U.P.B. Sci. Bull., Series C, Vol. 77, Iss. 3, 2015 ISSN 2286-3540

RESEARCH ON REDUCING COGGING TORQUE IN PERMANENT MAGNET SYNCHRONOUS GENERATORS

Ion TRIFU[1]

This paper presents different cogging torque reduction methods. The numerical methods used were experimentally validated using a permanent magnet synchronous generator.

Keywords: permanent magnet synchronous machine, finite element analysis, cogging torque reduction methods

1. Introduction

One of the electrical generators used in wind systems are synchronous generators with permanent magnets. This type of machines have an important disadvantage which is cogging torque that result due attraction of stator slots and excitation magnetic field of permanent magnets [1],[2]. Cogging torque generate vibrations an whear of the bearings and in case of eolian sistems prevent the tubine to start at small wind speeds [2]. This paper present several methods to reduce cogging torque on a permanent magnet synchronous generator by adjusting some of its geometrical parameters.

2. Generator description

The studied generator presented in Fig. 1, have rated power equal with S_n = 105 VA, rated voltage U_n = 32 V, 2p = 4 poles and Z_1 = 24 stator slots.

The rated torque of generator is M_n = 0.96 Nm. The permanent magnets are made of Koerdym 70P with remnant flux density B_r = 0.676 T and relative permeability μ_r = 1.353 and stator/rotor core is made of Stabolec 150-50. Cogging torque value is $T_{cog} \approx 0.04$ Nm that represent approximately 4% of the nominal torque value.

[1] Electrical Engineering Department, University POLITEHNICA of Bucharest, e-mail: trifuion@yahoo.com

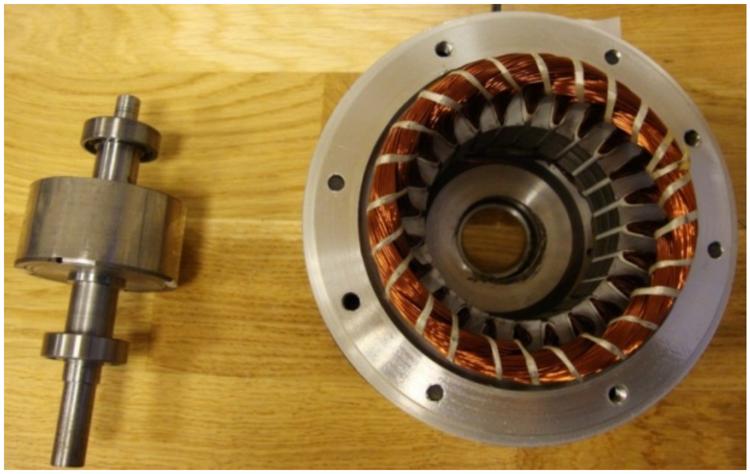

Fig. 1. PM synchronous generator

3. FEM analysis of the PM synchronous generator

For numerical analysis of the machine was used professional software package FLUX from CEDRAT. All the calculation is based on a 2D magnetostatic field model of the studied generator, presented in paragraph 2.

Computation domain, is represented in Fig. 2, composed of several distinct regions: turquoise – magnetic cores, magenta – permanent magnet (north pole), blue – permanent magnet (south pole), green – air, yellow – stator wedges, red – negative sense of current through coil, black – positive sense of current through coil.

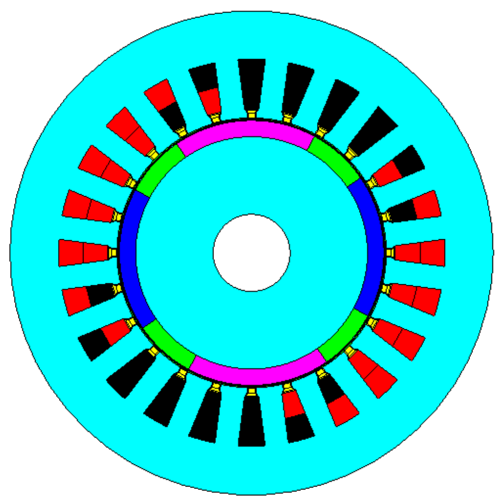

Fig. 2. Computation domain

Further were presented numerical results of the simulations of the PM generator for no-load and load operating regimes. In Fig. 3. was represented spectrum of magnetic field lines and chart of magnetic flux density through a cross-section through the machine.

