IMPROVE THE TORQUE CHARACTERISTIC OF AXIAL FLUX PERMANENT MAGNET MOTORS FOR INWHEEL MOTOR CYCLES

CẢI THIỆN MÔ MEN ĐỘNG CƠ NAM CHÂM VĨNH CỬU TỪ THÔNG DỌC TRỤC CHO XE ĐIỆN GẮN BÁNH TRỰC TIẾP

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ABSTRACT

Axial flux permanent magnet motor has been applied for many electric vehicles due to the high torque density and compact sizes and multipolar disc-type structure. In this paper, the axial flux permanent magnet motor with concentrated winding, axial flux, segmental rotor is proposed to compare with the conventional BLDC motor. The proposed topology has permanent magnet segments and slotted stator. In order to compare with the existing BLDC motors, an amount of permanent magnets is considered to scale up power and torque. This approach makes the assembly easier and reduce the cost compared to the conventional axial flux permanent magnet motor. Moreover, the multi sector-proposed topologies have usually a higher torque density and torque-to-weight ratio compared to reported axial flux switch reluctance motors. The detailed design and operation of the proposed machine are then presented, and the performance of the machine is evaluated for an in-wheel traction application. Especially, for a multipolar disc-type structure, the axial flux permanent magnet motor is easy to scale up power for the next models. The proposed model will be surveyed with the different stator topologies of the axial flux permanent magnet motor such as sector or I-core or core less motor.

Keywords: *Axial-flux permanent magnet motor, disc-type rotor, sector stator, wheel hub motor, central motor, concentrated winding, finite element method.*

TÓM TẮT

Động cơ nam châm vĩnh cửu từ thông dọc trục đã được ứng dụng cho nhiều loại xe điện do mật độ mô-men xoắn cao, kích thước nhỏ gọn và cấu trúc kiểu đĩa đa cực. Trong bài báo này, động cơ nam châm vĩnh cửu từ thông dọc trục với dây quấn tập trung, kết cấu đa đĩa cực rôto được trình bày và so sánh với nhau. Cấu trúc động cơ đề xuất có là đa đĩa cực nam châm vĩnh cửu và stato dạng rãnh. So với các động cơ BLDC hiện nay, động cơ được đề xuất có lượng nam châm vĩnh cửu giảm và đặc tính công suất và mô-men xoắn được cải hiện đáng kể. Với thiết kế này, việc lắp ráp dễ dàng hơn và giảm chi phí so với động cơ nam châm vĩnh cửu từ thông dọc trục thông thường. Hơn nữa, cấu trúc thiết kế trong bài báo có mật độ mô-men xoắn và tỷ lệ mô-men xoắn trên trọng lượng cao hơn so với động cơ từ trở hướng trục. Thiết kế chi tiết và đặc tính làm việc được đề xuất sẽ ứng dụng cho xe điện gắn bánh trực tiếp. Đặc biệt, với cấu trúc dạng đĩa đa cực, động cơ nam châm vĩnh cửu từ thông dọc trục dễ dàng mở rộng quy mô công suất cho các model tiếp theo. Bài báo này sẽ so sánh một số thiết kế động cơ nam châm vĩnh cửu từ thông dọc trục với các cấu trúc thiết kế stato khác nhau như dạng phân mảnh hoặc lõi.

Từ khóa: *Động cơ nam châm vĩnh cửu từ thông dọc trục, rôto cấu trúc dạng đĩa, phân đoạn stator, động cơ hướng tâm, dây quấn tập trung, phương pháp phần tử hữu hạn.*

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1. INTRODUCTION

Axial flux permanent magnet (AFPM) motors play an important role in practices due to high torque and power densities, higher torque-to-weight ratio with less core materials, smaller size, planar and easily adjustable air-gap, lower noise and vibration [1-2]. Therefore, they have been designed for electrical vehicles from motorbycle to the small or hybrid car [3-8]. A new rotor design of the APFM with 6/7 PM poles has been recently studied in [3]. The proposed AFPM with permanent magnet in back to back structure is being considered for an in-wheel electric vehicle application because of its compactness and high torque and power densities in this research. The AFPM motors could be effectively applied for the direct-drive in-wheel applications due to their compact multipolar disc-type structure and easy to scale and manufactures. The multi-disc AFPM motors have high power and high torque density, because permanent magnet or stator sector can be mounted both sides in back to back [9-12]. In this paper, the AFPM back to back stator is applied for the slot-ring and I-core type.

