2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)

Effects of Radial Divided Magnet Shifting on Cogging Torque of Axial Flux Permanent Magnet Generator for Small Scale Wind Turbine

Nasywa Imanuddin
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
nasywaimanuddin@gmail.com

Jihad Furqani
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
jfurqani@itb.ac.id

Arwindra Rizqiawan
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
windra@staff.stei.itb.ac.id

2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS) | 979-8-3503-1867-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICHVEPS58902.2023.10257501

***Abstract*—Transitioning energy sources from fossil fuels to renewable energy is demanding currently due to global warming issues. Those require advanced technology of each component that supports renewable energy to achieve high efficiency, for example, permanent magnet generator (PM generator) for wind power plants. PM generator is widely known for high efficiency, high energy density, low maintenance, and simplicity. Although a PM generator has a lot of advantages, it still has drawbacks specifically for cogging torque generated between the permanent magnet and stator core which causes vibration and decreases the net torque from the shaft due to its counter direction from the rotor direction. Several methods have been proposed to reduce cogging torque such as traditional skewing magnet, selecting appropriate slot opening, pole arc to pole pitch ratio arrangement, and placing flux barrier between 2 slots. This paper discusses the implementation of radially divided magnet shifting to axial flux PM generator with yokeless and segmented armature configuration. The impact of magnet shifting on reducing the cogging torque is also discussed. The proposed design is a permanent magnet divided into 2, 3, 4, and 5 parts and shift the magnet with a common angle respected to the inner side of the magnet. 3D finite element analysis is performed to analyze and simulate the axial flux PM generator model. An Analytical approach is discussed further to satisfy the relationship between magnet common angle and generated cogging torque. The results show that higher number of divided permanent magnet leads to decreased cogging torque, although the smaller size of permanent magnet will be challenging in manufacturing process.**

Keywords—axial-flux, permanent magnet, magnet shifting, magnet skewing, cogging torque.

I. INTRODUCTION

Large scale wind turbines often used a wound synchronous generator in the past or even induction generator instead of brushless synchronous generator due to the limitations flux capacity and material of permanent magnet. However, nowadays since the rare-earth material is founded as a great magnetic field source, permanent magnet generator become massively used either in large or small scale of wind turbines generator [1]–[3]. It has a lot of advantages compared to wound synchronous generator specifically in simplicity and lower maintenance. On the other hand, permanent magnet is uncontrollable and ideally produce a constant of magnetic field, moreover this disadvantage will lead to another problem that discussed in this paper named cogging torque.

According to [4], cogging torque is a counter-direction torque generated by the relationship between permanent magnet and stator core due to the difference's permeability among them. The impact is rotation of the rotor will not as smooth as ideal rotation and lead to the vibration and torque pulsation, therefore the net torque from the shaft will decrease. Several methods have been proposed by researchers to solve this problem, such as using conventional skewing method[5]–[7], magnet shifting [5], [8], slot opening optimization [9], and more optimization methods to reduce the value of cogging torque. However, most of published research was discussed about radial flux machines, and rarely discussed about axial flux machines specifically. Dual disc axial flux machines have been discussed by [5], but for specific in single disc configuration is not discussed and resulting different characteristics for application of radial dividing and shifting the permanent magnet to obtain lower cogging torque.

This paper discusses further about the radial dividing and shifting magnet methods to reduce the cogging torque from axial flux PM generator with yokeless and segmented armature configuration. As known that cogging torque occurs due to the magnetic flux distribution in the coupling field that interacts directly to the stator core. If one pole of permanent magnet placed in a phase, certainly additive of magnetic flux lead to higher cogging torque occurred. Dividing the permanent magnet will reduce this additive effect and then shifting each segment to slightly change the amount of magnetic flux distribution in a phase. The permanent magnet divides into 2, 3, 4, and 5 parts and shifts with common angle respected to the inner side of magnet. Then, 3D Finite Element Analysis (3D FEA) is performed to analyze the characteristics of model and extract the value of cogging torque generated to each model. Furthermore, analytical approach related to the methods that have been published is discussed to compare with the result from simulation.

