Adrian Mlot, Marian Lukaniszyn
Opole University of Technology, Opole
Mariusz Korkosz
Rzeszow University of Technology, Rzeszow

MAGNET EDDY-CURRENT LOSS REDUCITON IN A HIGH-SPEED PERMANENT MAGNET MACHINE WITH CONCENTRATED WINDINGS

REDUKCJA STRAT WIROPRĄDOWYCH W MAGNESACH W WYSOKOOBROTOWYM SILNIKU SYNCHRONICZNYM Z UZWOJENIAMI SKUPIONYMI

Abstract: A radial high-speed permanent magnet (PM) machine with concentrated windings (operating frequency up to 800Hz) is selected for automotive application based on hybrid variants. This paper presents selected methods for magnet eddy-current loss reduction by rotor and stator modifications. The first approach to rotor modification regards magnet segmentation in circumferential and axial directions. The second approach is based on changes in tooth-tips shape. The best variants of tooth-tip shapes are determined for further investigation, and adapted with rotor having magnet segmentation. The machine with segmented magnet leads to magnet loss reduction by 81%. Further loss reduction by 45% can be realized with the proposed tooth-tip shape. Furthermore, the most important machine parameters are investigated. The 2-D and 3-D finite element analysis (FEA) is used for electromagnetic analysis. An experimental approach based on a partially wound stator is employed to verify the 3-D FEA.

Streszczenie: Celem pracy jest zaprezentowanie wybranych technik redukcji prądów wirowych w magnesach w wysokoobrotowym (częstotliwość zasilania do 800Hz) silniku synchronicznym z magnesami trwałymi, przeznaczonym do aplikacji w ciężkich pojazdach z napędem elektrycznym. W pierwszym podejściu zastosowano segmentacje magnesów w kierunku osiowym i radialnym (redukcja prądów wirowych indukowanych w magnesach do 80%). W drugiej metodzie zbadano kształt profilu nabiegunników stojana (obniżenie strat mocy w magnesach do 45%). Finalnym celem pracy będzie wybranie najlepszych wariantów nabiegunnika stojana i zaadoptowanie ich do silnika z segmentacją magnesów, co powinno znacznie poprawić sprawność silnika. Dla tych rozwiązań zbadano najważniejsze parametry silnika. Obliczenia numeryczne przeprowadzono na modelach polowych 2-D i 3-D bazujących na metodzie elementów skończonych.

Keywords: magnet loss reduction, magnet segmentation, permanent magnet machine, high-speed motor
Słowa kluczowe: *redukcja strat mocy w magnesach, segmentacja magnesów, silnik z magnesami trwałymi*

1. Introduction

Permanent magnet synchronous brushless machines (PMSM) having a high power density and good dynamic performance are widely used in the need for cleaner technology in many industries. Major areas of applications of electric motors range from wind turbines for electricity generation to hybrid electric vehicles (HEV) for propulsion power [1-11]. Over time, many investors, engineers and manufacturers believe electric vehicles (EVs) such as hybrid capability and fully EVs will be more widely adopted as the consumers become more familiar with them. High-speed PMSM with large size for the bus, military vehicle and truck unit requires from engineers focusing on the machine having light weight

high-performance, high efficiency and fuel reduction units with appropriate level of durability. The axial-flux technology to package more torque and power into a smaller, lighter unit is already developed by prominent industry and it seems the perfect solution for many pure EVs and HEVs applications [7]. Vehicles with large size and large weight used in transport/military sectors require high quantity of torque and power. In this case the radial-flux PMSM would be also easily integrated into the huge vehicle.

A major problem in large size machines is eddy-current (EC) loss in magnet, which has to be properly understood for designing of the rotor and stator [8]. The problem of EC loss in PMs has recently had more attention for electrical machines used for automotive applica-

tion being investigated especially for high-speed PMSM [1, 9-12]. Less attention has been paid to an alternative method for magnet segmentation [13-16]. Some of these methods based on modified stator and rotor shapes are developed mostly for interior PM motors in order to reduce the magnet EC loss [16, 17].

