www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 9, No: 3, 2022 (1005-1012)

El-Cezerî Journal of Science and Engineering
Vol: 9, No: 3, 2022 (1005-1012)
DOI : 10.31202/ecjse.1023600

ECJSE

Research Paper / Makale

Torque Effects of the Stator Slot Opening Geometry Error in Production of Axial Flux PM Motors

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Received/Geliş: 15.11.2021 **Accepted/Kabul:** 26.02.2022

Abstract: Axial flux permanent magnet machines (AFPM) became popular due to their effective profile. But AFPM machines have hard processes on production. Thus, some errors happen at the slot opening area and these errors affect the torque production. So, torque ripples occur. This paper shows the slot opening errors' effect on the torque. An analytical model has been used to demonstrate the problem. Also, random slot opening width taken randomly with the ten per cent constraint. Results show that slot opening errors have impacts on the torque ripples.

Keywords: Axial flux motors, Slot opening, Torque ripple, Axial flux permanent magnet motor.

Eksenel Akılı PM Motorlarının Üretiminde Stator Olukları Açarken Gerçekleşen Hataların Moment Etkileri

Öz: Eksenel akılı kalıcı mıknatıslı makineler (EASM), etkin profilleri nedeniyle popüler hale geldi. Ancak EASM makinelerinin üretimde zorlu süreçleri vardır. Böylece oluk açma bölgesinde bazı hatalar meydana gelir ve bu hatalar moment üretimini etkiler. Böylece moment dalgalanmaları meydana gelir. Bu çalışma, oluk açma hatalarının moment üzerindeki etkisini göstermektedir. Problemi göstermek için analitik bir model kullanılmıştır. Ayrıca, yüzde on kısıtlaması ile rastgele alınan rasgele oluk açma genişliği kullanılmıştır. Sonuçlar, oluk açma hatalarının moment dalgalanmaları üzerinde etkileri olduğunu göstermektedir.

Anahtar Kelimeler: Eksenel akılı Motorlar, Oluk açıklıkları, moment dalgalanması, eksenel akılı mıknatıslı motor.

1. Introduction

Electric machine design became crucial since increasing the necessities of higher efficiency at many different applications. Higher efficiency may challenge in each individual design. If the application has sensitivity with torque performance and low acoustic noise such as robotics and electric vehicles, torque ripples must be eliminated to the utmost. In contrast of torque density been considered, torque ripple must be considered in each machine design. Torque ripple occurs in case of interactions between stator slots and rotor magnet poles. The torque reduction must consist all of the sources of it. Actually, some manufacturers reckon without some of the sources of the torque ripples either as knowing or unknowing because of complexities of the production process. If the manufacturing machine is axial flux permanent magnet (AFPM) motor, the transaction becomes a twofold increase in the time, cost, and adversity.

Bu makaleye atıf yapmak için
Çetin E., "Eksenel Akılı PM Motorlarının Üretiminde Stator Olukları Açarken Gerçekleşen Hataların Moment Etkileri", El-Cezerî Fen ve Mühendislik Dergisi 2022, 9 (3); 1005-1012.

How to cite this article
Çetin E., "Torque Effects of the Stator Slot Opening Geometry Error in Production of Axial Flux PM Motors", El-Cezerî Journal of Science and Engineering, 2022, 9 (3); 1005-1012.
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Many different topologies researched in several studies both rotor magnet pole and stator slot sides of the permanent magnet motors on account of reducing torque effects [1-19]. Skewing or displacing magnet poles [1,2,4], recasting slot or teeth numbers or geometries [5,8,15,18]. Some cogging torque reducing proposals can be applied to axial flux permanent magnet motors [1,12,16,22] Beyond the minimization, the mass production is considered by some researchers [5,9,22-24]. However, these studies are insufficient for torque ripple mitigation due to production errors which will be depicted in section III.

This study is focused on the effects of stator slot opening geometry errors of the axial flux permanent motors that made by mass production devices. The main contribution is to prove the effects of the errors on the stator slot openings. It's researched on a single gap AFPM motor topology as seen in Fig. 3. Section II is defining the purely smooth slot opening of an axial flux permanent magnet motor. In section III the slot opening geometry error is introduced and analytically expressed.