In section II introduces the basic knowledge of axial flux permanent magnet generator, the model that utilized in this paper with the detail of material also presented. Then, the basics of cogging torque and radial divided shifting magnet methods are also discussed in this section with the expression of each method that have been published. In section III contained the simulation result and discussion comparing to the previous related research. And the last section is section IV that contain the conclusion of this research.

II. METHODOLOGY

A. Axial Flux Permanent Magnet Synchronous Generator

A permanent magnet synchronous generator (PMSG) is an electrical machine which converts torque from the shaft into electrical current synchronously via magnetic field generated by permanent magnet perpendicularly crossing to the wound. A permanent magnet which produces flux magnetic simultaneously and relatively constant replaces the position for rotor wound to synchronize magnetic field speed from rotor and stator. Therefore, without any additional wound in the construction, it will ease the manufacture, operation, and so does maintenance will reduce.

Based on the direction of induced magnetic flux, there are separated to radial and axial flux configurations. If both configurations are compared, with perspective of getting higher power density, the radial flux PM (RFPM) have limitation due to the bottleneck flux path from PM to stator core, much amount of rotor core around the shaft that is not accounted for magnetic circuits, and heat dissipation issues. The axial flux PM (AFPM) is about to answer the problems occurred in RFPM configuration with the advantages special properties such as larger diameter to length ratio, which is contributes to higher torque and lower dimension, then the airgap in AFPM is adjustable, more simple construction considering of modularity, and less amount of material utilized particularly core material, after that the more diameter of core, the greater number of poles can be accommodated [10].

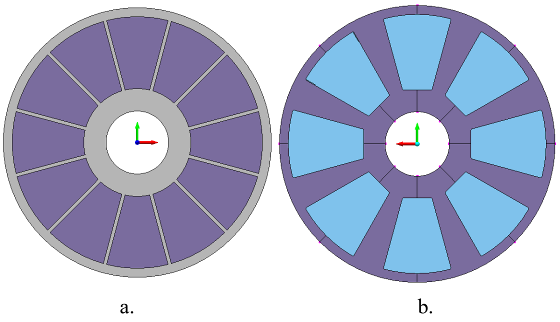
This paper utilized a single disc type which consists of a single rotor and single stator with 8 poles and 12 slots of axial flux PM generator configuration with the yokeless and segmented armature to obtain the characteristic value of cogging torque. The number of poles and slot used as based on the [11] as one of the efficient and relatively low of cogging torque value. The model is shown in Fig.1. For more detailed information about the model is shown in Table I. Yoke in the core acts as a mechanical support that connects each stator slot, but due to the common or similar material utilized with the core, it causes a problem to the connected magnetic field each stator slot. Eliminate yoke in the stator core disconnect magnetic field each slot that will reduce the core losses, reduce weight overall, and those factors are leads to the higher efficiency, and power density of the machines.

Therefore, with the absence of the yoke, to maintain the mechanical integrity of the stator, diamagnetic material is utilized with similar mechanical strength capability and low mass density to achieve higher power density. Epoxy resin material which has strength capability is utilized in this paper as a mechanical support of stator core.

Non oriented silicon steel is utilized as core material which has magnetic permeability properties as shown in Fig 2. This type of material has maximum flux density reaching up to 2.4 T. For the permanent magnet using N35 type of Neodymium Iron Boron (NdFeB) magnet with peak flux density 1.2 T as shown in Fig.3. N35 is made of rare-earth material and is one of the strongest magnets invented. Undoubtedly cogging torque will increase as stronger magnetic field as well. So, it is reasonable to use N35 to obtain the effectiveness of method to reduce the cogging torque.

