New Cogging Torque Reduction Methods for Permanent Magnet Machine

F. S. Bahrim, E. Sulaiman, R. Kumar, L.I. Jusoh

Research Center for Applied Electromagnetics, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

Corresponding author: fatihahshafiqah@gmail.com, erwan@uthm.edu.my

Abstract. Permanent magnet type motors (PMs) especially permanent magnet synchronous motor (PMSM) are expanding its limbs in industrial application system and widely used in various applications. The key features of this machine include high power and torque density, extending speed range, high efficiency, better dynamic performance and good flux-weakening capability. Nevertheless, high in cogging torque, which may cause noise and vibration, is one of the threat of the machine performance. Therefore, with the aid of 3-D finite element analysis (FEA) and simulation using JMAG Designer, this paper proposed new method for cogging torque reduction. Based on the simulation, methods of combining the skewing with radial pole pairing method and skewing with axial pole pairing method reduces the cogging torque effect up to 71.86% and 65.69% simultaneously.

1. Introduction

For the last decade, the demand of permanent magnet motors (PMs) with wide application prospect are receiving spotlight due to the advance development of high performance permanent magnet materials and manufacturing technology. In various PM motors, an interior-type permanent magnet motor (IPM) which magnet are inserted inside the rotor rather than bounding the surface shows better performances in flux weakening operation and achieve higher flux density due to the small air gap that allows to impose a magnetizing current effectively[1]. IPM motors are commonly used for industrial drives, electrical vehicle applications and generation systems as it has high element execution, and vitality change efficiency. However, due to PM air gap length, IPM create an extensive cogging torque issues.

The cogging torque or also known as detent torque and ‘no-current’ is a famous issue, which happened in PM motors. The components of cogging torque are produce by the interaction PM and slotted iron structure, and shows itself by the propensity of a rotor to adjust in various stable positions even when a motor is not energized. This deteriorates the machine operation, performance of position control system, generating acoustic noises and vibrations, speed pulsations, harmonics distortion, and premature wear of the bearings during low speed [2]. The communications between PMs mounted on the rotor and anisotropy began by stator windings slots raised the cogging torque and variations of the magnetic field energy during the rotation, as indicated by [3]:

$$T_{cog} = \delta W_m / \delta \Theta \quad (1)$$

where T_{cog} is the cogging torque, δW_m, is energy in the air-gap and $\delta\Theta$, is angle of rotor. Since the interaction between the PM on the rotor with the stator slot openings cause cogging torque, the cogging torque period is connected with the number of slots and poles by [3]:

$$N_p = N_r / \text{HCF}\,[N_r, N_s] \quad (2)$$

$$N_e = N_p[N_s/N_r] \quad (3)$$

Where N_p act as a constant, N_r for the rotor poles number, HCF for the highest common factor and N_e for the cogging torque period. The subsequent cogging torque is the total of the elementary torque created by the collaboration between the interaction between each magnet and the edge of the slot opening. Hence, high cogging torque is due to the low value of N_p while low cogging torque is due to the high value of N_p. To increase the performance, quality and life span of PM motors, minimizing the effect of cogging torque is an essential factor to consider when designing a machine. There is a certain degree of torque pulsation when the machine is running since the torque pulsation effect is worse at low speeds. For automobile application the cogging torque should be lower than 0.5% of the nominal torque[4]. Therefore, various cogging torque predicting and reducing methods are study in documents and presented in the literatures. In general, the well-known cogging torque minimization can be accomplish by modification of motor design. There are two aspects in motor design, which include modifications from the rotor side and stator side as illustrated in Figure 1.

