Cogging Torque Reduction Techniques for Spoke-type IPMSM

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Abstract. A spoke-type interior permanent magnet synchronous motor (IPMSM) is extending its tentacles in industrial arena due to good flux-weakening capability and high power density. In many of the application, high strength of permanent magnet causes the undesirable effects of high cogging torque that can aggravate performance of the motor. High cogging torque is significantly produced by IPMSM due to the similar length and the effectiveness of the magnetic air-gap. The address of this study is to analyze and compare the cogging torque effect and performance of four common techniques for cogging torque reduction such as skewing, notching, pole pairing and rotor pole pairing. With the aid of 3-D finite element analysis (FEA) by JMAG software, a 6S-4P Spoke-type IPMSM with various rotor-PM configurations has been designed. As a result, the cogging torque effect reduced up to 69.5% for skewing technique, followed by 31.96%, 29.6%, and 17.53% by pole pairing, axial pole pairing and notching techniques respectively.

1. Introduction

Recently, permanent magnet (PM) electric motors, including synchronous motors, stepping motors and brushless direct current motors has been extensively used in high performance industrial and commercial drive applications. It is mainly due to their incredible advantages, as it were high in power and torque density, better dynamic performance, as well as simpler motor assembly and maintenance. In different PM motors, for an interior-type PM (IPM) motor utilized for variable-speed drives, a division of PMs brought on by the centrifugal force at high speed can be avoided since the PM is embedded into the rotor core[1].

There are several advantages in Interior Permanent Magnet Synchronous Motor (IPMSM) compared with surface permanent magnet synchronous motor (SPMSM). IPMSM has a structure that is mechanically steady by the PM inserted in rotor. The motor has a marginally higher torque density per unit volume than the other kind of motors[2]. IPMSM also has a large area of speed control since it has low magnetic field operation and high efficiency. Hence, it is known as an incredible machine for the drive system of electric vehicles in motor enterprises. However, IPMSM produces an extensive cogging torque because of a long compelling air gap of the length of PM and the self-air gap of the machine. Cogging torque or also called detent torque and 'no-current' torque produced due to the interaction between the rotor magnets and the stator teeth of the machines. These parasitic ripples can prompt to both mechanical vibration and acoustic commotion. Cogging torque is additionally

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unfavorable to the execution of position control frameworks, for example, robots and to the execution of speed control frameworks especially at low speed[3]. The interactions between permanent magnets mounted on the rotor and the anisotropy originated by stator windings slots arised the cogging torque and variations of the magnetic field energy during the rotation, according to:

$$\tau_{cog} = \delta Wm/\delta\theta \qquad (1)$$

the rotor tends to reach a minimum reluctance position. Cogging torque acts as a disturbance, superimposing over electromagnetic torque produced during machine operation. Since the cogging torque is caused by the interaction between the PM on the rotor with the stator slot openings, the cogging torque period is linked with the number of slots and poles by[4]:

$$N_p = N_r/HCF[N_r, N_s] \qquad (2)$$

$$N_e = N_pN_r/N_s \qquad (3)$$

N_e is referring to the number of cogging torque cycles, N_p is a constant, N_r is the number of rotor poles and HCF is the highest common factor. The resulting cogging torque is the sum of the elementary torque produced by the interaction between each magnet and the edge of the slot opening. Therefore, the low value of N_p leads to high cogging torque while higher values of N_p lead to low cogging torque. Cogging torque can be expressed by means of Fourier series as stated in Equation 4.

$$\tau_{cog} = \sum_{k=1}\sin(kQ\theta_m+\text{Ø}k) \qquad (4)$$

There are numerous techniques attempt to reduce the amplitude of the main harmonics by acting on either of these physical amounts since the magnetic energy could be express as a function of permeance and squared magnetomotive force (MMF)[4].