2. STATOR AND ROTOR BACK TO BACK OF THE AFPM

The double rotor and stator back to back (DSRB) topologies are well known proposed for electric motorbycles. Especislly, the double back to back stator and outer rotor has more advantages than the double back to back rotor because of their robustic and small size and compact. For the inwheel application, the outer rotor and back to back stator is more convenient. The detailed structure of the proposed double back to back stator and rotor AFPM is presented in Figure 1. The double-rotor variants are difficult to balance two rotor discs or keep small airgap due to rotor heat losses. The double stator are very space saving, because the both side rotor are enclosed to the outer wheel. This reduces the overall cost, since the less material is needed for the permanent magnets. In addition, the halbach array of permanent magnets will help to reduce magnet volume.

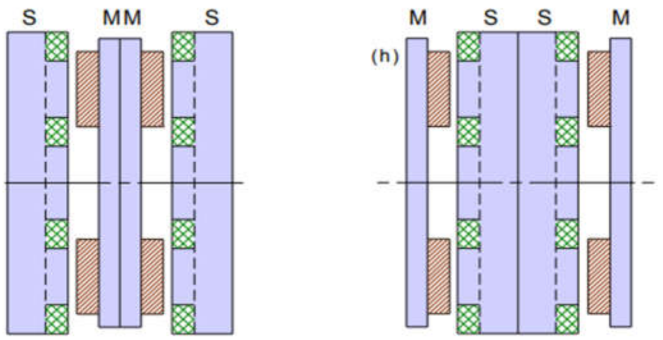


Figure 1. Variants of axial-flux permanent magnet synchronous machines back to back rotor (left) and stator (right)

An analytical expression of the sizing equation for the axial flux permanent magnet synchronous machines is given as:

$$P_R = \frac{m}{m1}\frac{\pi}{2}K_e K_i K_p K_l \eta B_g A_S (D_o^2 - D_i^2)L_e \quad (1)$$

The effective stack or axial length of the AFPM depends on the of rotor and stator axial lengths as:

$$L_e = L_s + 2L_r + 2g \quad (2)$$

The axial length of the rotor may be obtained from the axial length of rotor core and the length of the permanent magnets. The geometry parameters of stator and rotor can be calculated as the process in Figure 2. The analytical model have been recently developed by many authors to define basic parameters [1-3]. Based on the torque and volume ratio from 65 to 80kNm/m^3 [5], the the rotor diameter (D) is equal to the length size (L), that is:

$$T = \frac{\pi}{4}.D^2.L_s.TRV \quad (3)$$

where T is the electromagnetic torque (N.m), D is the out diameter (m), L_S is the length of core (m) and TVR is the torque and volume ratio (kWm/m^3).

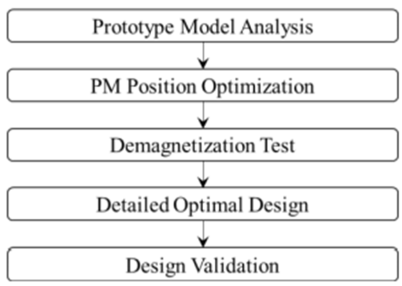


Figure 2. Computation steps

In general, the design process of AFPM is similar to that of the induction motor. The main parameters (such as outer diameter, rotor diameter, motor length, stator slot, airgap length) are defined by considered some practical factors with desired input requirements. Two models of the DSRB-AFPM of 3kW-1000 rpm is designed for in wheel electric vehicle. They are 12 stator slots and 8 poles in one disc/ sector. In order to increase power and torque, two sectors/discs are in the serial structuring flatform shown in Figures 3 and 4.