The purpose of the paper is to investigate a number of EC loss minimization techniques in the radial-flux PMSM machine with exterior mounted magnets onto the rotor. In the first stage, the magnet EC loss reduction is approached by magnet segmentation in circumferential direction and in axial direction. Those techniques are commonly used to improve the performance of PMSM [7, 10-13]. Next, the interest is to analyze the EC loss that can be reduced by modified stator tooth-tips. It will be interesting to do further investigation of EC loss analysis by adopting both techniques: segmented magnet and modified tooth-tip shape.

The research concerns the design of a compact (2kW/kg continuous rated) water jacket cooled PMSM for a large-size vehicle traction application. 2-D and 3-D modeling of the PMSM with respect to the electromagnetic numerical simulations of motor performance, electromagnetic torque and magnet loss are presented. The FE model is also validated by a number of experimental tests of AC losses at high frequency operation.

2. Finite element model verification

The founding of high-speed 3-phase PMSM comprises an 8-pole rotor with solid magnets (N33EH) mounted onto the rotor and that leads consequently a high operating frequency up to 800Hz; 12-slot laminated stator is made of 0.35mm silicon iron (M300-35A) with a double layer concentrated winding. The main machine parameters are given in Table I.

Table 1. The reference machine definition

Parameter	Value
Stator inner/outer radius (mm)	87.5/145
Slot height (mm)	35
Stator/rotor yoke height (mm)	17/13
Magnet height (mm)	10
Magnet pole pitch (el.deg.)	147
Machine length (mm)	250

Fig.1a shows cross section of the 3-D FE model of the PMSM used for PM losses and motor performance analysis. Only 1/8 region is modeled because of the symmetry and peri-

odicity. The model comprises the standard tooth-tip shape.

For thermal tests and to evaluate the power loss within the analyzed machine a simplified approach has been adopted utilizing the segmented stator topology [18]. A three-tooth sector of the stator with a single wound coil surrounded by unwound segments can be used to provide valuable data for both theoretical and experimental validation, Fig.1b-c. To simplify the analysis the influence of the rotor and the mutual coupling between phases is assumed to be negligible.
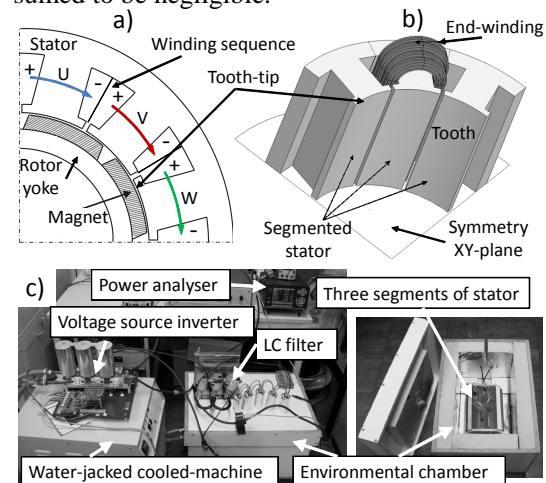

Fig.1 Cross-section of the PMSM with periodic solution domain (a), 3-D numerical model of a three tooth sector of the stator (b) used in the verification executed by experimental test (c)

Three segments of stator are mounted on a cold plane cooled via an outer water jacket and set up in the environmental chamber, Fig.1c. The theoretical investigation of AC loss has been carried out using a 3-D FEA based on a steady state AC harmonic formulation, and takes into account the distribution of the eddy-current induced in the conducting regions.