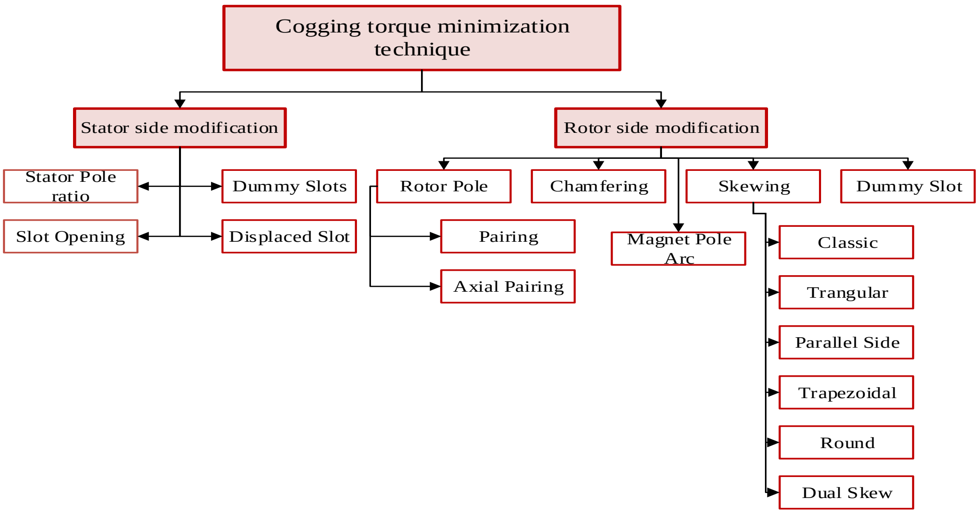
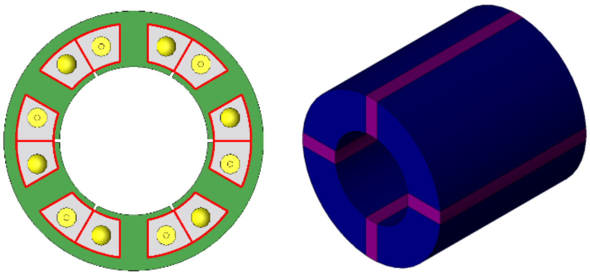


Fig. 1: Cogging torque minimization technique

In addition, the maximum generated cogging torque values must not exceed 10% of the average torque because it is unnecessary for the performance of the machine, which may lead to high vibration and noise drawbacks. Numerous approach to minimize the cogging torque effect were proposed and investigated in the past several years on both radial and axial type PM machines[5]. Not all of these methods can be directly apply to Synchronous motor. In general, the well-known cogging torque minimization can be accomplished in two aspects, which include modifications from the rotor side and stator side as illustrated in Figure 1. Basically, the stator side modification comprises the stator pole ratio[6], stator tooth pairing[7], slot opening[8], dummy slots and displacement slot[9]. In contrast, the rotor side modification consists of rotor pole radially and axially paired[10,11], chamfering, magnet pole arc[12], magnet shaping or shifting[13], skewing[14,15], and nothing or dummy slots[1,2,16]. Modification in rotor part has been widely used compared to the stator part. The important drawback of modification in rotor part is to minimize the cogging torque segment is that it confuses the stator producing and consequently expands the assembling expense of the machine. Therefore, modifications from the stator side are not practical in majority machines and usually not preferred. However, there is less study for solid rotor PM motors with the spoke-type IPMSM in recent years. Hence, in this paper, the minimization of cogging torque effect of 6S-4P spoke-type IPMSM using skewing, notching, pole pairing and axial pole pairing have been analysed and compared based on a commercial 3D FEA package by JMAG Designer version 14.1.

2. Cogging Torque Reduction for spoke-type IPMSM.

To highlight the benefits of the cogging torque reduction techniques, a conventional 6S-4P spoke-type IPMSM with the conventional rotor-PM configurations was implemented for the comparison. A six slot stator with concentrated windings and circumferentially magnetized NdFeB magnets in a spoke-type array is inserted in the rotor as shown in Fig.2.