TABLE I. DESIGN SPESIFICATION

Parameters	**Value**
Number of stator slots	12
Number of poles	8
Diameter of outer core stator	168 mm
Diameter of inner core stator	72 mm
Diameter of outer generator	180 mm
Diameter of shaft	42 mm
Core axial length	6 mm
Magnet length	5 mm
Air gap length	1 mm
Total axial length	53 mm
Material of magnet	N35 (NdFeB)
Material of stator enclosure	Epoxy
Material of core	Non-oriented silicon steel



a. b.

Fig. 1. AFPM Generator 8 poles 12 slots, a. Stator, b. Rotor.

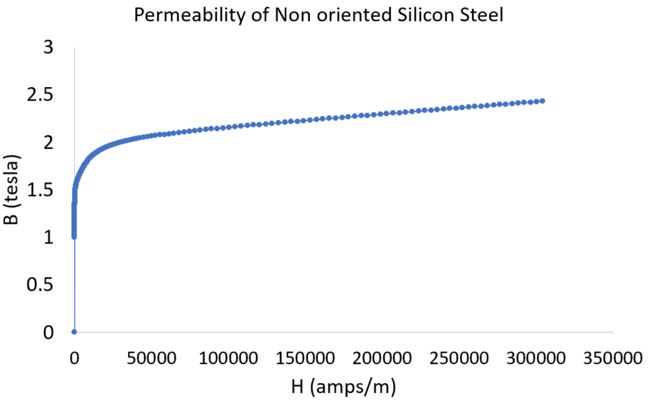


Fig. 2. Magnetic permeability of non oriented silicon steel.

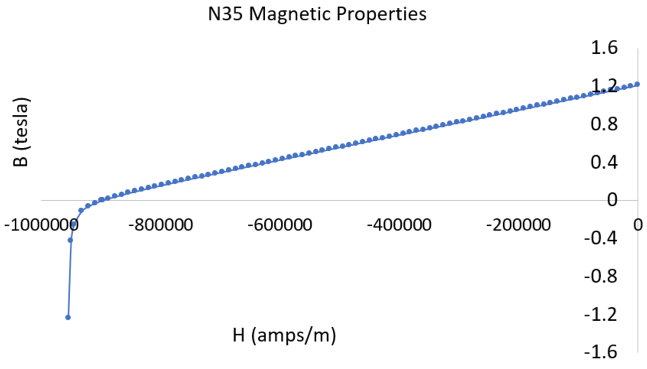


Fig. 3. Magnetic properties of N35 .

B. Cogging Torque

Cogging torque is one of the losses that occurred naturally in PM machines. If turned back to the electromechanical energy conversion theory, coupling field act as a bridge to the interaction between electrical component and mechanical component. Energy is transferred from electrical to mechanical components via coupling field and vice versa. In terms of rotating electric machinery, coupling field is representation of an air gap. As shown in (1), W_F which is total energy transferred to coupling field is a sum of energy stored in coupling field (W_f) and energy losses such as hysteresis, eddy current or dielectric losses (W_{fL}).

$$W_F = W_f + W_{fL} \tag{1}$$

While in the coupling field there is W_f as an energy stored, and another term should be considered is co-energy which is given by (2) [12]. From (2), co-energy equation consists of 3 components, there are co-energy of self-inductance represents in first term, co-energy from permanent magnet represents in second term, and in the third term represents co-energy of mutual flux. Then obtaining value of the energy stored and co energy stored in the coupling field or air gap is necessary to obtain the value of electromagnetic torque as shown in (3).

$$W_c = \frac{1}{2}Li^2 + \frac{1}{2}(\mathcal{R} + \mathcal{R}_m){\phi_m}^2 + Ni\phi_m \tag{2}$$

$$T(\theta) = \frac{\partial W_c}{\partial \theta} = \frac{1}{2}i^2\frac{dL}{d\theta} - \frac{1}{2}{\phi_m}^2\frac{d\mathcal{R}}{d\theta} + Ni\frac{d\phi_m}{d\theta} \tag{3}$$

$$T_{cog}(\theta) = -\frac{1}{2}{\phi_{airgap}}^2\frac{d\mathcal{R}}{d\theta} \tag{4}$$

Where L is inductance, i is electric current, $\mathcal{R}$ is magnetomotive force source reluctance, $\mathcal{R}_m$ is magnetic field reluctance, ϕ_m is magnetic flux in the air gap linking magnet and exciting coil, N is number of coil turns, and θ is represents a mechanical angle.