2. Slot Opening

The main loss in PMs (permanent magnets) are generated because of slot openings particularly just in slotted stator of AFPM machines. The air gap of AFPM machine is adjustable, so that it can arrange to minimum length as possible without any hard manufacturing process. Thus, the magnetic flux density getting lower under every individual slot opening on account of decreased magnetic permeance or increased magnetic reluctance. So, air gap parameter has a key role on design tool. The fictional air gap difference due to mean magnetic flux reduction caused by slot opening is defined by Carter's coefficient (k_C) as follows [20];

$$g' = g.k_c \tag{1}$$

$$k_c = \frac{t_s}{t_s - \gamma . g} \tag{2}$$

$$\gamma = \frac{4}{\pi}\left[\frac{W_{so}}{2g}\tan^{-1}\left(\frac{W_{so}}{2g}\right) - \ln\sqrt{1+\left(\frac{W_{so}}{2g}\right)^2}\right] \tag{3}$$

where γ is the fictional air gap coefficient, W_{so} is the stator slot opening width and t_s is the average slot pitch. As seen at (1) and (2), fictional air gap (g') is greater than actual air gap (g) because Carter's coefficient is always greater than one ($k_C>1$), excluding slotless AFPM machines. Average slot pitch (t_s) can be expressed by the following

$$t_s = \frac{\pi(r_o + r_i)}{N_s} \tag{4}$$

where r_o is the outer radius of AFPM machine, r_i is the inner radius of the AFPM machine and N_s is the number of slots. Inner and outer radiuses have critical role in the torque production. By keeping in mind, the slot opening length is $(r_o - r_i)$, this critical role is concentrated upon the slot openings. Considering a single rotor and stator axial flux machine structure with a single air gap, the electromagnetic torque equation can be derived. By assuming the PMs creating a trapezoidal wave air gap flux density with the value of B_g, and the current that carried by conductors is instantaneously perpendicular to the air gap flux density at time, the electromagnetic torque production of single air gap AFPM machine can be expressed as [26-28];

$$\partial T_{em} = 2\pi r_i J_{in} B_g r dr \tag{5}$$

$$T_{em} = \pi B_g J_{in} (r_o)^3 \alpha_d (1 - \alpha_d{}^2) \tag{6}$$

where α_d is the diameter ratio and calculated by ${r_i}/{r_o}$.

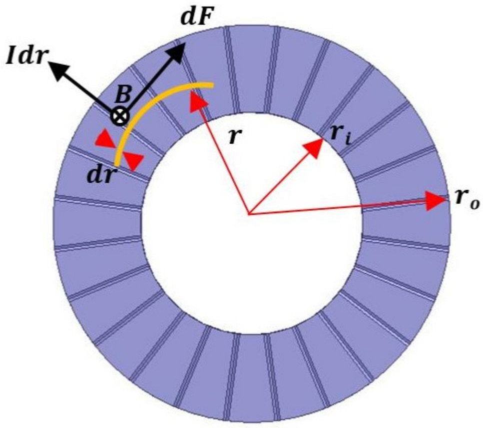

Figure 1. Torque production principle in AFPM machines

The diameter ratio is very significant for AFPM design process according to equation (6). Since investigation of diameter ratio, the per unit torque value can be derived for different diameter values. Accepting r_i and r_o changes from 0 to 1, and also $r_i < r_o$ constraint is kept in mind, the optimum value of α_d is 0.58 obtained for the maximum per unit torque production as seen on the Fig. 2. This result can be calculated from (6) analytically, but in reality, some researchers achieved to make the maximum torque between values of $\alpha_d = 0.60 - 0.65$ practically [28].