Preliminary results, obtained from numerical analysis of the PM generator, was compared with experimental data, determined in the laboratory, to validate the numerical model. The test bench used to measure values of cogging torque was represented in Fig. 4. and the test bench used to measure no-load and load voltage and currents was represented in Fig. 5.

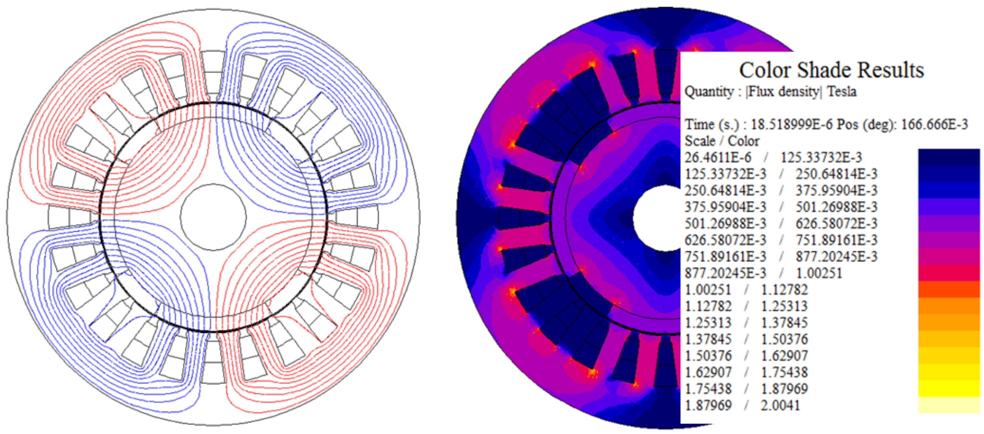

Fig. 3. Spectrum of the PM synchronous generator magnetic field lines and chart of magnetic flux density.

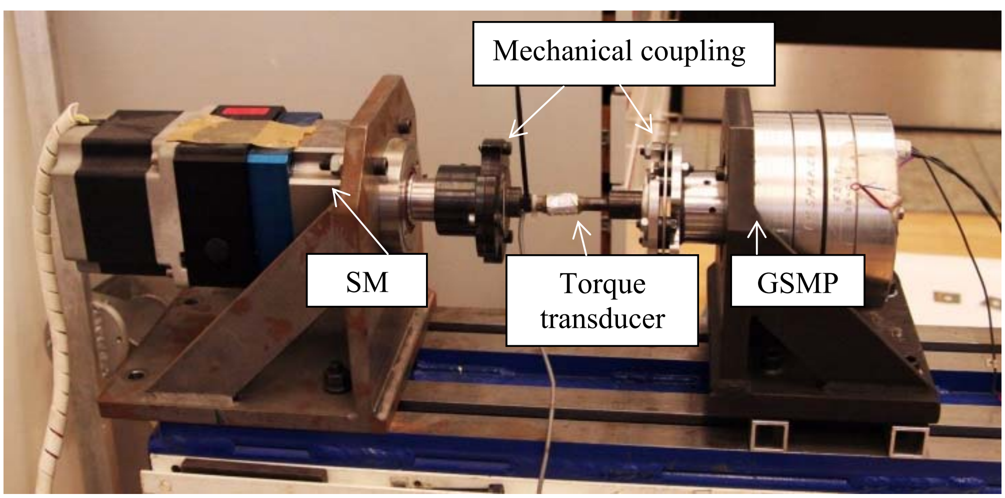

Fig. 4. Test bench used to measure cogging torque [3]