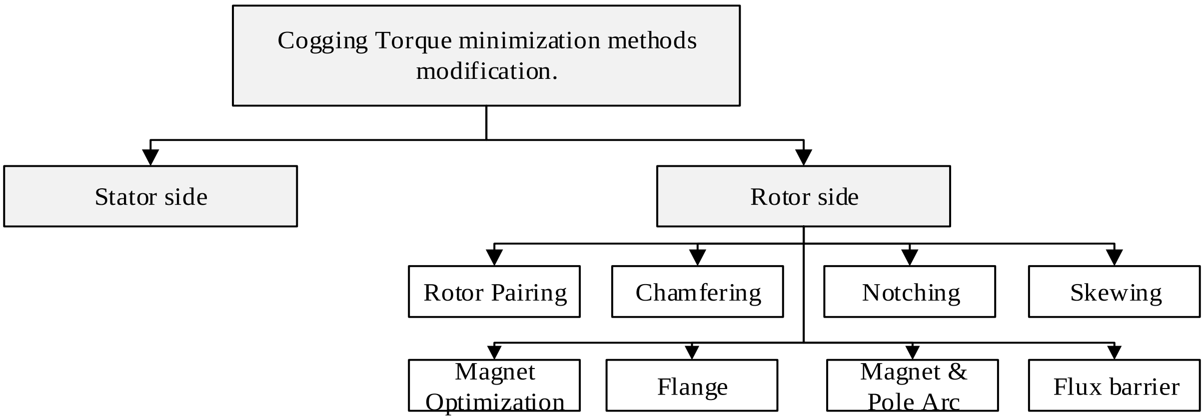

Figure 1: Methods for cogging torque minimization

Generally, the common stator side modification comprises the stator pole ratio[5], stator tooth pairing[2,6], dummy slots[7], displacement slot[7]. Conversely, the rotor side modification consists of rotor pole radially and axially paired[8,9], chamfering[10], magnet pole arc[11], magnet shaping or shifting[12], skewing[9,13], and notching[14]. Change in rotor part has been generally utilized compared to the stator part as the important drawback to minimize the cogging torque segment is that it confuses the stator producing and consequently expands the assembling expense of the machine. Hence, the stator side modification is not practical in most of the electrical machines and usually not preferred. In addition, there is less study for solid rotor-PM motors with the spoke-type IPMSM in recent years. Therefore, this paper analysed method on minimizing the cogging torque effect of 6S-4P spoke-type IPMSM using 3 existing methods as well as new combination methods. A commercial 3D-FEA package by JMAG Designer version 14.1 are used to compare the methods performances with various rotor-PM configurations.

2. Review of Cogging Torque

The project implementation of JMAG-Designer Software, released by Japan Research Institute (JRI) is divided into three parts which are motor design, performance analysis and optimization. To highlight the advantages of each reduction methods, a typical 6S-4P spoke-type IPMSM with basic rotor and PM configuration are actualized for the correlation comparison. Figure 2 shows the basic model configuration of four rotor pole and six stator slots with concentrated windings. This study is divided into two sections where the first section analyses the existing cogging torque minimization method. For instance, skewing, radial pole pairing and axial pole pairing. Then, novel techniques constituting the combinations of existing methods are additionally investigated from an outline point of view. First combination method combining skewing with radial pole pairing (SkPop) and the secondly combining skewing with axial pole pairing (SkApp).

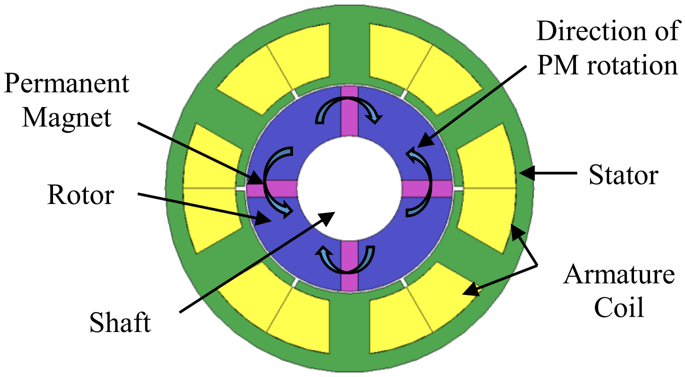

Figure 2: Basic model of of 6S-4P Spoke-type IPMSM

The motor specification and design parameters for conventional and cogging torque reduction method in designing process is as shown in Table 1 and Table 2. To get the best comparison performances, several parameters are fix such as stator and rotor size, number of coil turn, stack length, air gap as well as permanent magnet weight for each rotor-PM designs.

Table 1: Conventional design parameters of 6S-4P Spoke-type IPMSM

Initial design parameters	Unit	IPMSM
Outer radius of stator	mm	44.0
Inner radius of stator	mm	13.0
Outer radius of rotor	mm	25.5
Inner radius of rotor	mm	13.5
Stack length motor	mm	54.0
Width of permanent magnet	mm	4.2
Length of air gap	mm	0.5
Volume of permanent magnet	kg	0.83
Rotation Speed	rpm	4800

Table 2: Cogging torque reduction methods parameters

6S-4P Spoke-type IPMSM		**Cogging torque reduction techniques**		
Parameters	Unit	Skewing	Pole Pairing	Axial Pole Pairing
Inner arc rotor pole	mm	15.9	3.9,25.8	10.0,17.7
Outer arc rotor pole	mm	32.9	10.2,49.0	28.0,33.0
Permanent magnet width	mm	4.2	4.2	2.0,1.0
Skewing angles	ϴ	2.8	-	-
Volume of permanent magnet	kg	0.83	0.83	0.83

To affirm the principle operation of the PM motor, suitable materials and condition are carefully chosen. For this study, rotors are equipped with NdFeB permanent magnets with axial magnetization and Nippon steel 35H250 are set for the both stator and rotor. The coils are arranged then linked with a three phase circuit at rated speed of 4800rpm. Further steps included performance analysis during load and no load conditions. The no load condition can be described as no current supply to the armature coil which means armature density, J_a is equal to zero. The flux source during this condition is permanent magnet that is not easily be controlled. It is generally divided into three parts which are flux linkage, induce voltage and cogging torque analysis. Meanwhile, the performances of the motor in term of torque and power against speed characteristic has been carried out during the load condition.