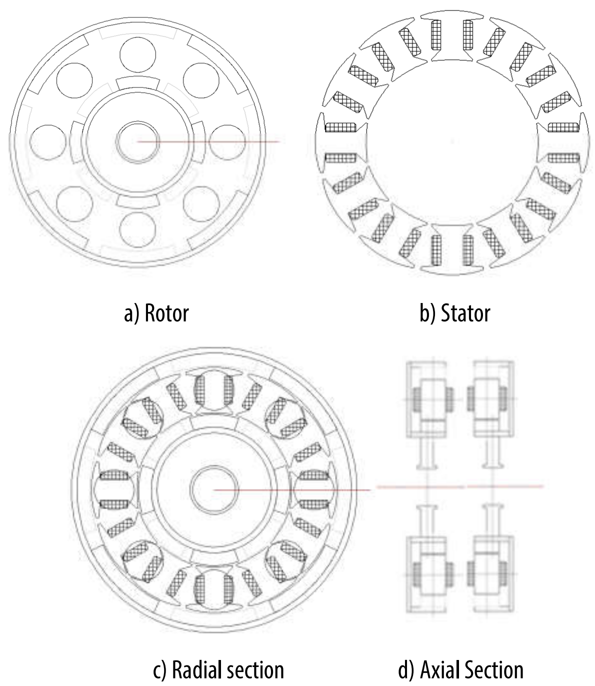


Figure 3. I-Core of double stator and rotor in back to back

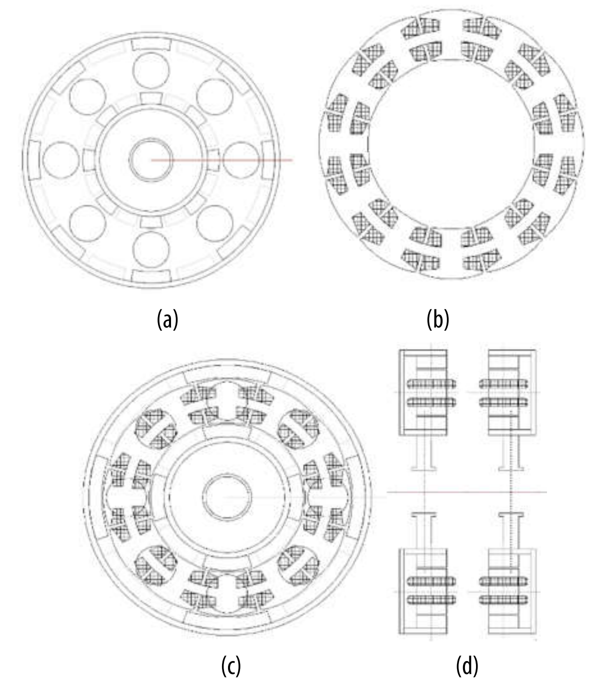


Figure 4. Slot ring of double stator and rotor in back to back

In one sector of 12/8 poles, the output power and torque is 1500W and 30N.m with the efficiency requested 90%. To power up 3kW, two sectors of the AFPM 12/8 poles are back to back connected. The proposed machine is designed for an in-wheel electric vehicle application with the high specific torque. The design parameters and output specifications for the DSRM are given in Table 1. The main part of the process is to design the rotor configuration which is embedded permanent magnet.

Table 1. Design parameters

Parameters Value	Parameters Values
Power Output	3000W
Operational Voltage	72 Volt
Efficiency	>85%
Current density	6.5A/mm^2

For the proposed tooth wound configuration, the magnetic flux will flow through one stator tooth to the next one via the rotor segments without flowing through the stator back. Therefore, segmental stator poles can be designed with improved fill factor and slot design for this tooth wound topology. Moreover, the leakage flux in stator segments embedding in the non-magnetic wheel (aluminum) will also reduce to improve the percentage of active materials used for the torque production. The design optimization and performance analysis of the tooth wound AFPM will be mentioned in this paper. The stator parameters of the designed machine are given in Table 2.