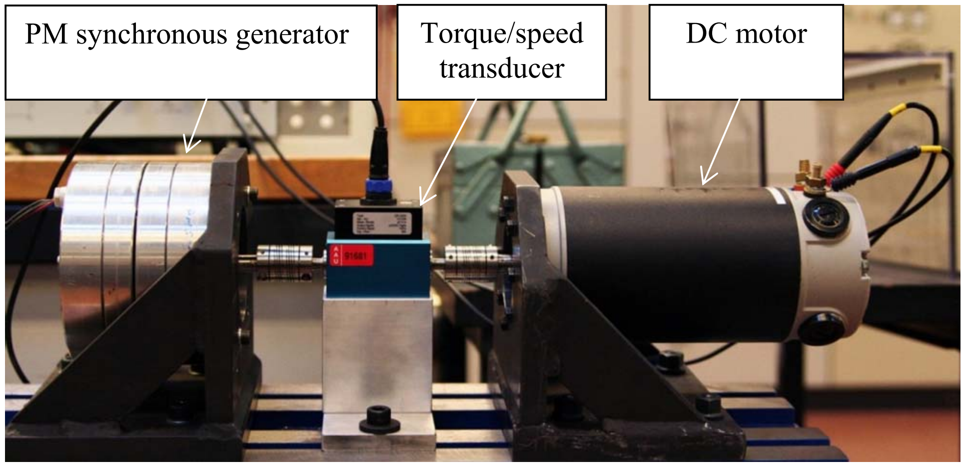

Fig. 5. Experimental bench for cogging torque measurement

In Fig. 6. was compared the calculated and measured values of cogging torque T_{cog} which shows a good approximation of T_{cog} value through FEM analysis.

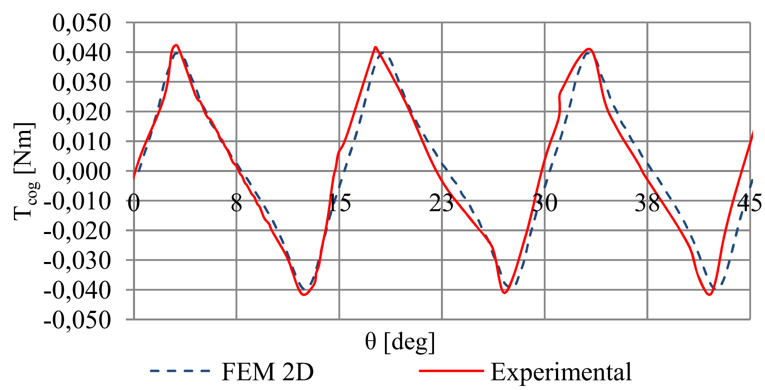

Fig. 6 Cogging torque [3]

Comparing the results obtained by experimental and numerical determination of no-load voltage, represented in Fig. 7, can be observed a good approximation of no-load voltage using numerical methods FEM.

In Fig. 8. was represented, the operation of PM generator on a resistive load, instantaneous values over a period, of measured and calculated values of current and voltage of the PM generator. As well as in no-load case can be seen a good agreement between measured and calculated values.

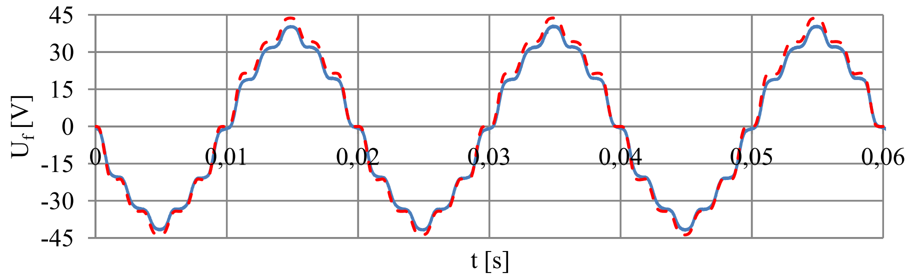

Fig. 7. No-load phase voltage

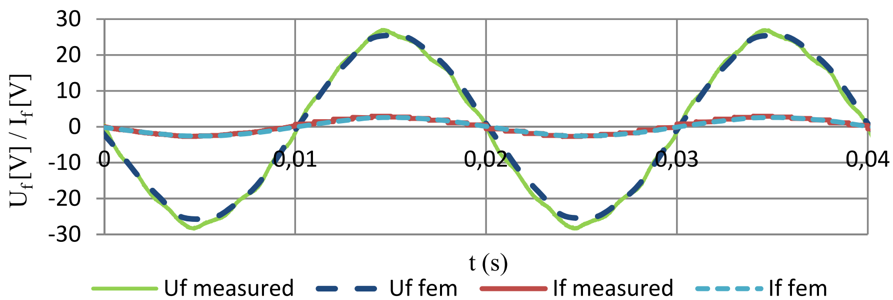

Fig. 8. Load phase voltage and current – operation on a resistive load R = 3 x 10 [Ω]