3. Rotor-PM Configuration

In designing electrical motor with low cogging torque effect, several parameters such as low manufacturing cost and high motor performance need to be considered. An ideal shape of stator and rotor can increase the quality of the motor. Therefore, in this paper, the optimal rotor configuration of 6S-4P Spoke-type IPMSM are analysed using 3D-FEA. Three existing and two proposed methods that are related with PM can minimize the cogging effect has been applied in this study which are rotor skewing, rotor pole pairing, and rotor pole axial pairing. These optimal design approach will dramatically reduce the cogging torque of IPM motor.

3.1. Skew rotor design.

The famous and widely used method on reducing the cogging torque issues in PM motors are known as skewing. The basic idea behind skewing is to influence the interaction between the stator slots and the rotor magnets. In theory, the cogging torque can be eliminated. In contrast, it may not perfectly reach zero, but be significantly reduced. Skewing method can be done by skewing of either the rotor or the stator stack. Both have detriments. Skewing the magnets expands the magnet cost. Skewing the slots increase the copper losses because of expanded slot length, bringing about the more drawn out wire. Also the slots skewing is related with high production cost[9]. In IPM machines, only stator skewing or rotor step (discrete) skewing is a feasible solution Furthermore, depending on the skewed angle the both skew methods decrease the output torque of the machine. For large scale manufacturing motors, stepped skew technique is chosen because it's simpler and simple to execute, and also leads to decreased PM eddy current losses. To make the rotor manufacturing simpler, the skewing might be approximated by putting the PM pivotally skewed by discrete steps. Equation below shows the angle of skew between two adjacent steps [13].

$$\Theta_{skewing} = 2\pi / nN_cQ \qquad (4)$$

ϴ is the skewing angle, n is skewing steps number, Q is the number of stator slots, and N_c is the cogging torque period as mentioned in equation 1. Based on the Equation 4, the suitable skewing angle for the 6S-4P Spoke-type IPMSM 2.8°. The skewed model is as illustrated in Figure 3(a) and (b).

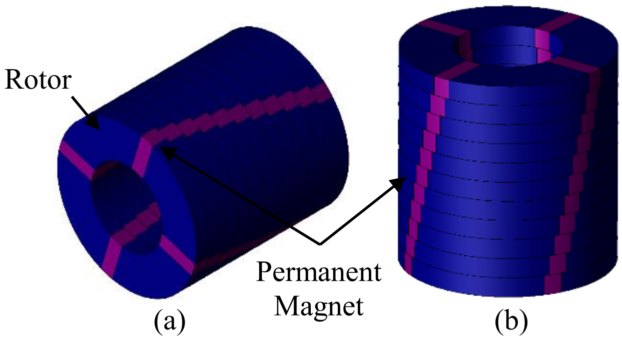

Figure 3: Skew rotor design a) Isometric view b) Top view

3.2. Radial pole pairing

Another cogging torque reduction method is teeth or pole pairing. This is a method of pairing the two different pole size or width in the rotor design and can be applied in both stator [6][2][15] and rotor part[7][16]. The variable magnetic resistance of air gap and rotor not only change the waveform of cogging torque, but also reduce the amplitude of cogging torque. To obtain smaller amplitude of the cogging torque, it is also necessary to choose the proper width ratio of armature teeth to magnet pole. Based from the Fourier series expansion in [8], the maximum cogging torque is reduced by 85% by pairing the stator teeth and in [16], experimental results show pairing rotor pole reduces the cogging torque by 85% along with an acoustic noise of 3.1dB. In this study, two pair of rotor pole are radially paired with the optimized outer arc length of 10.2mm and 49.0mm as shown in Figure 4(a) and (b). It is believed the cogging torque of this scheme could be minimize.