Table 2. Stator parameters

Parameters	Parameters Value
Number of Magnet Pole	8
Number of Slot	12
Outer Diameter	166mm
Inner Diameter	80mm
Length	45mm
Number of Coil	48
Number of Strands	4

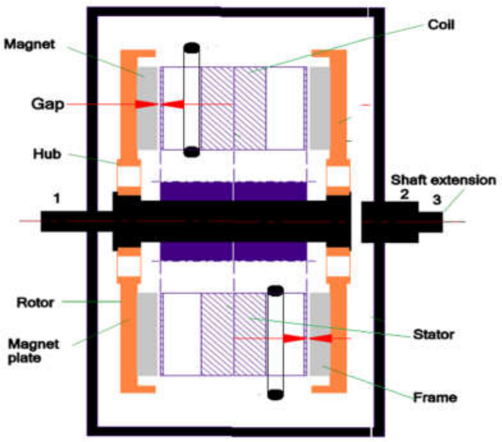


Figure 5. Double stator/rotor I- core of the AFPM

There are several mechanical structrures for supporting the rotor enclosed to the wheel. For the DSRB, a whole motor assembly is shown in Figure 5. In detail design, the cooling system and acoustic noise reduction method are also backed to figure out the whole power system.

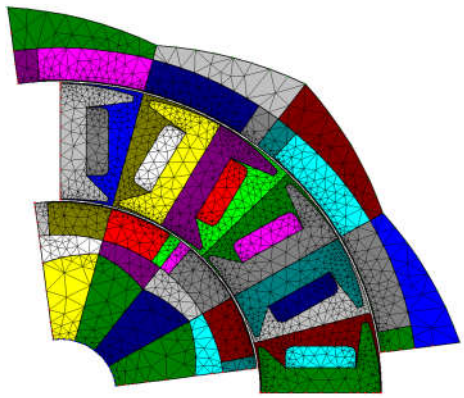
3. NUMERICAL RESULTS

In order to compare with the conventional motor such as the radial stator and rotor, the 2D-model is a big challenge due to the unsymmetric structure. Thus, to present the 2D flux density simulation, several parts such as the shaft, housing and supporting for magnet are simplyfied. The finite element analysis of DSRB has been implemented for a single disc of rotor and stator. Each component meshed will influence on the flux density results in the air gap. The element number after meshing is 5800 elements for one/two poles or one phase. The parameter for meshing process is shown in Table 3.

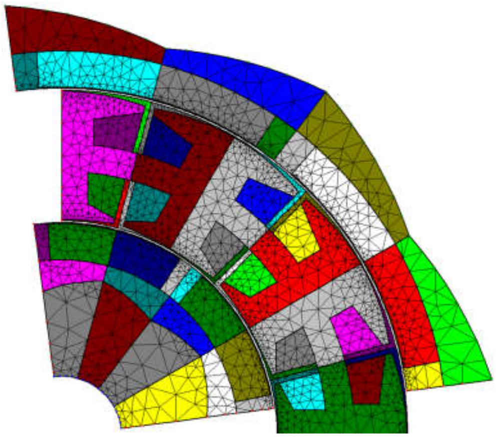
Table 3. Meshing size of an element

Name	Area	AvgA	Energy	CoEnergy
	[mm2]	[mWb/m]	[J]	[J]
Stator_Steel	1793.77635	0.00359	0.02537	0.02493
Coil_0	672	0.00444	0.05043	0.05043
Stator_Air_0	1107.78781	0.00403	5.81085	5.81085
Rotor_Steel	2611.3178	0.00084	87.57652	87.57652
Inner_Magnet_1	286.28615	0.00443	43.55217	28.54708
Rotor_Inner_Surface_Air	135.17509	0.00448	6.76881	6.76881
Inner_Magnet_2	286.28615	-0.00089	42.98369	29.23327
Outer_Magnet_1	538.22662	0.00579	168.80514	16.39629
Rotor_Outer_Surface_Air	249.48886	-0.00036	10.16925	10.16925
Outer_Magnet_2	538.22662	-0.00666	169.06593	16.52085
Air_Gap	109.95227	0.00082	4.7701	4.7701
Total	8328.52371	0.02053	539.57825	205.86837