(a) (b)

Fig. 2: basic model a) Stator with coil winding b) rotor with magnet

The motor specification and design parameter with fixed number of stator slot, rotor pole, stator outer diameter, and total permanent magnet weight are shown in Table 1 and Table 2.

Table 1: Design parameter for skewing, notching, pole pairing and rotor pole axial pairing of 6S-4P IPM motor.

6S-4P IPMSM	Parameters			
	Rotor pole inner arc length	**Rotor pole outer arc length**	**Permanent magnet width**	**Skew angle**
Skewing	15.9mm	32.9mm	4.2mm	2.8°
Notching	15.9mm	32.9mm	4.2mm	-
Pole Pairing	3.9mm, 25.8mm	10.2mm, 49.0mm	4.2mm	-
Pole axial pairing	10.0mm, 17.7mm	28.0mm, 33.0mm	2.0mm, 10.0mm	-

Table 2: Design parameters for basic motor design of 6S-4P IPM motor.

Parameters	**6S-4P IPMSM**
Stator slot numbers	6
Rotor pole numbers	4
Stator outer radius (mm)	44
Stator pole shoes width (mm)	2.1
Air gap length (mm)	0.5
Rotor pole inner arc length (mm)	15.9
Rotor pole outer arc length (mm)	32.9
Outer Radius of rotor (mm)	24.6
Shaft radius (mm)	12.6
Inner radius of stator (mm)	25.1
Permanent magnet width (mm)	4.2
Stator tooth width (mm)	9.43
Speed (rpm)	4800

Materials and conditions for all motor models are as shown in Table 3. Rotation motion, torque and arrangement of FEM coil are set under condition setting. Arrangement of the FEM coil are linked with a three phase circuit and a rated speed of 4800rpm is used for magnet and rotor rotation in this paper.

Table 3: materials and conditions

Parts	**6S-4P IPMSM**	
	Materials	**Conditions**
Rotor	Nippon Steel 35H250	Motion: rotation Torque: nodal force
Stator	Nippon Steel 35H250	—
Armature Coil	Conductor Copper	FEM Coil
Permanent Magnet	Neomax-35AH (irreversible)	Motion: rotation Torque: nodal force

3. Spoke-type IPMSM rotor design

IPMSM focuses on the stator parts ,rotor modification, and length of the air gap in order to study the cogging torque minimization. Techniques to reduce the effect of cogging torque are determined by the terms of easy implementation with minimal cost and machine performance. Therefore, this paper deals with the optimal shape design of Spoke-type IPMSM and the design parameters are derived by an analytical method and the rotor shape is optimized using FEA. There are four methods associated with permanent magnet that can reduce cogging torque, which are rotor skewing, rotor notching, rotor pole pairing, and rotor pole axial pairing. These optimal design approach will dramatically reduce the cogging torque of IPM motor.

3.1. Skewing

One of the most popular technique for cogging torque reduction is to skew either the rotor or the stator stack. The basic idea behind skewing is to influence the interaction between rotor magnets and the stator slots. The purpose of this technique is making $dR/d\theta$ zero for each face of the magnet. Hypothetically, the cogging torque impact can be eliminated but essentially, it may not flawlessly achieve zero. However, it will significantly reduced. Skewing can be executed on either the magnets or the slots and both have drawbacks. Skewing the magnets increases the magnet cost. Skewing the slots increases the copper losses due to increased slot length, resulting in the longer wire[17]. The skewing angle for the skewed model is between two adjacent steps which is equal to:

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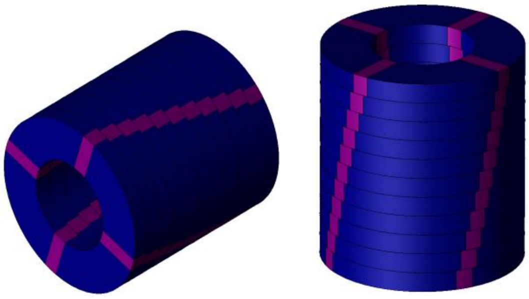
$$\theta_{skewing} = 2\pi/nN_cQ \quad (5)$$