Derivation of co-energy stored in the airgap field with the rotor rotation angle resulting negative form in the second term that means to the inversely proportional between inductance and reluctance. Therefore, the second term represents the interaction between magnetic flux in the air gap and change of air gap reluctance to the rotor mechanical angle and evaluated as cogging torque as shown in (4). Due to the stator slotting, there is a gap between each slot, it causes variation in airgap reluctance and rotation of rotor causes change in value of airgap reluctance periodically. Hence (4) can be expressed in periodic function as Fourier series in (5).

$$T_{cog}(\theta) = \sum_{k=1}^{\infty} T_{mk}\sin(mk\theta) \tag{5}$$

where m is defined as least common multiple of number of slots and pole, k is integer number, and generally T_{mk} is Fourier coefficient [6].

C. Radial Divided Magnet Shifting

One of the few methods to reduce the cogging torque is segmentation of the permanent magnet. This paper discusses further about this method specific in radially segmented or radially divided. In the base model, the whole permanent magnet is placed normally, and segmentation magnet is about to divide the magnet into several segments equally with respective to the center of machine as shown in Fig. 4. Variation of number of segmentations is utilized to determine the effect of those numbers to reduce the cogging torque. The number of segmentations utilized in this paper is 2, 3, 4, and 5 segments. Then, each variation will be shifting with various angles with the shifting scheme as shown in Fig. 5. The angle of shift represented with α and the 1st segment acts as a reference to the next segment, therefore it is still unshifting. The term α_1 is shift angle for 2nd segment with respect to the center point of rotor and the value of α_1 is common with α_2, α_3, and α_4. As a boundary to this research, angle of shifting will be set to 1, 2, 3, 4, and 5 degrees, therefore will be 20 possibilities model to show differences between each variation. The number of angles is chosen with the consideration to find out what will occur if slot & pole pitch ratio is changed. Ideally, if slot and pole pitch ratio is changed, the distribution of magnetic flux also changes and will directly impact the cogging torque value. The shifting angle value is not exactly optimal, but with the variation will roughly describe the condition in each angle.

As magnet utilized is divided into several segments, the expression in (5) slightly changed due to the change of distribution of magnetic flux in the airgap as expressed as (6) [13].

$$B_{nN_L} = \frac{{B_0}^2}{\pi n \frac{L}{N_p}}\sin\left(nL\frac{\alpha_{mb}}{2}\right)\cos\sum_{i=0}^{N-1}\cos(inL\beta) \tag{6}$$

More detail from (6), B_{nN_L} is magnetic flux distribution affected by number of segmentations, α_{mb} is magnet block span originally, β is magnet block span to next magnet, L is least common multiple of number of slot (N_s) and pole (N_p). Expression in (6) was performed by researcher to the radial flux machines. Specifically for the axial flux configuration does not exist yet and will be the future works to determine. The main reason is in (6) state that greater number of segments directly proportional to the decrease of cogging torque. Otherwise, based on the 3D FEA simulation performed in this paper shown that in the single disc axial flux configuration, different characteristic is invented.