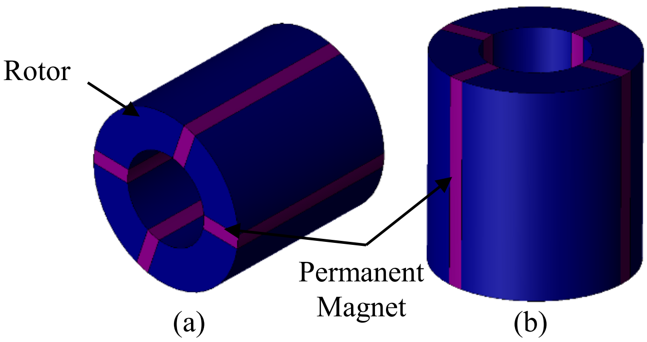

Figure 4: Radial pole pairing rotor design a) Isometric view b) Top view

3.3. Axial Pole Pairing

Rotor axial pole pairing is another technique of pole pairing by altering the stack length of design, corresponding to the magnitude of cogging. Executing circumferential pole paired can likewise lessen the cogging torque of PM motor adequately. The stacks length is fixed and only pole arc is varied so that cogging torque using axial pole arc pairing is examined as results. Soo-Gyung Lee in [17] proposed an improved pole pairing considering axial stack length using analytical formulas which reduces the cogging torque by 71.98%. Researcher in [9] mentioned, by selecting the optimal rotor pole arc, the effect of cogging torque not only can be reduced, but also results in improved harmonic content of the back EMF. For this study, an axial rotor pole pairing configuration with outer pole outer pole arc of 28.0mm and 33.0mm is as illustrated in Figure 5(a) and (b) below.

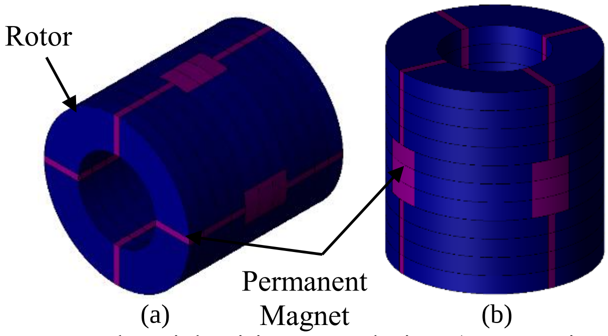

Figure 5: Rotor pole axial pairing rotor design a) Isometric view b) Top view

3.4. Combination Method

Combination method is the possible combination of two or more existing cogging torque reduction techniques. There are several combination techniques are studied for the last several years. For example, F. Yusivar combined the slot and pole number[18], Bin Zhang combined teeth notching with rotor magnets skewing[19] and Gyeong-Chan Lee has combined the stator tooth pairing with stator displacement which results in reducing the cogging torque effect up to 93.3% [2]. In this paper, the combination methods are combining skewing with pole pairing (SkPop) and skewing with axial pole pairing (SkApp) at the rotor part. The combination rotor model is as illustrated in Figure 6 and Figure 7.

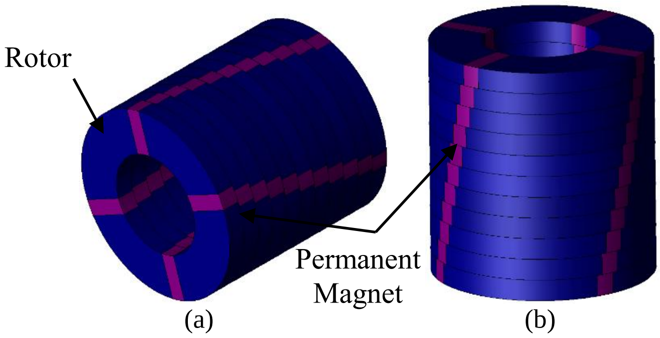

Figure 6: SkPop rotor model a) Isometric view b) Rotor top view

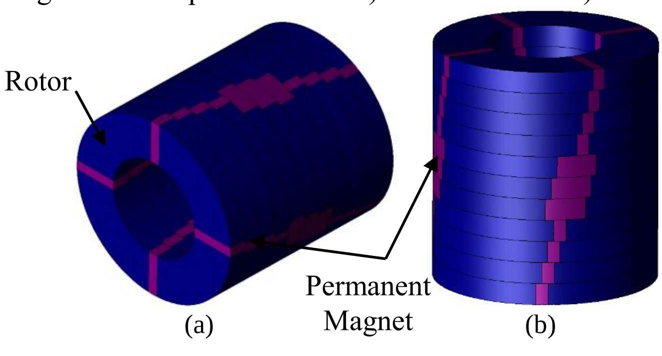

Figure 7: SkApp rotor model a) Isometric view b) Rotor top view

4. Analysis of cogging torque reduction method

Several analysis are conducted to investigate the properties and performances of each rotor designs including flux linkage, induced voltage, cogging torque, torque and power versus armature current density and finally characteristics of torque and power against speed.

4.1. Flux Linkage

For investigation of flux from PM only or under open circuit condition, the armature current density is fixed at 0A/mm^2. From Figure 8, it is clearly shown that higher flux amplitude emerges from rotor pole pairing design technique with 0.156Wb whereas basic, skewing, axial pole pairing, SkPop and SkApp are only measured at 0.151Wb, 0.148Wb, 0.143Wb, 0.151Wb and 0.144Wb respectively. The lack performances of flux amplitude are are because of the weakening flux density distribution and long distance flux flow inside the stator as well as proposed rotor structures.