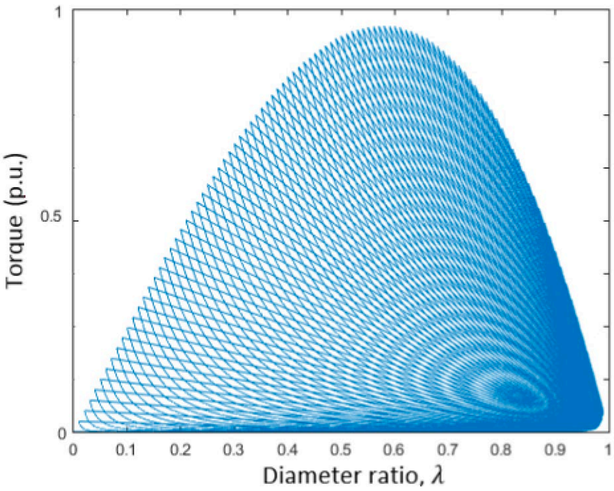

Figure 2. The maximum per unit torque production per diameter ratio

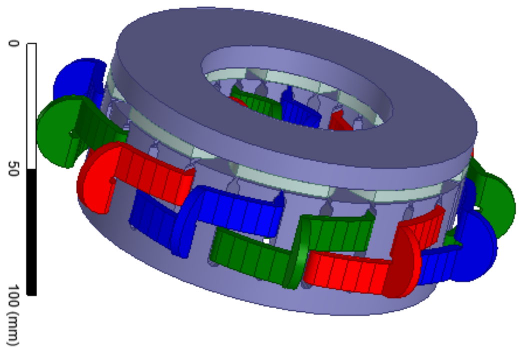

Figure 3. Studied AFPM motor topology

The analytical expressions of the electromagnetic torque have been explained in [29]. Also, Korkosz et.al. studied about the effects of the slot openings on the motor performance [30]. As seen by the detailed expressions, slot opening dimensions has critical role at producing torque.

3. Production Errors and Effects

Axial flux machines have many hard processes on production. One of the hardest parts is the opening of the slots. In recent productions, manufacturers use a punch machine to open slots. This machine reams and wraps the round strip steel on a line. But this process brings some problems. One is the notches at the slot openings as seen on the Fig. 4. These notches have effects on torque because it effects the effective air gap and permeance.

Figure 4. Notches (errors) at the slot openings

The permeance of the axial flux machine is shown as the equation (10) below. The relative permeance is demonstrated at the equation (11).

$$\lambda_{Leakage} = \frac{\mu_0}{g' + \frac{h_m}{\mu_r} + \frac{2\pi r_l}{4}} \tag{10}$$

$$\lambda'_{Leakage} = \frac{\lambda_{Leakage}}{\frac{\mu_0}{g' + {h_m}/{\mu_r}}} \tag{11}$$

where, μ_0 is the permeability of free space, μ_r is the relative permeability that is taken 660 for the M250-35A grade electric steel in this study. Also h_m is the magnet height. A model has been set on the MATLAB software to analyze the electromagnetic effects of the errors on the stator slot openings. An iterative solution is applied to the model to prove the situation best. Slot opening widths have been randomly created in the model. And electromagnetic torque results obtained from the each randomly created slot openings due to that errors become randomly in mass production.

The analytic solution proposes a random slot opening width to model the error seen on Fig. 4. Because the error occurs randomly. Also 10 per cent constraint has been indicated to the model not to create insubstantial solution. After these assumptions the resultant torque graph is seen at the Fig. 6. This figure illustrates the torque production due to the stator teeth with the errors. Each individual tooth's contribution to the torque is modeled in the solution. This figure is one of the prove of the electromagnetic torque changes by the radius in axial flux machines as a result of the structure seen in the Fig. 1. Each tooth has a little bit distinctive electromagnetic contribution between 174.26 N.m. and 174.32 N.m.

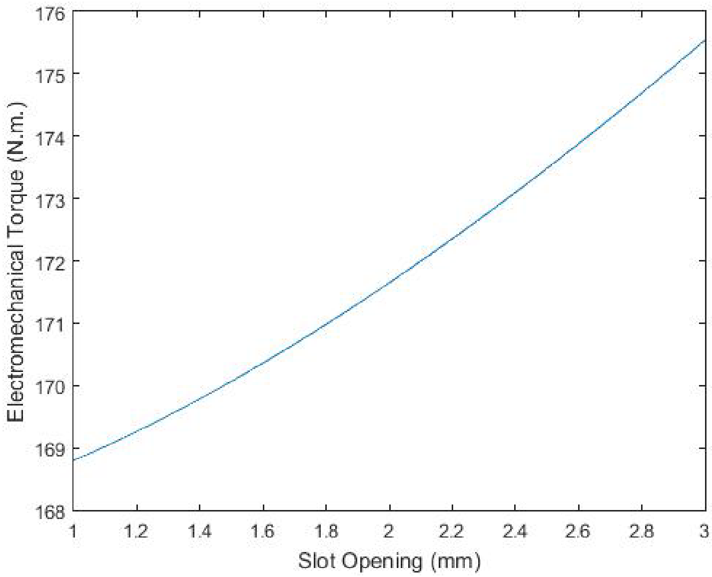

Figure 5. Electromechanical torque change versus slot opening width.