As magnet segmentation methods are affecting the value of magnetic flux distribution in the air gap as mentioned before, referred to [6], shifting of magnet are also affecting the cogging torque characteristic. There are differences in expression for integral and fractional number of slots per pole. Specifically for the configuration that has fractional number of slots per pole, the cogging torque expression is shown in (7).

$$T_{cog}(\theta) = \frac{N_p}{\gamma}\sum_{h=0}^{\gamma-1}\sum_{k=1}^{\infty} T_{pN_s\frac{N_p}{\gamma}k}\sin\left(N_s\frac{N_p}{\gamma}k\left(\theta - \frac{2\pi h}{N_s\gamma}\right)\right) \tag{7}$$

Equation (7) is present the change of cogging torque expression due to the shifting magnet into γ number of magnet groups. $T_{pN_s\frac{N_p}{\gamma}k}$ is defined as permanent magnet coefficient due to the shifting magnet and h is harmonics component.

Despite this expression is developed for radial flux machines, it is not ruling out the possibility to apply for the axial flux machines configuration with a few adaptations. This will be prepared as a future work to develop comprehensively about the analytical approaches for the combination of radial divided magnet and shifting for reduce cogging torque purposes.

III. RESULT & DISCUSSION

For simulating the torque performance of model, 3D Finite Element Analysis (3D-FEA) is performed in this paper with no load condition aiming to achieve natural response of cogging torque. The analysis started from the torque performance of the base model as mentioned before in Fig. 1. Then, to the proposed model with segmented magnet and no shifting, the result is shown in Fig. 5. RMS value of base model without optimization by dividing and shifting is 2.1 Nm, 2 segments model is 2.6 Nm, 3 segments is 2.1 Nm, 4 segments is 2.8 Nm and 5 segments is 1.9 Nm as shown in Table II.

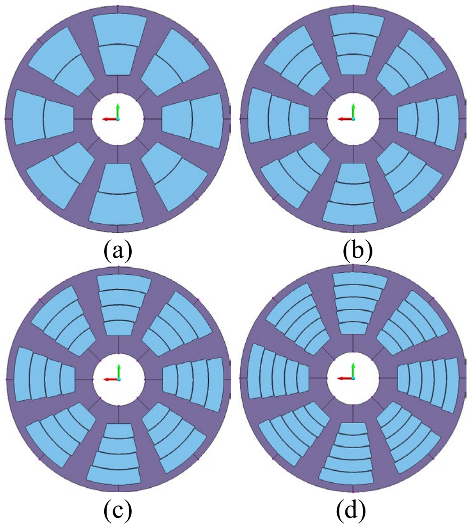

(a) (b)
(c) (d)

Fig. 4. Radially divided magnet configuration. (a) 2 segments, (b) 3 segments, (c) 4 segments, (d) 5 segments.

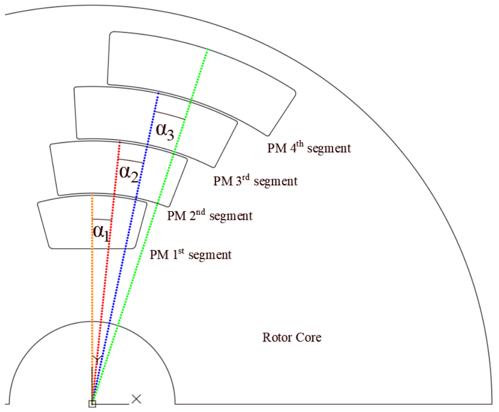


Fig. 5. Scheme of shifting the segmented permanent magnet

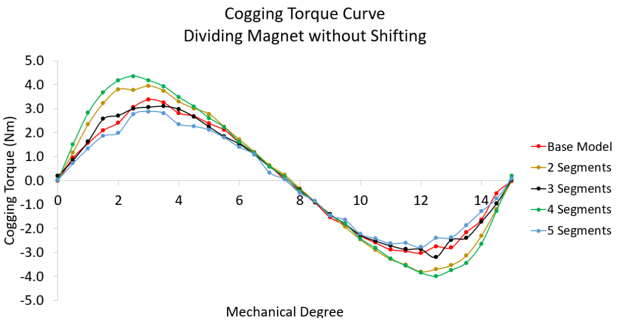


Fig. 6. Cogging torque curve variation without shifting.