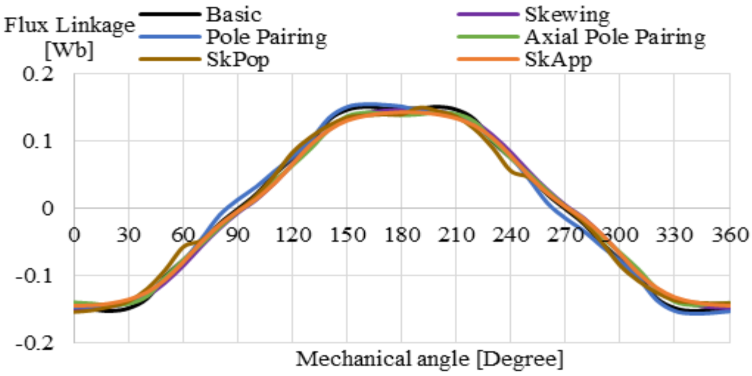

Figure 8: Flux Linkage of all rotor-PM designs.

4.2. Induced Voltage

During open circuit condition, induced voltage are used for regenerative breaking. By rotating the rotor, the rotor speed is constant at the rated speed one 4800r/min. The back electromotive force (EMF) of six rotor model with various rotor-PM designs are analysed and compared as in Figure 9. SkPop model results in highest amplitude of EMF with approximately 833.7V followed by radial pole pairing, basic, SkApp, axial pole pairing and skewing model. The high back-EMF is due to armature reaction, which creates demagnetizing effect in the machine. However, the high amplitude value of EMF are still within the worthy range.

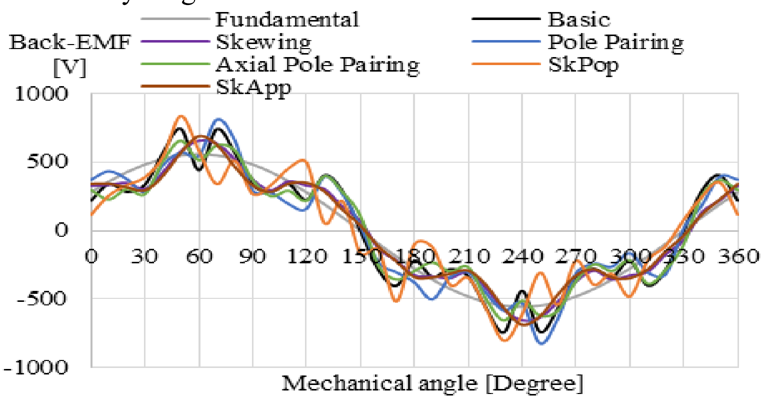

Figure 9: Phases of Back EMF.

4.3. Cogging torque reduction analysis

The characteristic of cogging torque phenomena leads to torque pulsation which correlate to improper vibration and noise, poor position control, reduction in performances and running disappointment. By setting the armature current density of J_a=0 Arms/mm^2, the complete one electric cycle of generated torque can be examined as illustrated in Figure 10. The peak to peak value of cogging torque for different rotor-PM configurations are shown in Figure 11. Clearly shows that Basic rotor model contribute to the highest peak-to-peak value with approximately 1.02Nm followed by axial pole pairing, pole pairing, SkApp, skewing and SkPop with 0.69Nm, 0.53Nm, 0.35Nm, 0.3Nm and 0.27Nm respectively. As referred to the conventional or basic rotor model, SkPop method shows the highest cogging torque reduction compared to skewing model and the other rotor model. With this high percentage of reduction achievement as shown in Figure 12, it is expected that the motor fluctuation, acoustic commotion and performances are improved.

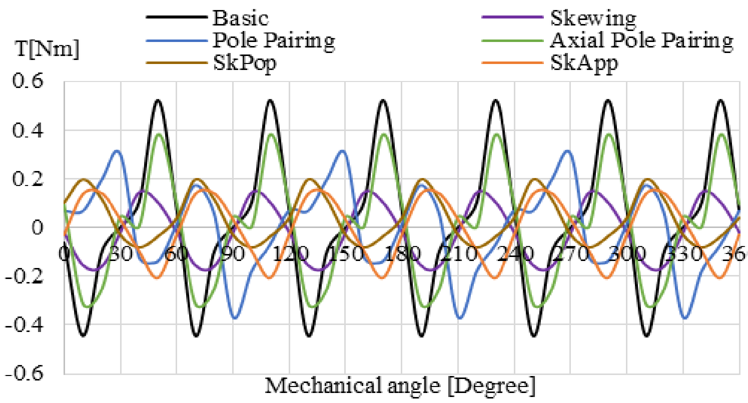

Figure 10: Cogging torque cycle of proposed design.