Where n is the number of skewing steps, Q is the number of stator slots, and N_c is the period of cogging[18]. This method diminished of the adjustment in the reluctance, which seen by the magnets rotor and thus the cogging torque. The cogging torque varies approximately linearly from its peak with an unskewed rotor and stator to ideally zero with one slot pitch skewing. In practice, even with a full slot pitch skew, end-effects and rotor eccentricities result in a nonzero residual cogging torque of the order of one percent of rated torque[19]. Skewing additionally has the impact of enhancing the stator windings distribution and significantly reduces higher order back-EMF harmonic subsequently creating more sinusoidal back-EMF wave-shapes. In this paper, skewed model with an angle skew of 2.8° as shown in Fig. 3(a) and Fig. 3(b) has been designed and analyzed.

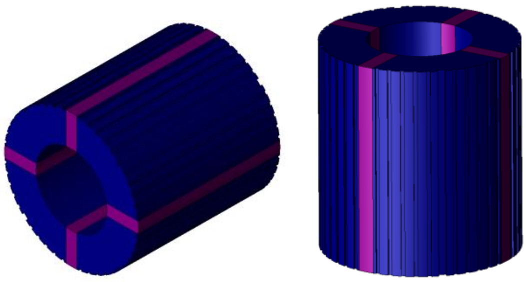


(a) (b)

Fig 3: Skewing rotor model a) Isometric view b) Rotor top view

3.2. Notching

Notches are dummy slots in either stator or rotor of the machine. This approach can be effectively applied to reduce the cogging torque effect in IPMSM by reducing the flux of the air-gap[20]. Air-gap flux is directly reduced as the magnet flux density is lowered by changing the magnet grades. In [3], notching has the same influence on cogging torque production as the real slots if appropriate notches are displayed uniformly on the teeth.



(a) (b)

Fig 4: Notching rotor model a) Isometric view b) Rotor top view

Eleven notches in the rotor pole were chosen as shown in Fig.4 (a) and 4(b). Rotor pole-notching will decrease the variation amplitude and increase the variation periods, resulting in a reduced peak value of the cogging torque. The notch depth and the width could be carefully chosen as it influences the cogging torque effect. The optimum width and depth values are chosen for IPM motor are 0.5mm x 1mm and 2mm x 1mm.

3.3. Pole Pairing

Rotor pole pairing is a method of pairing the two different size or width in the rotor pole. 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. It is necessary to choose the appropriate width ratio of

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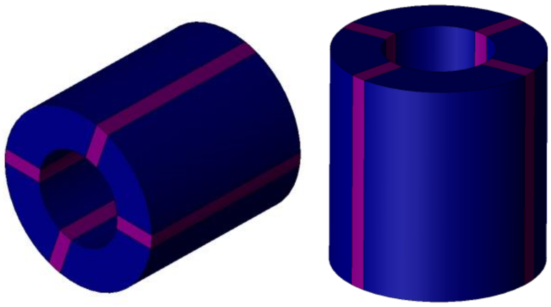
armature teeth to magnet or rotor pole to obtain smaller amplitude of cogging torque. In this paper, a Spoke-type IPMSM rotor with different rotor pole widths has been assembled as illustrated in Fig. 5(a) and Fig 5(b). Width of these 2 poles could be optimized to minimize the cogging torque by this scheme.