In the first stage of armature design the winding includes 14 turns with 7 parallel conductors within a bundle. A number of tests were carried out to assess the power loss generated within the setup under AC operation. The winding was energized with sinusoidal current of $40A_{rms}$ at 400/600/800Hz. AC loss predictions including both winding and laminated stator are compared with measurements giving a good agreement, Fig.2. The error of the AC measurements and 3-D FEA can be caused by

geometry precision of the numerical model according to the winding strands, air-gap between stator segments, and the end-winding shape [18].
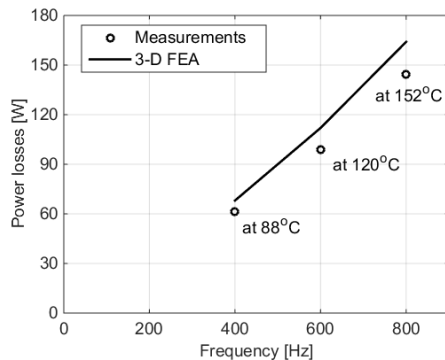

Fig.2 Experimental power loss with the numerical 3-D FEA for 14-turn winding with 7 parallel bonded conductors (copper, ϕ1.60mm)

At 100 A_{rms} the temperature of copper at 800Hz reached very quickly 152°C (Fig.2), and still was increasing. The maximum variable frequency sinusoidal current is assumed to be 150 A_{rms}. Then the wire may starts to overheat substantially, therefore, the 15 AWG wire size is proposed to be used. This leads to increase the number of parallel conductors from 7 to 14 for RMS copper current density limitation. Then the number of turns per coil was reduced from 14 to 9. And that new coil is finally used to the numerical model with a 50% copper fill factor.

3. The magnet eddy-current loss minimization techniques and performance analysis

Small changes in geometry dimensions can cause remarkable differences in the resulting performance of large PMSM. In this paper we focus on the EC loss in the PMs and torque computation for the machine with modified stator and rotor. Electromagnetic torque (T_e) is based on the stored magnetic co-energy change ($W_{co\text{-}eng}$) or the virtual work with a small displacement at constant current (i).

$$T_e = \left.\frac{\Delta W_{co-eng}}{\Delta \theta}\right|_{i=const} \qquad (1)$$

EC losses generated in the PMs mainly arise from the flux density variations due to the stator slot opening and MMF time harmonics. The last cause of EC losses is not considered

in this study since pure sinusoidal phase current excitation is assumed (high-frequency PWM effects neglected). In this paper the Joule loss of PMs in Watt unit is computed by FEA at 20°C and is expressed as:

$$W_{PM} = \iiint_V \mathbf{E} \cdot \mathbf{J} dV = \rho \iiint_V \mathbf{J}^2 dV \qquad (2)$$

where: $\mathbf{E}$ – electric field strength, $\mathbf{J}$ - current density in the PM, ρ – resistivity of the PM, V- PM volume.

The W_{PM} in the used sintered NdFeB magnet material (ρ = 180 µΩ·cm) is prominent as the magnets position is much closer to the stator. It can be easily concluded that changing air-gap distance between magnets and the stator tooth-tips by its shape modification may influence the magnet loss quantity. The evaluated EC vectors on magnets with rotor at d-axis at full load conditions are plotted in Fig. 3. From Fig. 3a it is found that the W_{PM} loss at the surface of the magnet is high.
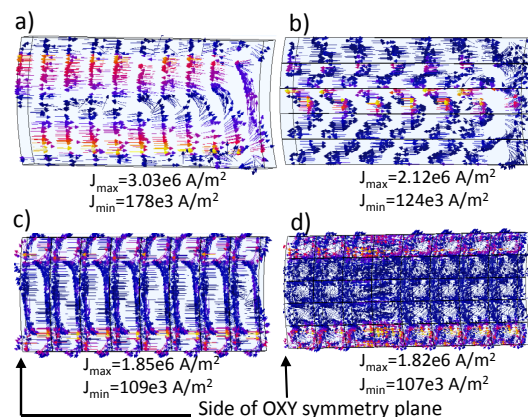

Fig.3 EC vector and density on PMs at full load operation (I = 150A_{rms}, f_e = 800Hz). Solid magnet (a), n=5 in circumferential direction (b), n=16 in axial direction (c), and both segmentation with 5 and 16 magnet segments in circumferential and radial directions respectively (d)