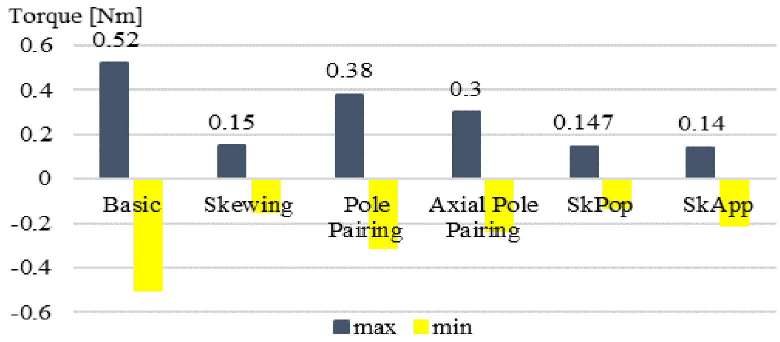

Figure 11: Maximum and minimum cogging torque amplitude.

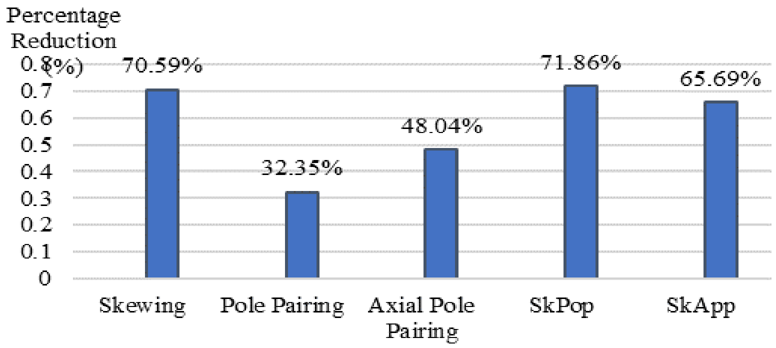

Figure 12: Cogging torque reduction percentage

4.4. Initial Torque and Power Performance in various Armature Current Density, J_a

The output torque and output power of various rotor configuration against various armature current density, J_a has been analysed in this study during load condition. Results are sketched in Fig. 13 and Figure 14, in which armature current density is varied from J_a=0 Arms/mm^2 up to J_a=30 Arms/mm^2. The graph shows that the output torque increase as the armature current density increased. Maximum torque of 5.12Nm is obtained by basic model when armature current density is set at 30A/mm^2. The high torque accomplishment is demonstrated by the orientations of magnetizing flux.

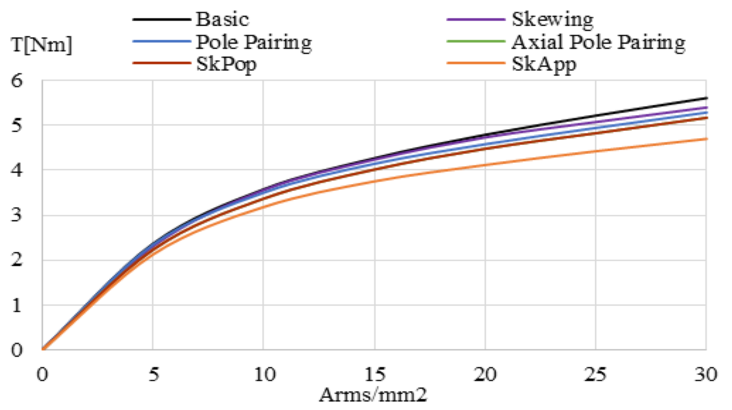

Figure 13: Initial torque output vs J_a.

At maximum J_a of 30 A/mm^2, the initial power achieved by basic model emerged as the highest with 658.8W followed by skewing, radial pole pairing, axial pole pairing, SkPop and SkApp with maximum initial power of 5.40W, 5.62W, 5.29W, 5.17W, 5.53W, and 4.70W simultaneously. All the initial power of proposed rotor design configuration increase with J_a as in Figure 14.

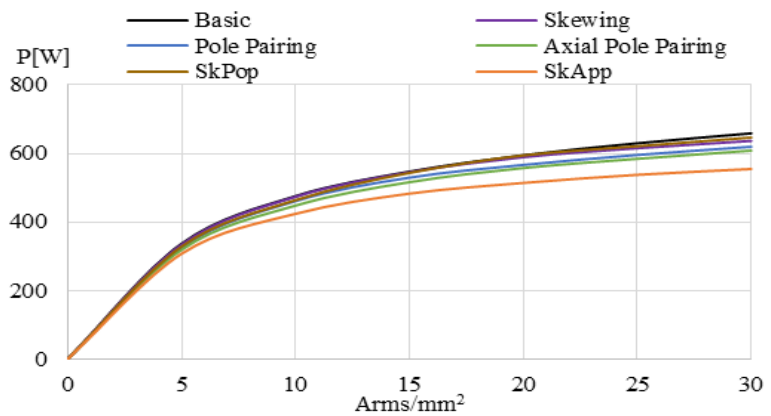

Figure 14: Initial power output vs J_a.

