni, M. Besbes, C. Marchand, A. Razec, R. Carlson, "Eddy Current Losses and Demagnesization in Permanent Magnets", *Proceedings of ICEM 2006* paper 416, sept. 4-7, 2006, Chania, Greece

[6] N. Bianchi, S. Bolognani, P. Frare, "Design criteria for high-efficiency SPM synchronous motors," *IEEE Transactions on Energy Conversion*, Vol. 21, Issue 2, 2006, pp. 396-404

[7] Aimeng Wang, Yihua Jia, W. L. Soong, "Comparison of Five Topologies for an Interior Permanent-Magnet Machine for a Hybrid Electric Vehicle," *IEEE Transactions on Magnetics*, 2011, Vol. 47, Issue 10, pp. 3606-3609, DOI: 10.1109/TMAG.2011.2157097

[8] Surong Huang, M. Aydin, T. A. Lipo, "Torque quality assessment and sizing optimization for surface mounted permanent magnet machines," *Conference Record of the 2001 IEEE Industry Applications Conference*. 36th IAS Annual Meeting (Cat. No.01CH37248), pp. 1603-610 vol.3, DOI: 10.1109/IAS.2001.955749

[9] V. B. Honsinger, "Performance of Polyphase Permanent Magnet Machines," *IEEE Transactions on Power Apparatus and Systems*, 1980, Vol. PAS-99, Issue: 4, pp. 1510-1518, DOI: 10.1109/TPAS.1980.319575

[10] Z.Q. Zhu, D. Howe, "Instantaneous magnetic field distribution in brushless permanent magnet DC motors. III. Effect of stator slotting", *IEEE Transactions on Magnetics*, 1993 Vol.: 29 , Issue: 1, pp: 143 – 151

[11] A.B. Proca, A. Keyhani, A. El-Antably, Wenzhe Lu, Min Dai, “Analytical model for permanent magnet motors with surface mounted magnets”, *IEEE Transactions on Energy Conversion*, 2003 Vol.: 18 , Issue: 3, pp. 386 – 391

[12] Z. J. Liu, J. T. Li, “Accurate Prediction of Magnetic Field and Magnetic Forces in Permanent Magnet Motors Using an Analytical Solution”, *IEEE Transactions on Energy Conversion*, 2008 Vol. 23, Issue: 3, Pages: 717 – 726

[13] L. J. Wu, Z. Q. Zhu, D. Staton, M. Popescu, D. Hawkins, “Comparison of analytical models for predicting cogging torque in surface-mounted PM machines”, *The XIX International Conference on Electrical Machines - ICEM 2010*, Pages: 1 – 6

[14] Z.Q. Zhu, D. Howe, “Influence of design parameters on cogging torque in permanent magnet machines”, *IEEE Transactions on Energy Conversion*, 2000, Vol. 15, Issue: 4, Pages: 407 – 412

[15] N. Bianchi, S. Bolognani, “Design techniques for reducing the cogging torque in surface mounted PM motors” *IEEE Transactions on Industry Applications*, 2002, Vol. 38, Issue: 5, pp. 1259–1265

[16] A. Rahideh, M. Mardaneh, T. Korakianitis, “Analytical 2-D Calculations of Torque, Inductance, and Back-EMF for Brushless Slotless Machines with Surface Inset Magnets”, *IEEE Transactions on Magnetics*, 2013, Vol. 49, Issue 8, pp. 4873-4884, DOI: 10.1109/TMAG.2013.2242087

Nomenclature

(Symbols)	(Symbol meaning)
r, θ	polar coordinates
R_c	air-gap radius
L	axial length of the stator
$B_{r,PM}$	radial component of the air-gap flux density generated by PM
$B_{\theta,PM}$	tangential component of the air-gap flux density generated by PM
μ_0	vacuum permeability