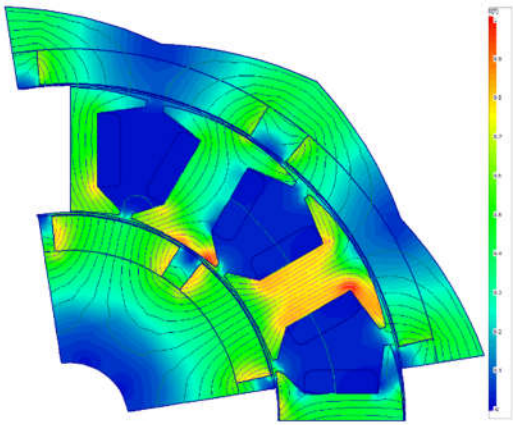
After simulating by the finite element method (FEM), the flux density results of two models is simulated in Figure 6. The flux density of I-Core AFPM is higher than the slot ring structure, because the I-core space for winding is lagger than the slot ring space and easier for NC wiring and insert I core-coil in stator yoke. With the same magnet volume, the copper weight higher, the turn por coil and wire area are higher, the I-core AFPM has better performances of torque and efficiency.



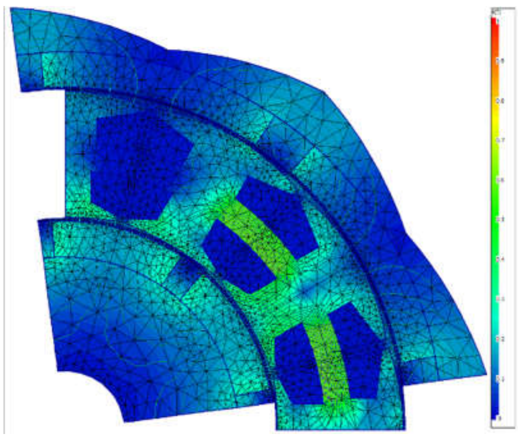
a) Element meshing of I- core



b) Element meshing of slot Ring



c) Flux density of I-core



d) Flux density of slot ring

Figure 6. Flux density results of DSRB I- Core and slot Ring of the AFPM

The I-core design is considered for the performance analysis with the single concentrated winding in 12 stator poles and 8 rotor segments on each sector. The current, back EMF and torque waveforms for the tooth wound AFPM topology is presented in Figure 7. This asymmetric back-EMF profiles is not fully the sinusoidal waveform but the total distortion harmonic is less 5%, this result is aceptable because the stator pole in air gap is the special design with the elip drawing to minimize torque ripple about 4%.

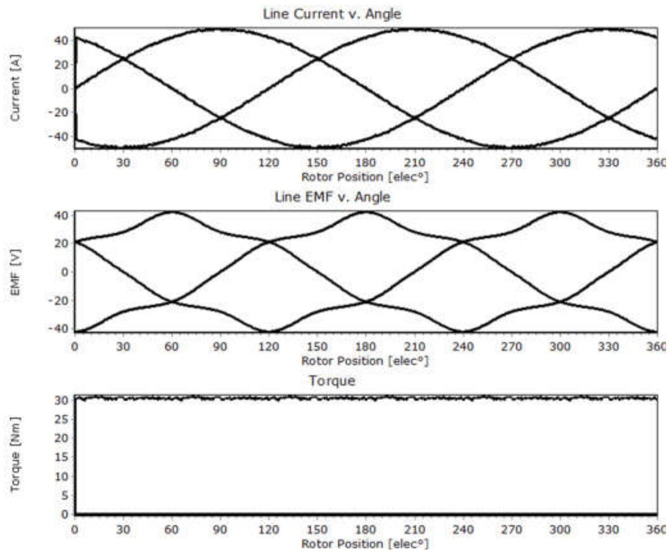


Figure 7. Phase Current, Back EMF and torque of AFPM

Table 3. Torque, power and efficiency performances

Drive	Sine	Vs	72.0000 V	RPM	500.0000 rpm
OpMode	Motoring	Tshaft	46.0593 Nm	Pshaft	2411.6586 W
Effcy	86.1330 %	TempRise	0.0000 °C	Pelec	2799.9236 W
EWtMotor	4.5098 kg	WtStator	2.5881 kg	WtRotor	1.9217 kg