The overall EC loss in the solid magnets (n=1) becomes considerably high at high speed, and generates up to 34.6 kW, 145kW and 674W at full load, three-phase symmetrical short-circuit (SC) and open-circuit (OP) conditions, respectively (Fig.4). And the loss leads to magnet temperature rise quickly and degradation of magnet performance. SC incidents on traction motors may have an adverse impact on vehicle stability. SC operation can cause pulsating or even steady state braking torque in AC drives causing a sudden halt to the electric hybrid

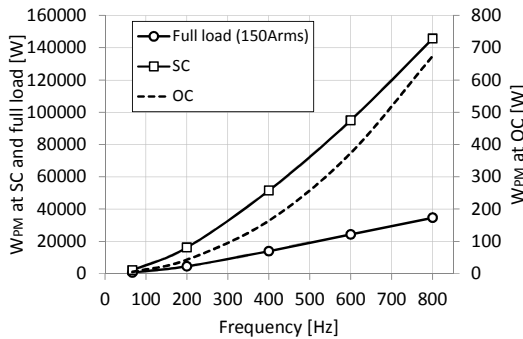vehicle. For these reasons it is important to analyze PM loss at SC condition.

Fig.4. Magnet losses in the solid magnets under load and short-circuit conditions vs. frequency

3.1 Magnet segmentation

The proposed machine with magnet radially and/or circumferentially segmented are comprehensively investigated by using 3-D FE models. The electrical insulation material 0.1 mm width is set to each segment direction. Fig.5 shows an example of the one pair pole of the rotor, where the magnet is divided into $n=5$ pieces in the circumferential direction, Fig.5a. Fig.5b shows an example where each magnet is subdivided into $n = 16$ pieces along the axial length. And both segmentation methods adopted to prevent the EC are presented in Fig.5c.
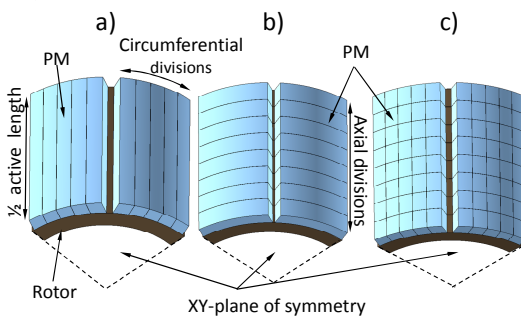

Fig.5 An example of magnet segmentation in circumferential direction (a), in axial direction (b), and both segmentations adopted (c)

Fig. 3b-c shows the effect of division of the magnet on the EC loss, which demonstrate the segmentation would cut and change the EC paths in the magnet. It is clarified that the EC losses decrease strongly as the number of division of magnet n increases. It is quantitatively clarified that the divided magnet is very useful to decrease EC loss in PMSM with surface mounted magnet.

The corresponding W_{PM} losses in the magnet with different numbers of magnet segments under SC and open-circuit (OP) conditions at 1000 rpm are analyzed in this study. The effect of the number of the division n on the EC is depicted in Fig.6a-b.
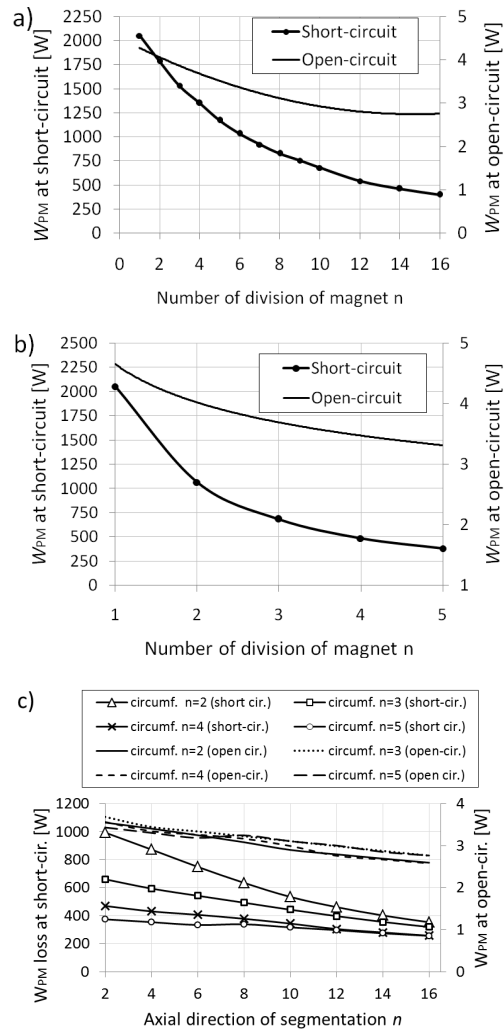