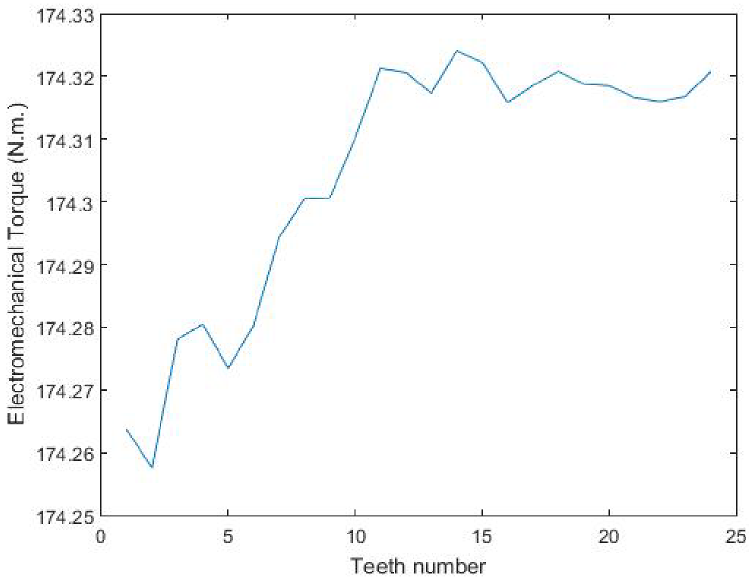

Figure 6. Electromechanical torque change versus per teeth number.

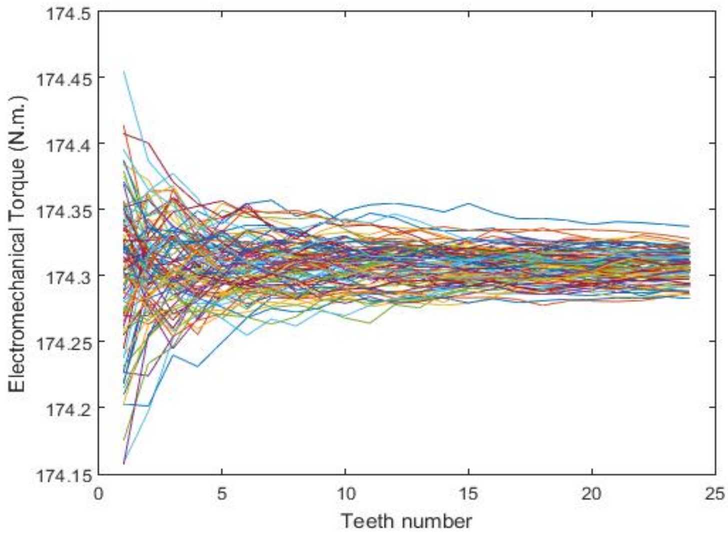

Figure 7. Electromechanical torque change versus per teeth number after many counts

Because of the slot opening width chosen randomly, the model is run many times in order to see the torque ripples in other solutions. The electromechanical torque ripple differs in 0.3 N.m. for each solution. This difference can be seen at the Fig. 7. This figure depicts many iterations performed by the simulation to obtain the electromagnetic torque effects. As the result, the torque ripple is differing in 0.3 N.m. In the other parameter illustration, electromechanical torque versus mean slot opening width can be demonstrated in the Fig. 8. Mean slot opening width means that the model executes different slot opening with value for each calculation of the electromechanical torque. After each calculation many slots openings value occurs from inner radius to outer radius. So that, the mean value of the slot opening width value is taken from inner radius to outer radius.