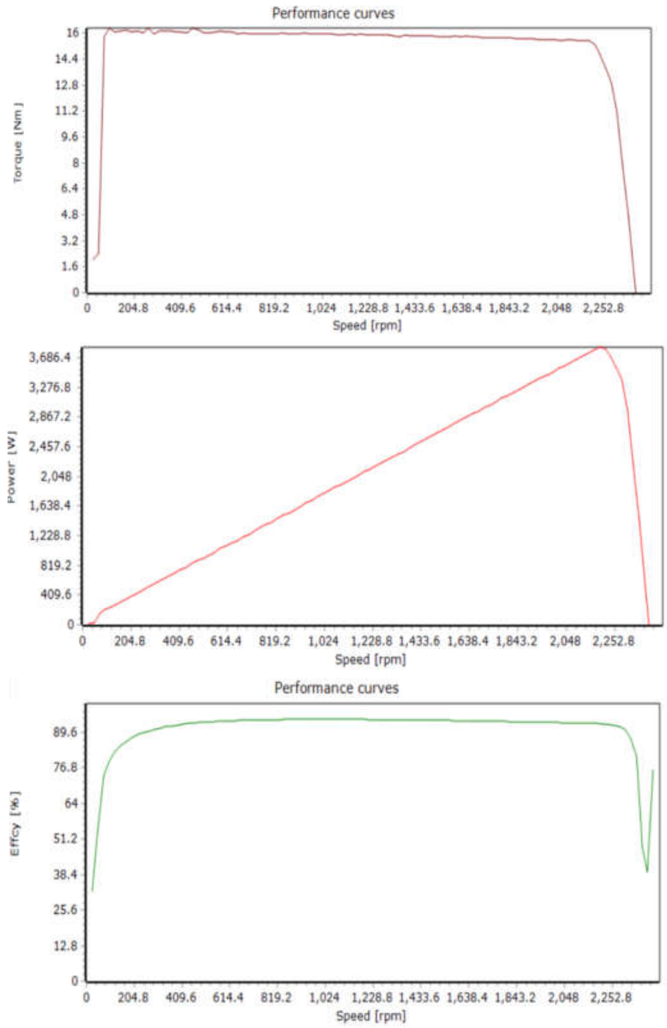


Figure 8. Output torque, Power and Torque of AFPM

The AFPM is evaluated under the design constraints presented in Table 1. The I-core AFPM is designed and simulated by using the FEM tool to compare their performances under the different speed. The dynamic simulations have been performed at 500rpm to evaluate their performances at the base speed. It is also compared with the torque capability and current density of 6.5A/mm^2 as shown in Table 3, where the total weight of stator, rotor and magnet is 9.8kg, the torque density is 4.6Nm/kg and 250W/kg. The proposed AFPM topology is excited with three-phase sinusoidal excitation. It is simulated under the current regulated unipolar excitation with each phase contributing for half of an electrical cycle. The dynamic torque profile under the dynamic mode for the designed AFPM is shown in Figure 8 for varying phase excitations. The simulated torque, power and efficiency and motor speed are presented in Figure 8. The peak power is 3900W at 2200r/min, the constant torque is obtained 16N.m and the efficiency is 89%. The proposed AFPM has a simplified and low cost structure compared to the AFPMs. For the multi sector stator and rotor, it can provide much higher torque density and torque to weight ratio Performance comparison of the designed AFPM with an axial flux rotor PM machine will be presented.