4.5. Torque and Power versus Speed Characteristics

In this section, all rotor models are analysed by running at various edge of armature current extents from 10º up to 90º to identify the maximum torque of the rotor designs. For the case of 6S-4P Spoke-type IPMSM, the maximum torque is obtained at 30º. According to results in Figure 15, basic and SkPop model indicate the best torque capabilities. The maximum torque of 6.6Nm for both model recorded recorded at base speed of 1167.2r/min and 1168.6r/min respectively. In contrast, SkApp model produce the lowest torque capabilities of 4.95Nm at base speed of 1150.9r/min. Moreover, Figure 16 compared the power performances against rated speed of six rotor model. Clearly shown that both basic and SkPop rotor-PM designs indicate the highest power of 806W as the relationship of power output can be executed by utilizing the information of torque and speed. As a last point, performances of overall proposed rotor model are summarized in Table 3.

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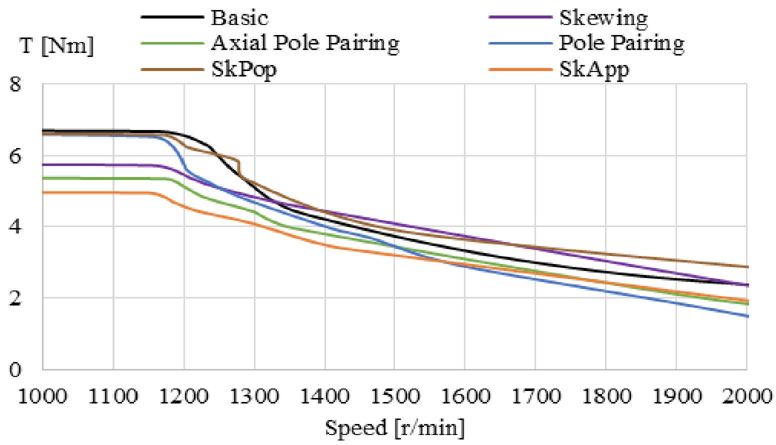

Figure 15: Torque vs speed characteristic.

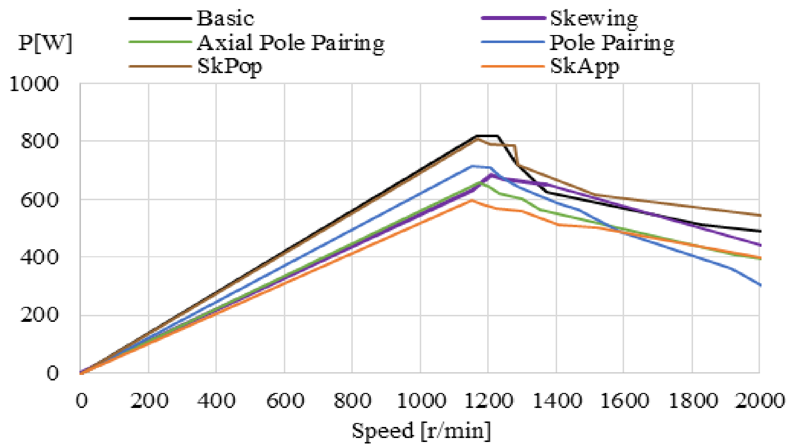

Figure 16: Power vs speed characteristic.

Table 3: Comparison of all rotor design of 6S-4P Spoke-type IPMSM

Rotor model	**Cogging torque (Nm)**	**Cogging Torquereduction (%)**	**Torque (Nm)**	**Power (W)**	**Speed (r/min)**
Basic	0.98	-	6.60	806.71	1167.2
Skewing	0.30	70.59	5.73	629.51	1154.1
Radial pole pairing	0.66	32.35	6.53	711.40	1153.0
Axial pole pairing	0.69	48.04	5.66	696.61	1173.1
SkPop	0.28	71.86	6.60	806.51	1168.6
SkApp	0.35	65.69	4.95	596.58	1150.9

5. Conclusion

The cogging torque in 6S-4P spoke-type IPMSM with existing and two proposed cogging torque reduction method are successfully reduced in this paper. In addition, the motor performances in term of flux linkage, induce voltage, torque and power characteristic as well as the efficiency also has been investigated and discussed based on 3D-FEA JMAG. The best method in reducing the cogging torque effect of 6S-4P Spoke-type IPMSM is SkPop method with the highest percentage of reduction of 71.86%. With these excellent design approach, this rotor-PM configuration maintain the performance of the conventional design as it produced better power and torque speed ranges as well as reducing the effect of cogging torque. Thus, advance study in cogging torque characteristic to reduce the effect of cogging torque for PM machine should be carry out in future study.