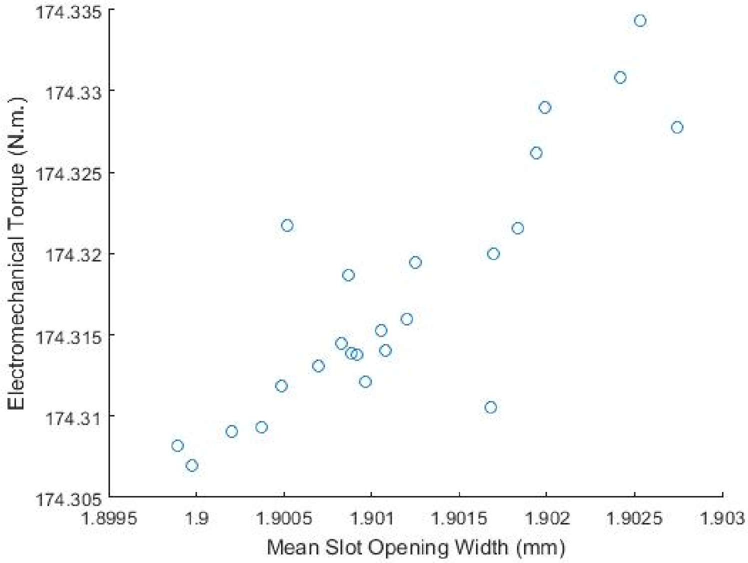

Figure 8. Mean slot opening change effects on the electromechanical torque.

The electromechanical torque has been changed in each mean slot opening width that is changing between 1.89 mm to 1.903 mm. These values confirm the 10 percent constraint due to the 2 mm starting value of slot opening width.

4. Conclusion

This study is about research of the effects of axial flux permanent magnet machine's slot opening errors. These errors happen as notches in slot opening area as seen on the Fig. 4. This paper prove that this error affects the torque performance. An analytical model demonstrated to solve the problem. This model includes random slot opening width in the constraint of 10 percent. Thus, torque ripples seen on Fig. 6 to Fig. 8.

This study, show that slot opening errors need to be handled not to gain torque ripples just at the production process. These errors can be reduced by using drilling method after the punching machine in the manufacturing.

Authors' Contributions

EC designed the machine model and simulated the machine. Author read and approved the final manuscript.

Competing Interests

The author declare that he has no competing interests.

References

[1]. Aydin, M., Zhu, Z. Q., Lipo, T. A., Howe, D., Minimization of Cogging Torque in Axial-Flux Permanent-Magnet Machines: Design Concepts, IEEE Transactions on magnetics, 2007, 43 (9), 3614-3622.

[2]. Chikouche, B. L., Boughrara, K., and Ibtiouen, R., Cogging Torque Minimization of Surface-Mounted Permanent Magnet Synchronous Machines Using Hybrid Magnet Shapes, Progress In Electromagnetics Research B, 2015, 62 (1), 49-61.

[3]. Ackermann, B., Janssen, J. H. H., Sottek, R. and van Steen, R. I., New technique for reducing cogging torque in a class of brushless DC motors, Proc. Inst. Elect. Eng. Elect. Power Appl., 1992, 139(4), 315-320.

[4]. Ishikawa, T. and Slemon, G. R., A method of reducing ripple torque in permanent magnet motors without skewing, Magnetics, IEEE Transactions on, 1993, 29(1), 2028-2031.

[5]. Jahns, T. M., Soong, W. L., Pulsating torque minimization techniques for permanent magnet AC motor drives - a review, IEEE Transactions on Industrial Electronics, 1996, 43 (2), 321-329.

[6]. Hanselman, D. C., Effect of skew, pole count and slot count on brushless motor radial force, cogging torque and back EMF, Inst. Elect. Eng. Proc.& Elect. Power Appl., 1997, 144(5), 325 -330.

[7]. Hwang, S. M., Eom, J. B., Hwang, G. B., Jeong, W. B. and Jung, Y. H., Cogging torque and acoustic noise reduction in permanent magnet motors by teeth pairing, IEEE Trans. Magnetics, 2000, 36(1), 3144-3146.

[8]. Paulsamy, S., “Reduction of Cogging Torque in Dual Rotor Permanent Magnet Generator for Direct Coupled Wind Energy Systems”, The Scientific World Journal, 2014, 2014(1).

[9]. Bianchi, N. and Bolognani, S., Design techniques for reducing the cogging torque in surface-mounted PM motors, IEEE Trans. on Industry Applications, 2002. 38(5), 1259-1265.

[10]. Boughrara, K., Chikouche, B. L., Ibtiouen, R., Zarko, D. and Touhami, O., Analytical model of slotted air-gap surface mounted permanent-magnet synchronous motor with magnet bars magnetized in the shifting direction, IEEE Trans. Magn., 2009, 45(2), 747-758.

[11]. Zhu, L., Jiang, S. Z., Zhu, Z. Q., Chan, C. C., Analytical methods for minimizing cogging torque in permanent-magnet machines, IEEE Trans. Magn., 2009, 45(4), 2023-2031.