4. Cogging torque reduction methods

4.1. Asymmetrical arrangement of magnets

One of the cogging torque reduction methods is represented by asymmetrical arrangement of permanent magnets on rotor [4],[6]. To asymmetrical arrangement the permanent magnets, the axes of PM can be rotated (around the center of symmetry of the rotor section of the machine) with different angles in relation with equidistant axes corresponding of the symmetrical machine. From example, in Fig. 9. was presented a cross section through the PM generator in which the upper magnetic pole has the symmetry axis identical with equidistant axis, and the other three magnetic poles axes are rotated with angles P1, P2 respectively P3, in relation with corresponding

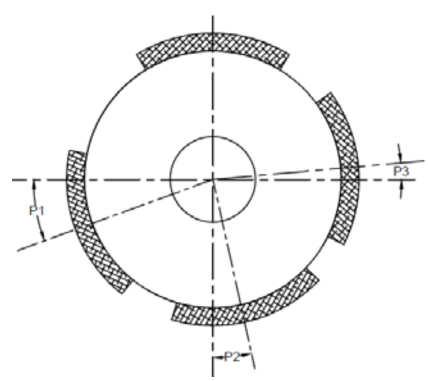

Fig. 9. Rotor of generator with PM's placed asymmetrically

equidistant axes.

In Fig. 10. was represented variation of cogging torque over a 15 geometrical rotation degrees, as it is noted the peak value of cogging torque drops by 85%, from $T_{cog} = 0.0403$ Nm for symmetrical arrangement of PM to $T_{cog} = 0.0065$ Nm for asymmetrical arrangement of PM.

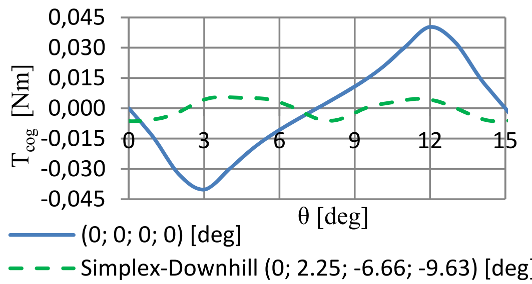

Fig. 10. Cogging torque when permanent magnets are asymmetrically placed

As a result of asymmetric arrangement of magnets in optimal configuration with displacement angles (0; 2.25; -6.66; -9.63), the peak value of phase voltage U_f decrease with approximately 4.5%. For the PM asymmetrical configuration the waveform of phase voltage U_f is closer to a sinusoid compared with the one obtained from PM symmetrical configuration.

After asymmetric arrangement of PM's in optimal configuration (0; 2.25; -6.66; -9.63), the peak values of radial forces (Fig. 11) are increased significantly. Thus, the maximum calculated peak value of radial force is $F_{r-m}=0.485$ *[N]*, for asymmetrical arrangement of magnets which is 17 times greater than value of radial force $F_{r-o}= 0.029$*[N]* obtained for the case when the generator has the PM symmetrical arranged.

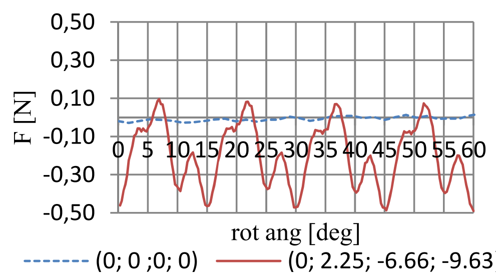

Fig. 11 Radial forces when permanent magnets are asymmetrically placed

4.2. Stator skew

A well-known cogging torque reduction method consists in inclination of the stator slots of the machine [4]-[7], the stator of the machine with skewed slots can be seen in Fig. 12. A way to calculate the optimum inclination angle of stator slots α_{sk} that lead to maximum minimization of cogging torque can be achieved by using equation (1) given in [6].

$$\alpha_{sk-s} = \frac{1}{N_p}\frac{360}{Z_1} = 15° \tag{1}$$

where N_p=1 is periodicity of T_{cog} curve on a slot pitch, and Z_1 = 24 stator slots.

As a result of inclination of stator slots with angle $\alpha_{sk\text{-}s}$ = 15º as in Fig. 12, the calculated value of cogging torque by FEM analysis is $T_{cog\text{-}sk}$ = 0.00068 Nm, value which is 59 times smaller than cogging torque of the machine without modification T_{cog} = 0.0403 Nm.