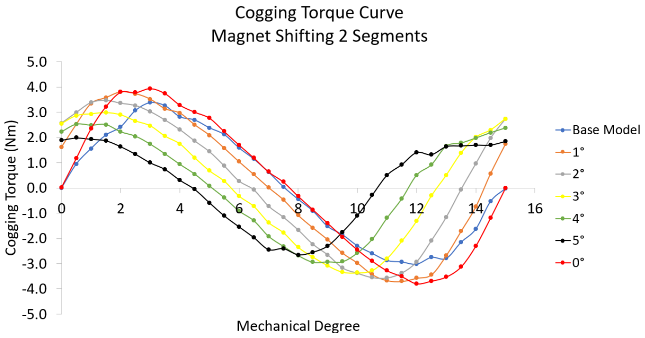


Fig. 7. Cogging torque curve of 2 segmented magnet model.

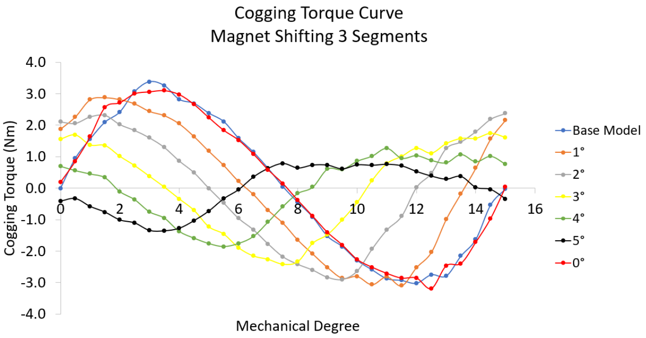


Fig. 8. Cogging torque curve of 3 segmented magnet model.

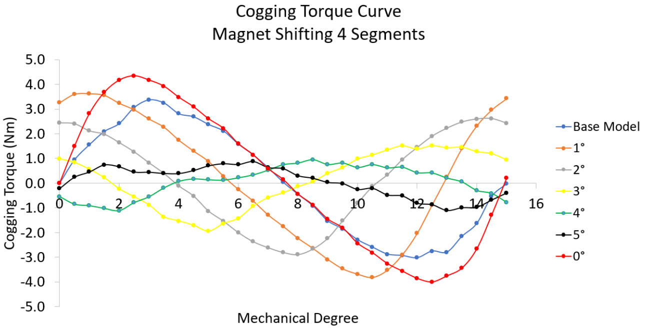


Fig. 9. Cogging torque curve of 4 segmented magnet model.

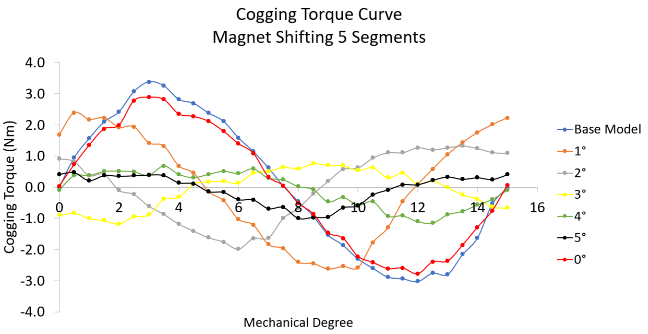


Fig. 10. Cogging torque curve of 5 segmented magnet model.