4. CONCLUSION

The multi sector topology for the I-core and slot ring AFPM with concentrated winding has been sucessfully presented. The torque and efficiency of the AFPM are higher and more advantage than the AFPM. For obtained results (torque density and torque-to weight ratio), it can be seen that the proposed AFPM I-core back to back stator is much better than the slot ring motor with the same design constraints. The designed AFPM motor have been simulated with the rated power of 3kW, 12 stator slots and 8 rotor poles. In addition, the motor's mechanical torque has reached a value of 30 Nm at a speed of 1500rpm with the input current of 60A and input voltage of 72V. Furthermore, the obtained motor efficiency has been obtained 90%. The design motor can be considered as a reference for the implementation and subsequent research. The obtained results from the design motor can be validated by testing through implementation.

REFERENCES

[1]. Z. Q. Zhu, M. F. H. Khatab, H. Y. Li, Y. Liu, 2017. *A novel axial flux magnetically geared machine for power split application*. Twelfth Int. Conf. Ecolo. Vehicles and Renewable Energies (EVER), pp. 1-8.

[2]. Wei Xu, Jianguo Zhu, Yongchang Zhang, Youguang Guo, Gang Lei, 2011. *New Axial Laminated-Structure Flux-Switching Permanent Magnet Machine With 6/7 Poles.* IEEE Transactions on Magnetics Volume 47.

[3]. Kahourzade S., Mahmoudi A., Hew Wooi Ping, Uddin M.N., 2014. *A Comprehensive Review of Axial-Flux Permanent-Magnet Machines.* Canadian Journal of Electrical and Computer Engineering, vol.37, no.1, pp.19-33.

[4]. Dong-Kuk Lim, Yong-Sun Cho, Jong-Suk Ro, Sang-Yong Jung, Hyun-Kyo Jung, 2016. *Optimal Design of an Axial Flux Permanent Magnet Synchronous Motor for the Electric Bicycle.* IEEE Transactions on Magnetics Volume 52, Issue 3.

[5]. Arihara H., Akatsu K., 2013. *Basic Properties of an Axial-Type Switched Reluctance Motor.* IEEE Transactions on Industry Applications, vol. 49, no. 1, pp. 59-65.

[6]. Rüya Akinci, Mehmet Polat, 2019. *Design and Optimization with Genetic Algorithm of Double Rotor Axial Flux Permanent Magnet Synchronous Motor (TORUS Type) for Electrical Vehicles.* 2019 4th International Conference on Power Electronics and their Applications (ICPEA).

[7]. J. Lin, T. Lambert, Y. Yang, B. Bilgin, R. Lankin, A. Emadi, 2016. *A Novel Axial Flux Switch Reluctance Motor with Multi-Level Air Gap Geometry.* IEEE Electrical Power and Energy Conference, pp. 1-8.

[8]. Q. A. S. Syed, Y. M. You, B. I. Kwon, 2012. *Design and Comparative Analysis of Single and Multi-stack Axial Flux Permanent Magnet Synchronous Generator*. International Journal of Applied Electromagnetics and Mechanics. vol. 89, no. 1-4, pp. 865-872.

[9]. A. Parviainen, 2005. *Design of Axial-Flux Permanent-Magnet Low-Speed Machines and Performance Comparison between Radial-Flux and AxialFlux Machines*. PhD dissertation, Lappeenranta University of Technology, Finland.

[10]. Q. A. S. Syed, I. Hahn, 2014. *Comparative Analysis of Surface Mounted and Flux Focusing Type Axial Flux Permanent Magnet Motor.* IET Inernational Conference on Power Electronics and Machine Drives, pp. 1-4.

[11]. M. Aydin, M. K. Guven, 2014. *Comparing Various PM Synchronous Generators: A Feasible Solution for High-Power, Off-Highway, Series Hybrid, Electric Traction Applications.* IEEE Vehicular Technology Magazine, vol. 9, no. 1, pp. 36-45.

[12]. T. S. Kwon, S. K. Sul, L. Alberti, N. Bianchi, 2009. *Design and Control of an Axial-Flux Machine for a Wide Flux- Weakening Operation Region*. IEEE Trans. Industrial Applications, vol. 45, no. 4, pp. 1258-1266.

THÔNG TIN TÁC GIẢ

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