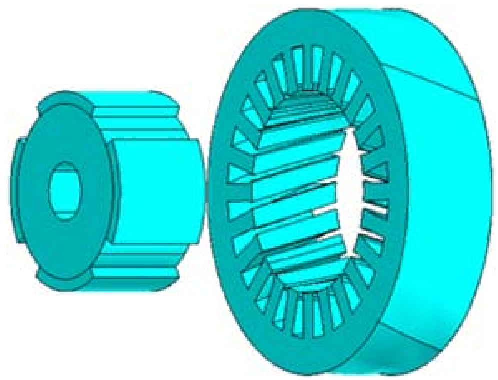

Fig. 12. PM machine with skewed slots

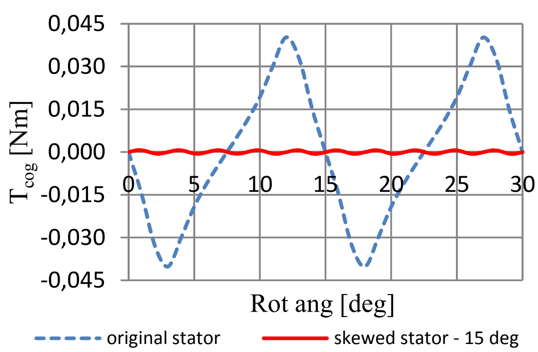

Fig. 13. Cogging torque obtained for skewed stator slots and for original configuration of the machine

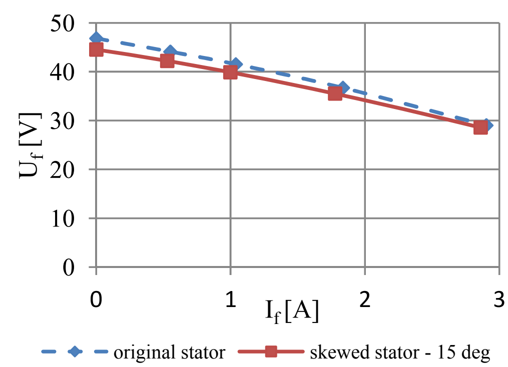

Fig. 14. External characteristic $U_f(I_f)$ for skewed stator slots and for original configuration of the machine

From external characteristic, represented in Fig. 14, can be observed that with inclination of stator slots the phase voltage U_f decrease, this drop was felt especially at lower values of load relative to rated load.

4.3. Rotor skew

As the cogging torque reduction method by skewing the stator slots presented in paragraph 4.2, this method refer to inclination of rotor permanent magnets to reduce cogging torque [8],[9]. The rotor with tilted permanent magnets can be seen in Fig. 15. By using this method the machine manufacturers must also consider that the inclination of permanent magnets is a difficult manufacturing process leading to a high production costs and the difficulty to magnetize the PM [6].

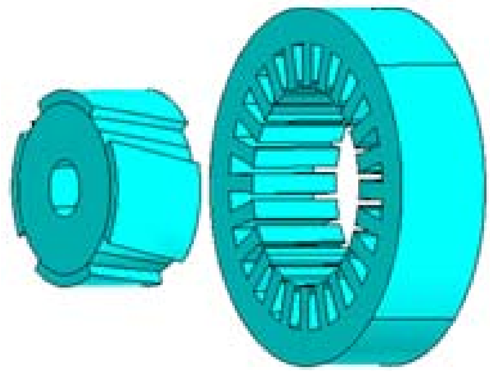

Fig. 15. PM machine with skewed rotor

Further we represented in Fig. 16, cogging torque curves obtained for original configuration of the machine and for tilted permanent magnets with an inclination angle equal with $\alpha_{sk\text{-}r}$ = 17.5º. As can be seen in Fig. 16, the peak value of cogging torque T_{cog} = 0.0055 [Nm], obtained by inclination of PM with $\alpha_{sk\text{-}r}$ = 17.5º, has sa value 7.3 times lower than the values of cogging torque obtained for original configuration of the machine T_{cog} = 0.0403 [Nm].

As can be seen in Fig. 17. with the inclination of the permanent magnets it is noted that the phase voltage decreases.