TABLE II. RMS COGGING TORQUE VALUE

	Base Model	**Number of Segments**	**Angle of Shifting**					
			0°	***1°***	***2°***	***3°***	***4°***	***5°***
RMS Value of Cogging Torque	2.142	2	2.63 (23%)	2.59 (21%)	2.48 (16%)	2.25 (5%)	1.94 (-9%)	1.64 (-23%)
		3	2.13 (-0.4%)	2.11 (-2%)	1.82 (-15%)	1.42 (-33%)	1.01 (-53%)	0.73 (-66%)
		4	2.78 (30%)	2.58 (21%)	1.92 (-10%)	1.13 (-47%)	0.62 (-71%)	0.61 (-72%)
		5	1.89 (-12%)	1.73 (-19%)	1.10 (-49%)	0.62 (-71%)	0.57 (-74%)	0.47 (-78%)

Although the expression in (6) states that greater number of magnet segmentation, distribution of magnetic flux is decrease and cogging torque value will decrease. Otherwise from the analysis specifically for the model utilized in this paper shown that the odd and even number of segmentations is influence to the cogging torque. Even number of magnet segmentation has an impact to increase the cogging torque value. And on the contrary, odd number of segmentations reduce the value of cogging torque. This result is quite different if referred to [5] that stated the greater number of magnet segmentation will directly be proportional to the weakening of cogging torque. This might be due to the different configuration of single and dual disc of rotor but with common yokeless and segmented armature. Since the cogging torque is the total forces occurred in the magnetic coupling field, it is supposed that in [5] is not affected by the odd or even number of segmentations, due to the relationship between two-disc rotor that has negated each other.

Next simulation is 2 segments permanent magnets model with several shifting angle variation as shown in Fig. 4a and the cogging torque curve is shown in Fig. 6. As mentioned before, in the even number of segmentations the cogging torque will increase without shifting angle. But with shifting, the RMS value of cogging torque decreased. As shown in Table II, for 2 segments model, RMS cogging torque decreases if the angle of shifting is 4-degree and above with 1.9 Nm in 4-degree shifting and 1.6 Nm in 5-degree shifting. Below 4 degree the cogging torque value is greater than the base model.

Then for the 3 segments model shown in Fig. 4b and the result is shown in Fig. 7. The result is from 0 degree of shifting, RMS value of cogging torque has reduced to 2.132 Nm from 2.142 Nm. And the lowest cogging torque is in 5-degree angle of shifting with 0.727 Nm. For the 4 segments model as shown in Fig. 4c, the result shown in Fig. 8 states that without shifting angle, the cogging torque increases to 2.779 Nm and the lowest cogging torque value in 4 segments model is 0.6 Nm in 5-degree shifting.

In 5 segments of permanent magnet model, as shown in Fig. 4d for the model and Fig 9 for the result, with no shifting, the RMS value of cogging torque has decreased to 1.886 Nm which is % lower than base model and, in this model, if the permanent magnet shifted about 5-degree, the RMS value of cogging torque decreased to 0.466 Nm which equal to 168% lower than base model. Methods of shifting the magnet is affected since the reduction by the increase of shifting angle is quite noticeable and directly proportional.

From the Table II, seen that either number of segmentation or shifting angle commonly reduce cogging torque despite in some cases the cogging torque is increase. Therefore, generally combinations of both methods are quite improving cogging torque quality as discussed in [5], [6], [14] also get a common result that shifting magnet can reduce greatly the cogging torque value. From the simulation result, we know that a greater number of permanent magnet segments will reduce more cogging torque. This occurred with reason that greater number of segments, the greater angle span of PM in the outer side respected to inner side. Initially, without shifting, the whole PM segments are in a cogging phase due to the position of PM and stator slot. Then, shifting each segment of PM is slightly change the initial position out of cogging phase, therefore full cogging effect avoided[6].

IV. CONCLUSION

Cogging torque need to be reduced significantly due to its behavior that led to the vibration and unstable rotation. The method proposed in this paper is approved by the simulation that able to reduce the cogging torque specifically to single disc rotor axial flux machines configuration. The fact appeared that odd number of magnet segmentation are affected to reduce the cogging torque, otherwise even number of magnet segmentation affected to the increases of cogging torque. Then, the effect of shifting each segment of permanent magnet led to reduction of cogging torque. The combination of both methods has led to a great reduction of cogging torque value.