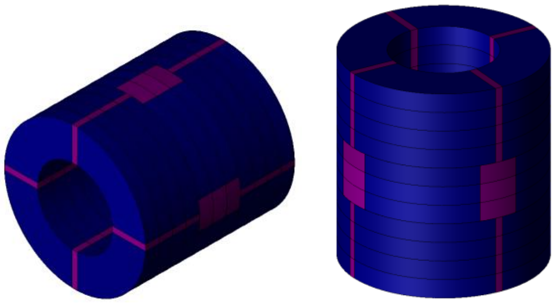


(a) (b)

Fig 5: Pole Pairing rotor model a) Isometric view b) Rotor top view

3.4. Rotor Axial Pole Pairing

Rotor axial pole pairing is another technique of pole-pairing in which the cogging torque can be reduced by altering the stack length of design, proportional to magnitude of cogging. The phase of cogging torque can be reversed as magnet pole arc changes.



(a) (b)

Fig 6: Rotor Pole Axial Pairing model a) Isometric view b) Rotor top view

These will reduce the total peak to peak value of cogging torque by conjoining magnets which having the same stack length with different pole arc, total peak to peak value of cogging torque can be reduced. Cogging torque is examined by altering the value of permanent magnet width and pole arc. Firstly stacks length is fixed and only pole arc is varied so that cogging torque using axial pole arc pairing is examined as results. An optimal stacks length pair of Spoke-type IPMSM obtained should be carefully chosen according to the study in, so the cogging torque effect can be reduce. Fig. 6(a) and Fig. 6(b) illustrate the rotor axial pole pairing design model in this study.

4. Analysis for cogging torque reduction

4.1. Flux linkages

The flux produced by armature current density of Ja 0 A_{rms}/mm^2 for all rotor designs are illustrated in Fig 7. Noticeably observed that higher flux amplitude emerges from rotor pole pairing design technique which approximately gauged at 0.156Wb whereas basic, skewing, notching and axial pole pairing are only measured at 0.151Wb, 0.148Wb, 0.151Wb and 0.143Wb respectively. This can be observed from Fig. 7. In addition, the lack performances of flux amplitude of all machines are due to the weakening flux density distribution and long distance flux flow inside the stator as well as proposed rotor structures.

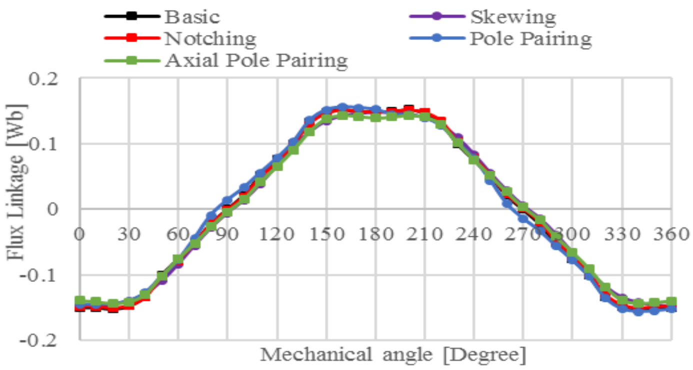


Fig 7: Flux Linkage of Basic, Skewing, Notching, pole pairing and pole axial pairing.

4.2. Induced voltage at open circuit condition

The induced voltage generated during no load condition is used for regenerative breaking and the value produce must not exceed the supply voltage as it will disturb the performance of the motor. By rotating the rotor at the rated speed of 4800r/min, the no-load back electromotive force (emf) of five 6S-4P Spoke-type IPMSM with different rotor-PM designs are illustrated in Fig. 8. It is clear that the pole pairing rotor-PM design results in highest amplitude of approximately 806.9V followed by notching, basic, axial pole pairing and skewing. The high back-EMF is due to armature reaction, which creates demagnetizing effect in the machine. Nevertheless the recorded emf values are still within the acceptable range.