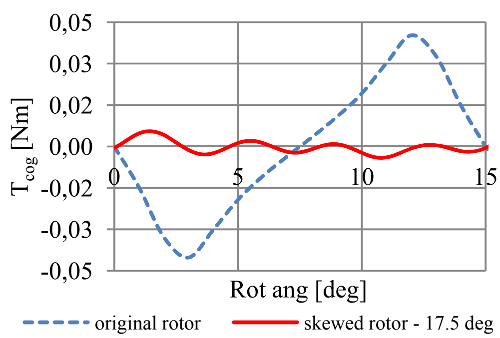

Fig. 16. Comparison of cogging torque curves obtained for skewed rotor and for original configuration of the machine

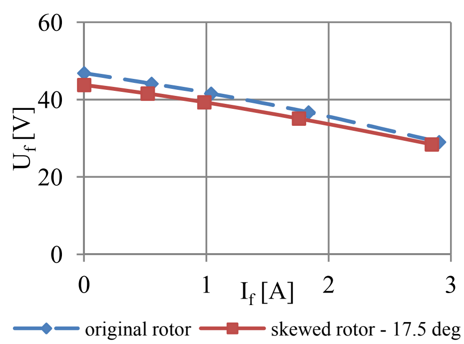

Fig. 17. External characteristics $U_f(I_f)$ obtained for skewed rotor and for original configuration of the machine

5. Conclusions

This paper studies of influence of geometrical parameters of a PM synchronous generator on cogging torque in order to reduce its value. From the point of view of cogging torque reduction the most efficient method is stator skit skewing the lead to a drastically decrease of T_{cog} by 59 times fallowed by rotor skewing that decrease cogging torque by 7.5 times and the less efficient T_{cog} reduction method for this machine configuration is when the permanent magnets of the rotor are disposed asymmetrically when cogging torque was decreased by 6.2 times. Other differences between the three methods are that asymmetrical displacement of magnets lead to increase of radial forces about 17 times but the advantage of this method is that can be applied on an already existing machine if magnets can be removed from rotor.

Acknowledgement

The work has been co-funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreements *POSDRU/107/1.5/S/76909.*

R E F E R E N C E S

[1] *J. A. Güemes, P. M. Garcia, A. M. Iraolagoitia, and J. J. Ugartemendia*, "Influence of slot opening width and rotor pole radius on the torque of PMSM, in Proc. 2009 ICREPQ Conf. Available: http://www.icrepq.com/papers-icrepq08.htm

[2] T. Tudorache, L. Melcescu and M. Popescu, "Methods for Cogging Torque Reduction of Directly Driven PM Wind Generators", *Proc. of International Conference on Optimization of Electric and Electronic Equipment* (OPTIM 2010), Moieciu, Romania, 2010.

[3] *Trifu, I.; Leban, K.; Ritchie. E;* "Influence of Closed Stator Slots on Cogging Torque", 10th Jubilee International Symposium on Advanced Electromechanical Motion Systems, Electromotion 2013, 21-22 October 2013, Cluj-Napoca, Romania

[4] *Daohan Wang; Xiuhe Wang; Yubo Yang; Ran Zhang,* "Optimization of Magnetic Pole Shifting to Reduce Cogging Torque in Solid-Rotor Permanent-Magnet Synchronous Motors," Magnetics, IEEE Transactions on , **vol.46**, no.5, pp.1228,1234, May 2010

[5] *T. Tudorache, L. Melcescu and M. Popescu*, "Methods for Cogging Torque Reduction of Directly Driven PM Wind Generators", Proc. of International Conference on Optimization of Electric and Electronic Equipment (OPTIM 2010), Moieciu, Romania, 2010.

[6] *N. Bianchi, S. Bolognani*, "Design Techniques for Reducing the Cogging Torque in Surface-Mounted PM Motors", IEEE Trans. Ind. Appl., **vol. 38**, no. 5, 2002, pp. 1259 - 1265.

[7] *S. M. Hwang, J. B. Eom, Y. H. Jung, D. W. Lee, and B. S. Kang*, "Various design techniques to reduce cogging torque by controlling energy variation in permanent magnet motors," IEEE Trans. Magn., **vol. 37**, no. 4, pp. 2806–2809, Jul. 2001.

[8] *M. Lukaniszyn, M. Jagiela, and R. Wrobel*, "Optimization of permanent magnet shape for minimum cogging torque using a genetic algorithm," IEEE Trans. Magn., **vol. 40**, no. 2, pp. 1228–1231, Mar. 2004.

[9] *L. Zhu, S. Z. Jiang, Z. Q. Zhu, and C. C. Chan*, "Analytical methods for minimizing cogging torque in permanent-magnet machines," IEEE Trans. Magn., **vol. 45**, no. 4, pp. 2023–2030, Apr. 2009.