Fig.6 EC loss in PM at 1000rpm under SC and OP condition. Segmented PM in circumferential direction (a), in axial direction (b) and both adopted methods of segmentation (c)

The W_{PM} losses of the proposed machine with 16 segments of axial direction, and 5 segments of circumferential direction at the SC condition are around 397W and 380W, respectively. And segmented magnets implemented to cut the paths of EC decreased the magnet loss about 81%. Further modification can be achieved when both circumferential and axial segmentations are adopted and the magnet loss

was reduced to 255W (n=16 in axial direction and n=5 in circumferential direction), Fig.6c. The major problem of segmentation in the circumferential direction is that the mechanical strength of the magnet decreases when the number of segments n increases. Also, the magnet segmentation in the axial direction with high number of division n can be expensive and more complex to assembly.

3.2 Modifying the tooth-tips of stator core

Fig.7 shows the selected cross-sections of the stator tooth-tips. Since the motor is a radial-flux topology, 2-D FEA was used to calculate various versions of modified tooth-tips. At this study, non-segmented PM array constructions are considered only. Each tooth-tip version is carried out to determine the final shape for the maximum W_{PM} loss reduction without significant torque reduction.
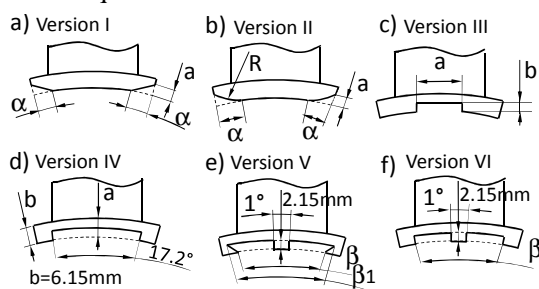

Fig.7 Outlines geometries of the PM motor versions selected for tooth-tip modification with variable parameters

Versions I and II represent the modified tooth-tips at the corners with two variable parameters (α and a), Fig.7a-b. In the second case when α increases, the radius (R) of tooth-tips increases as well and ranges from 2.6 mm to 17 mm. Versions III-IV and V-VI consist, single and double notches in the tooth-tips, respectively.

In study of versions I-III we focused to show the impact of changes in the tooth-tip variable parameters at wide range of W_{PM} and T_e, Fig.8a-c. The wide range of parameter modification approach is essential to clarify the most important parameters of the tooth-tips geometry having influence on variation of flux density at surface of magnet and to understand the phenomena of flux path circulation between tooth-tip and magnet. Then the tooth-tip design can indicate which version of the modification process will be carrying on. It has been clarified from the study [16] that the magnet