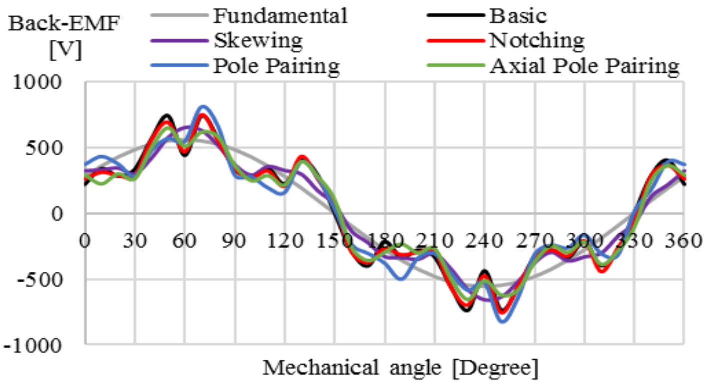


Fig. 8: Back EMF phase comparison

4.3. Cogging Torque Analysis

Cogging torque characteristic affecting the torque pulsation which corresponds to unacceptable vibration, acoustic noise, poor position, performance degradation and running failure can be examined by setting armature current density, Ja=0 Arms/mm^2. The cogging torque analyses for different rotor designs are illustrate in Fig. 9 and Fig. 10. Conventional or basic design configuration has the highest peak-to-peak cogging torque approximately 0.98Nm followed by notching, axial pole pairing, pole pairing and skewing with 0.8Nm, 0.7Nm, 0.66Nm and 0.3Nm respectively. Skewing technique shows the highest cogging torque reduction which is up to 69.5% as shown in Fig. 11 followed by pole pairing, axial pole pairing and notching. With this 69.5% reduction achievement, it is expected that the vibration, acoustic noise and deteriorating motor performance are reduced.

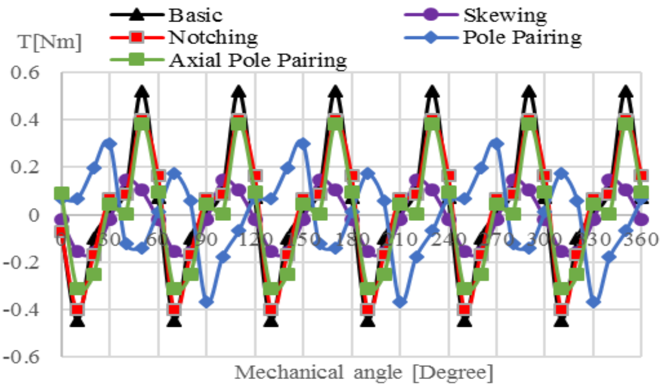


Fig. 9: Cogging torque of 6S-4P IPMSM

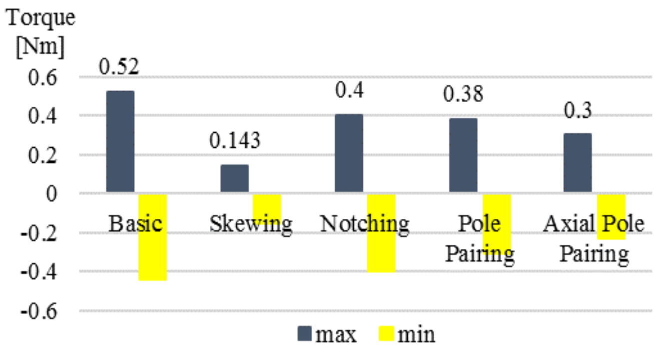


Fig. 10: Peak to peak cogging torque value for IPMSM model

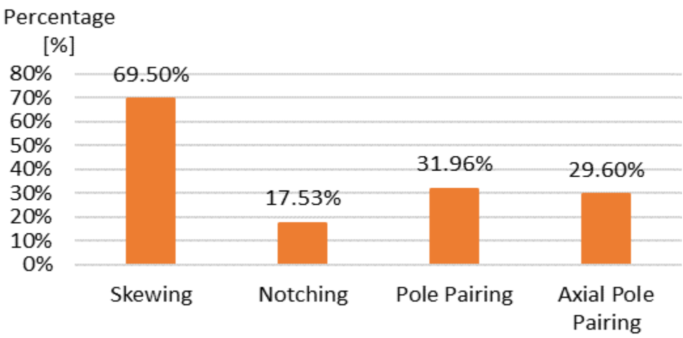


Fig. 11: Percentage of Cogging Torque reduction

4.4. Torque and Power Vs Armature Current Density

In Fig. 12, the output torque of all rotor designs of 6S-4P IPMSM are analyzed under the same armature current density from 0Arms/mm^2 up to maximum Ja of 30Arms/mm^2. At this level, the maximum torque of notching design is read at 5.62Nm approximately much higher than other rotor design. The high torque achievement is proven by the orientations of magnetizing flux.