REFERENCES

[1] D. Kostopoulos, “Rough Design of a 10 MW HTS Wind Generator,” Technical University Delft, Delft, 2013.

[2] A. Jassal, “Design of 2.25 MW Permanent Magnet Direct Drive Generator for Wind Energy Application with Concentrated Winding and Reduction of Eddy Current Losses in the Rotor Back Iron,” Technical University Delft, Delft, 2008.

[3] Y. Yasa and E. Mese, “Design and Analysis of Generator and Converters for Outer Rotor Direct Drive Gearless Small-scale Wind Turbines,” in *3rd International Conference on Renewable Energy Research and Application*, Milwakuee: IEEE, Oct. 2014, pp. 689–694.

[4] X. Wang, Y. Yang, and D. Fu, “Study of cogging torque in surface-mounted permanent magnet motors with energy method,” *J Magn Magn Mater*, vol. 267, no. 1, pp. 80–85, Nov. 2003, doi: 10.1016/S0304-8853(03)00324-X.

[5] S. Jamali Arand and M. Ardebili, “Cogging torque reduction in axial-flux permanent magnet wind generators with yokeless and segmented armature by radially segmented and peripherally shifted magnet pieces,” *Renew Energy*, vol. 99, pp. 95–106, Dec. 2016, doi: 10.1016/j.renene.2016.06.054.

[6] L. Dosiek and P. Pillay, “Cogging torque reduction in permanent magnet machines,” *IEEE Trans Ind Appl*, vol. 43, no. 6, pp. 1565–1571, Nov. 2007, doi: 10.1109/TIA.2007.908160.

[7] M. S. Huang, P. C. Chen, Y. S. Huang, and K. C. Chen, “Reduce the cogging torque of Axial Flux Permanent Magnet synchronous motor for light electric vehicle applications,” in

Proceedings of the IEEE International Conference on Industrial Technology, Institute of Electrical and Electronics Engineers Inc., May 2016, pp. 193–197. doi: 10.1109/ICIT.2016.7474749.

[8] K. Abbaszadeh, F. R. Alam, and S. A. Saied, “Cogging torque optimization in surface-mounted permanent-magnet motors by using design of experiment,” *Energy Convers Manag*, vol. 52, no. 10, pp. 3075–3082, 2011, doi: 10.1016/j.enconman.2011.04.009.

[9] K. Abbaszadeh, F. Rezaee Alam, and M. Teshnehlab, “Slot opening optimization of surface mounted permanent magnet motor for cogging torque reduction,” *Energy Convers Manag*, vol. 55, pp. 108–115, Mar. 2012, doi: 10.1016/j.enconman.2011.10.014.

[10] J. F. Gieras, R. J. Wang, and M. J. Kamper, *Axial flux permanent magnet brushless machines (Second Edition)*. 2008. doi: 10.1007/978-1-4020-8227-6.

[11] J. R. Hendershot and T. J. E. Miller, *Design of Brushless PM motors*, vol. 46, no. 11. 2016.

[12] C. Y. Hsiao, S. N. Yeh, and J. C. Hwang, “A novel cogging torque simulation method for permanent-magnet synchronous machines,” *Energies (Basel)*, vol. 4, no. 12, pp. 2166–2179, 2011, doi: 10.3390/en4122166.

[13] R. Lateb, N. Takorabet, and F. Meibody-Tabar, “Effect of magnet segmentation on the cogging torque in surface-mounted permanent-magnet motors,” *IEEE Trans Magn*, vol. 42, no. 3, 2006, doi: 10.1109/TMAG.2005.862756.

[14] T. Liu, S. Huang, and J. Gao, “A Method for Reducing Cogging Torque by Magnet Shifting in Permanent Magnet Machines,” in *2010 International Conference on Electrical Machines and Systems*, Incheon, South Korea: IEEE, Oct. 2010.