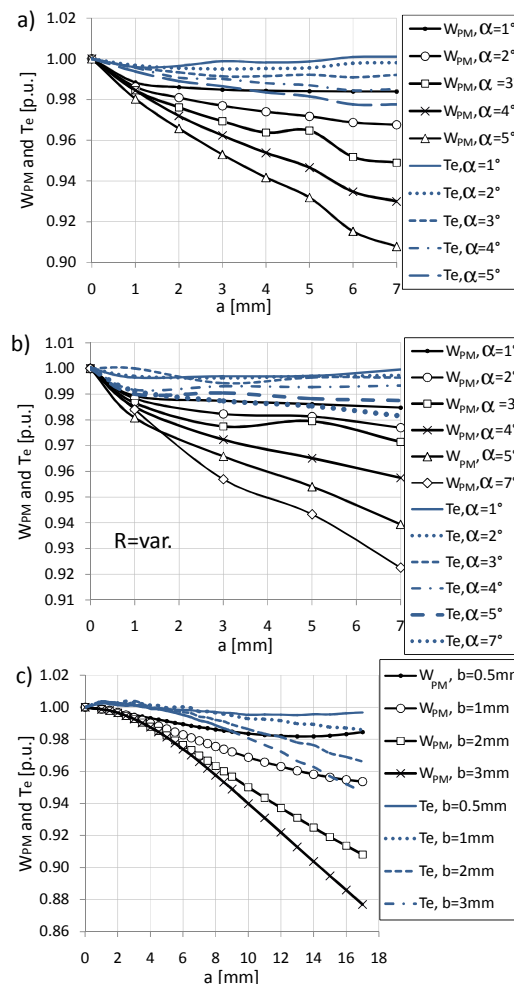EC loss is mainly produced by the variation of the magnetic path of the armature flux.

Fig.8 Magnet EC loss and torque regarded to the reference machine (n = 1) at 1000rpm, full load operation. Motor version I (a), version II (b) and version III (c)

Selected results from Fig.9 for versions IV-VI regard only the most promising fixed geometry parameters of the tooth-tip for W_{PM} reduction. Fig.9a shows the impact of the parameter ratio of a/b on magnet EC loss and torque.

In case of motor version V and VI the impact of the parameter β (notch arc) is investigated. Variable parameter of β_1 from version V is set to $\beta_1=\beta+1°$.

A parametric study shows that, changing the magnetic path of the armature flux by modifying the tooth-tips (with solid magnet) leads to cut down the magnet loss and torque around 45% and 10%, respectively, compared with the reference machine at full load operation ($150A_{rms}$).
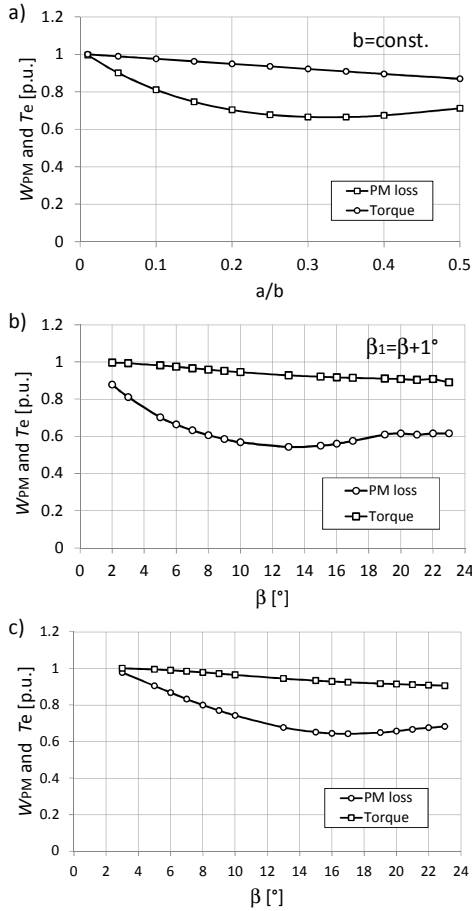
a)

b)

c)

Fig.9 Magnet EC loss and torque for the reference machine (n = 1) at 1000rpm, full load operation. Motor version IV (a), version V (b) and version VI (c)

3.3 Adopting both methods: segmented magnet and modified the tooth-tips

The most promising tooth-tips geometry for each cases presented in Figs.8-9 are selected and adopted to the machine with segmented magnets. The model with 4 and 16 magnet segments in the circumferential and axial directions, respectively, is used to explore the impact on W_{PM} and iron loss (P_{Fe}), Table 3.