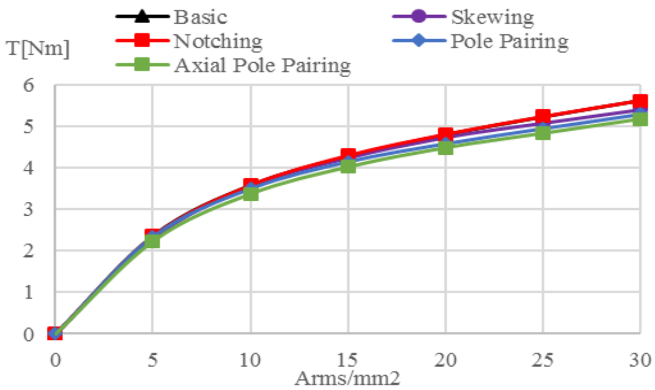


Fig. 12: Torque vs armature current density

Fig. 13 shows the power of all rotor design against armature current density. The calculation of output power can be executed by manipulating the data of torque and speed. Since all the required data have been obtained in previous analysis, equation (2) is used to substitute them in. Subsequently, for the rotational on a fixed axis, the calculated power is equal to the multiplication between torque and angular velocity of the rotating piece which are defined by equation (3), and (4).

$$P = \tau\omega \quad (3)$$

$$\omega = 2\pi S\ 60 \ (4)$$

Where P is power in kilowatt (kW), τ is torque in Newton metre (Nm), and S is speed in revolution per minute (r/min). Notching has emerged as the highest machine capability with power of 661.2W instead of 4 other rotor designs. Basic rotor design, skewing, pole pairing, and rotor axial pole pairing indicates the maximum initial power of 658.8W, 636.6W, 619.7W and 608.4W simultaneously.

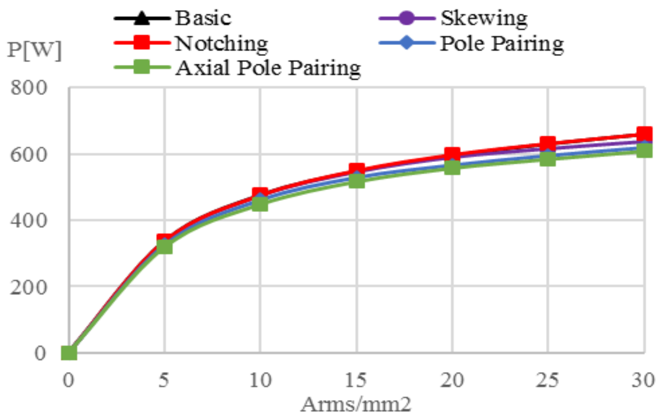


Fig. 13: Power vs armature current density

4.5. Torque and Power Vs Speed Characteristics.

The torque and power versus speed characteristic of 5 rotor-PM designs of 6S-4P Spoke-type IPMSM has been illustrated in Fig 14. The investigation of torque performances was carried out at maximum armature current densities, Ja=30 Arms/mm^2 for all design machines. According to the graph, it is obvious that the notching rotor-PM design shows the best torque speed ranges as well as much higher torque capabilities compared to other rotor-PM designs. The maximum torque of 6.67Nm has been achieved for notching technique at base speed of 1173.1r/min. In contrast, a maximum torque of

5.66Nm at base speed of 1175.9r/min is produced for axial pole pairing rotor design. Meanwhile, the comparisons of power versus speed characteristics of all 6S-4P Spoke-type IPMSM rotor-PM designs are analysed as shown in Fig. 15. Obviously, the initial power curve characteristic of all rotor-PM designs are increased up to the maximum point but starts to reduce when the speed is increased. Notching rotor-PM design indicate the highest power of 823.1W with based speed of approximately 1173.1r/min. and 696.6W with the base speed of 1173.11r/min for axial pole pairing rotor-PM design. As a final point, the overall performances of all proposed model designs are visualized in Table 4 below.