6. Acknowledgement

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References

[1] O. Kudrjavtsev and A. Kilk, "Cogging Torque Reduction Methods," Tallinn University of Technology, Tartu, Estonia, 2012,pp. 212–214.
[2] G. Lee, "Cogging Torque Reduction Design of Dual Stator Radial Flux Permanent Magnet Generator for Small Wind Turbine," TENCON Spring Conference, 2013 IEEE, pp. 85–89, 2013.
[3] C. Studer and S. M. A. Keyhani, "Cogging Torque in Permanent Magnet Machines," IEEE Transactions on Industry Applications,pp. 42–49, 1997.
[4] G. Dajaku and D. Gerling, "New Methods for Reducing the Cogging Torque and Torque Ripples of PMSM." 2014 4th International Electric Drives Production Conference (EDPC)
[5] Y. Pang, Z. Q. Zhu, and Z. J. Feng, "Cogging Torque in Cost-Effective Surface-Mounted Permanent-Magnet Machines," IEEE Transactions on Magnetics, vol. 47, no. 9, pp. 2269–2276, 2011.
[6] G. Lee and T. Jung, "A Design on Reduction Cogging Torque of Dual Generator Radial Flux Permanent Magnet Generator for Small Wind Turbine," J Electr Eng Technol Vol.8, No.6: 1590-1595, 2013, vol. 8, no. 6, pp. 1590–1595, 2013.
[7] V. Keloth, M. Mijas, and M. Pa, "Analysis of Cogging Torque Reduction Techniques of a Slotless PMBLDC Motor," International Conference on Magnetics, Machines & Drives (AICERA-2014 iCMMD) 2014.
[8] E. Engineering, G. Xin, H. Guangxian, C. Zhi, and W. Zongpei, "Research of Cogging Torque in the Brushless DC Motor with Fractional Ratio of Slots and Poles," Electrical Machines and Systems, 2005. ICEMS 2005, pp. 1–5.
[9] W. Fei and P. C. K. Luk, "A New Technique of Cogging Torque Suppression in Direct-Drive Permanent Magnet Brushless Machines," Electric Machines and Drives Conference, 2009. IEMDC '09, pp. 9–16, 2009.
[10] W. Xu, J. Zhu, Y. Zhang, and J. Hu, "Cogging Torque Reduction for Radially Laminated Flux-Switching Permanent Magnet Machine with," IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society, pp. 3590–3595, 2011.
[11] G. Lee, S. Kang, and T. Jung, "Permanent Magnet Structure Design of Outer Rotor Radial Flux Permanent Magnet Generator for Reduction Cogging Torque with Design of Experiment," 2013 International Conference on Electrical Machines and Systems, pp. 315–319, 2013.
[12] T. Liu, S. Huang, and J. Gao, "A Method for Reducing Cogging Torque by Magnet Shifting in Permanent Magnet Machines," The National Natural Science Found (50907020) ,no.50907020, pp. 2–5.
[13] V. Gr, L. Tutelea, and I. Boldea, "and Torque Pulsation Reduction via FEM."
[14] Hong Uk Kim, Woo You Lee, Yong Bae Kim, Pan Seok Shin , A Notch Shape Optimization of IPMSM Rotor Surface for Cogging Torque Reduction by PSO Method with FEM, 013 International Conference on Electrical Machines and Systems, Oct. 26-29, 2013, Busan, Korea.
[15] L. Hao, M. Lin, D. Xu, N. Li, and W. Zhang, "Cogging Torque Reduction of Axial-Field Flux-Switching Permanent Magnet Machine by Rotor Tooth Notching," IEEE Transactions on Applied Superconductivity vol. 51, no. 11, pp. 2–5, 2015.
[16] S. Hwang, J. Eom, G. Hwang, W. Jeong, and Y. Jung, "Cogging Torque and Acoustic Noise

Reduction in Permanent Magnet Motors by Teeth Pairing," IEEE Transactions on Magnetics, vol. 36, no. 5, pp. 3144–3146, 2000.

[17] S. Lee, K. Jung, S. Chai, and J. Hong, "Cogging Torque Reduction in Surface-mounted Permanent Magnet Synchronous Motor by Axial Pole Pairing," EVS28 International Electric Vehicle Symposium and Exhibition, , pp. 6–10, 2015.

[18] F. Yusivar, V. H. S. Roy, R. Gunawan, and A. Halim, "Cogging Torque Reduction With Pole Slot Combination and Notch," 2014 IEEE International Conference on Electrical Engineering and Computer Science 2014, Bali, Indonesia, pp. 260–263, 2014.

[19] B. Zhang, X. Wang, R. Zhang, and X. Mou, "Cogging Torque Reduction by Combining Teeth Notching and Rotor Magnets Skewing in PM BLDC with Concentrated Windings," 2008 International Conference on Electrical Machines and Systems, pp. 3189–3192.