In Table 4 the most important motor parameters are listed. Torque constant (k_t) was reduced up to 12%, and voltage constant (k_e, line-to-line) was reduced by 8.5% compared with the values of the reference motor.

The proposed machine modifications prove that the eddy-current losses in the magnets can be effectively attenuated by segmenting the magnets with the suggested shape of modified tooth-tips, from Table 3 and 4.

Table 3. Magnet and iron loss at 1000rpm. Motor with segmented magnet

Motor version	W_{PM} [W]			P_{Fe} [W]		
	SC	OP	Full load	SC	OP	Full load
Ref. motor	2051	4.94	609	75	212	422
Ver.1 a=7mm α=5°	208	85	149	54	185	412
Ver.2 a=17mm α=7° R=17mm	210	67	132	57	169	439
Ver.3 a=17mm b=3mm	277	75	113	72	185	391
Ver.4 a=2.15mm	248	54	86	60	183	466
Ver.5 β=13°	260	49	91	68	189	394
Ver.6 β=17°	249	56	86	63	180	370

Table 4.Selected motor parameters at 1000rpm. Motor with segmented magnet

Motor version	T_e full load (Nm)	ε (%)	I_{SC} (A$_{rms}$)	k_t (Nm/ A$_{rms}$)	k_e (V·s/ rad)
Ref. motor	507	17	306	3.4	1.89
Ver.1 a=7mm α=5°	484	24	328	3.2	1.84
Ver.2 a=17mm α=7° R=17mm	487	23	324	3.2	1.85
Ver.3 a=17mm b=3mm	460	34	276	3.1	1.77
Ver.4 a=2.15mm	453	24	278	3.0	1.73
Ver.5 β=13°	470	22	281	3.1	1.82
Ver.6 β=17°	461	29	283	3.1	1.75

4. Conclusion and recommendation

This paper presents a modified radial-flux machine with PM in order to improve the performance. The magnet with different number of segments in the circumferential and/or axial directions, and the shape of stator tooth-tip are modified for the purpose of decreasing the magnet eddy-current loss at high rotational speed under AC operation. From the results of the 3-D FEA, it is clear that the proposed stator and rotor can significantly reduce the magnet eddy-current loss for a large size machine without significant decreases in torque con-

stant voltage constant. However, considerable work can be required to further improve the performance and efficiency of the motor and make it commercially practical for heavy vehicle applications. A high torque ripple and cogging torque are the main disadvantages of the presented, modified teeth-tip shapes. To minimize those effects, it is strongly recommended to use the segmented Halbach magnet array and magnetic wedges in slot.

7. References

[1]. H. Toda, Z. Xia, J. Wang, K. Atallah " Rotor eddy-current loss in permanent magnet brushless machines", *IEEE Trans. Magn.*, no. 4, pp. 2104 - 2106, 2004.

[2]. P. Lindh, J. Nerg, J. Pyrhonen, M Polikarpova, H. Jussila, M. Rilla "Interior permanent magnet motors with non-overlapping concentrated winding or with integral slot winding for traction application", *Przeglad Elektrotechniczny*, no. 7b, pp. 9 - 12, 2012.

[3] A.M. EL-Rafeie, J.P. Alexander, S. Calioto, P.B. Reddy, K.K. Huh, P. Bock, X. Shen "Advanced high-power-density interior permanent magnet motor for traction applications", *IEEE Transactions on Industry Application*, no. 5, pp. 3235-3248, 2014.

[4] A. Wang, W. Xi, H. Wang, Y. Alsmadi, L. Xu "FEA-based performance calculation of IPM machines with five topologies for hybrid-electric vehicle traction", *Transportation Electrification Asia-Pacific, IEEE Conference and Expo*, pp. 1-5, 2014.