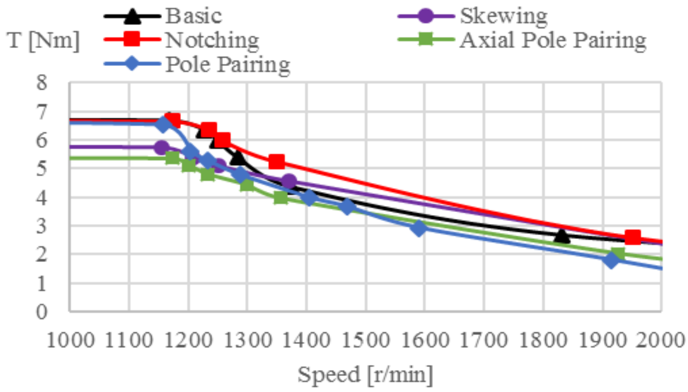


Fig. 14: Torque vs speed

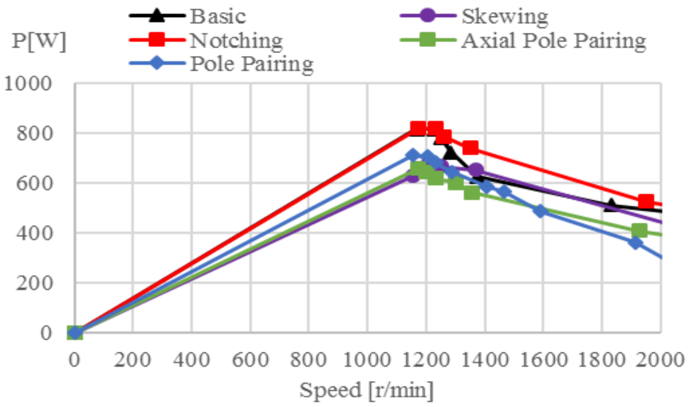


Fig. 15: Power vs speed

Table 4: Performance comparison of all 6S-4P IPMSM rotor design.

	cogging torque (nm)	**percentage reduction (%)**	**maximum torque (nm)**	**maximum power (w)**	**speed (r/min)**
Basic	0.98	-	6.60	806.71	1167.2
Skewing	0.3034	69.50	5.73	629.51	1154.1
Notching	0.8	17.53	6.70	823.07	1173.1
Pole Pairing	0.66	31.96	6.53	711.40	1153.0
Axial Pole Pairing	0.69	29.60	5.66	696.61	1173.1

5. Conclusion

In this paper, the cogging torque effect of 6S-4P spoke-type IPMSM with various rotor-PM designs has been investigated and discussed based on 3D FEA JMAG. Different rotor-PM design techniques, which are rotor skewing, notching, pole pairing and axial pole pairing techniques, has been analysed to compare the cogging torque effect and motor performance. The best technique to reduce the cogging torque effect for 6S-4P Spoke-type IPMSM is skewing techniques as it reduces the cogging torque effect up to 69.50%. In addition, the best rotor-PM performance is notching techniques as it produced better torque speed ranges as well as much higher torque and power capabilities. With these excellent design approach, the cogging torque of 6S-4P Spoke-type IPMSM has been dramatically reduced. Hence, further optimization and improvement of cogging torque reduction technique in 6S-4P Spoke-type IPMSM for better power and torque performance should be carry out in future study.

6. Acknowledgment

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