[12]. Choi, J. H., Kim, J. H., Kim, D. H., Baek, Y. S., Design and parametric analysis of axial flux PM motors with minimized cogging torque”, IEEE Trans. Magn., 2009, 45(6), 2855-2858.

[13]. Fei, W., Luk, P., A new technique of cogging torque suppression in direct-drive permanent-magnet brushless machines, IEEE Trans. Ind. Appl., 2010, 46(4), 1332-1340.

[14]. Ashabani, M., Mohamed, Y.-R., "Multi objective shape optimization of segmented pole permanent-magnet synchronous machines with improved torque characteristics," IEEE Trans. Magn., 2011, 47(4), 795-804.

[15]. Sung, S. J., Park, S. J., Jang, G. H., Cogging torque of brushless DC motors due to the interaction between the uneven magnetization of a permanent magnet and teeth curvature, IEEE Trans. Magn. , 2011, 47(7), 1923-1928.

[16]. Chun, Y. D., Cogging torque reduction in a novel axial flux PM motor, Proc. Int. Symp. Power Electron., Elect. Drives, Autom. Motion, 2006, (1), 1020-1023.

[17]. Fei, W. and Zhu, Z. Q., Comparison of cogging torque reduction in permanent magnet brushless machines by conventional and herringbone skewing techniques”, IEEE Trans. Energy Convers., 2013, 28(3), 664-674.

[18]. Dorrell, D. G., Popescu, M., Odd stator slot numbers in brushless dc machines—An aid to cogging torque reduction, IEEE Trans. Magn., 2011. 47(10), 3012-3015.

[19]. Han, S.H., Jahns, T.M., Soong, W.L., Guven, M.K., Illindala, M.S., Torque Ripple Reduction in Interior Permanent Magnet Synchronous Machines Using Stators With Odd Number of Slots Per Pole Pair, IEEE Transactions on Energy Conversion, 2010, 25(1), 118-127.

[20]. Gieras, J. F. et al. Axial Flux Permanent Magnet Brushless Machines. Dordrecht, NL: Kluwer, 2005.
[21]. Hanselman, D.C., Brushless Permanent Magnet Motor Design. Orono, ME: Mcgrawhill, 1994
[22]. Brown, T., Heins, G., Hobbs, S., Thiele, M., Davey, J., Cogging torque prediction for mass-produced axial flux PMSM stators, Proc. IEEE IEMDC, 2011, (1), 206-211.
[23]. Gasparin, L., Cernigoj, A., Markic, S., Fiser, R., Additional cogging torque components in permanent-magnet motors due to manufacturing imperfections, IEEE Trans. Magn., 2009, 45(3), 1210-1213.
[24]. Khan, M. A., Husain, I., Islam, M. R., Klass, J. T., Design of experiments to address manufacturing tolerances and process variations influencing cogging torque and back EMF in the mass production of the permanent-magnet synchronous motors, IEEE Trans. Ind. Appl., 2014, 50 (1), 346-355.
[25]. Verez, G., Barakat, G., Amara, Y., Influence of slots and rotor poles combinations on noise and vibrations of magnetic origins in `u'-core flux-switching permanent magnet machines, Progress In Electromagnetics Research B, 2014, 61(1), 149-168.
[26]. Vun, S. T., McCulloch, M.D., Optimal Design Method for Large-Scale YASA Machines, Energy Conversion, IEEE Transactions on, 2015, 30 (3), 900-907.
[27]. Nasiri, G. Z., Lesani, H., Optimal Design of Adjustable Airgap, Two-Speed, Capacitor-Run, Single-Phase Axial Flux Induction Motors, Energy Conversion, IEEE Transactions on, 2013, 28 (3), 543-552.
[28]. Parviainen, A., Design of axial-flux permanent-magnet low-speed machines and performance comparison between radial and axial-flux machines, Dissertation, Lappeenranta University of Technology, 2005.
[29]. Tak, B. -O., Ro, J. -S., Analysis and Design of an Axial Flux Permanent Magnet Motor for in-Wheel System Using a Novel Analytical Method Combined with a Numerical Method, IEEE Access, 2020, 8(1), 203994-204011.
[30]. Korkosz, M., Warzocha, K., Szura, J., Bak, P., The analysis of influence of stator slot opening on multipole axial flux motor characteristics, Innovative Materials and Technologies in Electrical Engineering (i-MITEL), 2018, (1), 1-4.