[5] J. Wang, X. Juan, K. Atallah "Design optimization of a surface-mounted permanent-magnet motor with concentrated windings for electric vehicle application", *IEEE Transactions on Vehicular Technology*, no. 3, pp. 1053-1064, 2013.

[6] R. Dutta, M.F. Rahman "A segmented magnet interior permanent magnet machine with wide constant power range for application in hybrid vehicles", *Vehicle Power and Propulsion, IEEE Conference*, pp. 7-9, 2005.

[7] A.C. Malloy, A. Mlot, M.J. Cordner, M. Lamperth "Axial flux machines for hybrid module application", *IEEE International Electric Vehicle Conference*, 2014.

[8] T. Aslan, E. Semail, J. Legranger "General analytical model of magnet average eddy-current volume losses for comparison of multiphase PM machines with concentrated winding", *IEEE Transaction*, no. 1, pp. 72-83, 2014.

[9] W.Y. Huang, A. Bettayeb, R. Kaczmarek, J.C. Vannier "Optimization of magnet segmentation for reduction of eddy-current losses in permanent magnet synchronous machine", *IEEE Transactions on Energy Conversion*, no. 2, pp. 381-387, 2010.

[10] K. Yamazaki, Y. Fukushima "Effect of eddy-current loss reduction by magnet segmentation in synchronous motors with concentrated windings", *IEEE Transaction on Industry Applications*, no. 2, pp. 779-788, 2011.

[11] D.A. Wills, M.J. Kamper "Reducing PM eddy current rotor losses by partial magnet and rotor yoke segmentation", *XIX International Conference on Electrical Machines*, pp. 1-6, 2010.

[12] Y. Kawase, T. Ota, H. Fukunaga "3-D eddy current analysis in permanent magnet of interior permanent magnet motors", *IEEE Trans. Magn.*, no. 4, pp. 1863-1866, 2014.

[13] D. Ishak, Q. Zhu, D. Howe "Eddy-current loss in the rotor magnets of permanent-magnet brushless machines having a fractional number of slots per pole", *IEEE Trans. Magn.*, no. 9, pp. 2462-2469, 2005.

[14] G. Dajaku, D. Gerling "A novel tooth concentrated winding with low space harmonic contents", *IEEE International Electric Machines & Drives Conference*, pp. 755-760, 2013.

[15] G. Dajaku, D. Gerling "Eddy current loss minimization in motor magnets of PM machines using high-efficiency 12-teeth/10-slot winding topology", *International Conference on Electrical Machines and Systems*, pp. 1-6, 2011.

[16] K. Yamazaki, Y. Kanou, Y. Fukushima, S. Ohki, A. Nezu, T. Ikemi, R. Mizokami "Reduction of magnet eddy-current loss in interior permanent-magnet motors with concentrated windings", *IEEE Transactions on Industry Applications*, no. 6, pp. 2434-2441, 2010.

[17] K. Yamazaki, H. Ishigami "Rotor-shape optimization of interior-permanent-magnet motors to reduce harmonic iron losses", *IEEE Transactions on Industrial Electronics*, no. 1, pp. 61-69, 2010.

[18] A. Mlot, M. Korkosz, M. Lukaniszyn "Investigation of end winding proximity losses in a high-speed PM machine", *Analysis and Simulations of Electrical and Computer Systems, Lecture Notes in Electrical Engineering*, pp. 171-186, 2015.

Authors

dr inż. Adrian Młot, *a.mlot@po.opole.pl*
prof. dr hab. inż. Marian Łukaniszyn,
m.lukaniszyn@po.opole.pl
Faculty of Electrical Engineering, Automatic Control and Informatics, Opole University of Technology, ul. Prószkowska 76, 45-758 Opole, Poland
dr hab. inż. Mariusz Korkosz, *mkosz@prz.edu.pl*
Faculty of Electrical and Computer Engineering, Rzeszow University of Technology, ul. Wincentego Pola 2, 35-959 Rzeszów, Poland