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# Cogging Torque Reduction of IPM Motor using Skewing, Notching, Pole Pairing and Rotor Pole Axial Pairing.

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**Abstract**

Interior Permanent Magnet (IPM) motor has been widely used in a range of industrial application due to high power density and good flux-weakening capability. In many of the applications, the high strength of permanent magnets causes the undesirable effects of high cogging torque that can aggravate performance of the motor. Large cogging torque is significantly produced by IPM motor due to the similar length and the effectiveness of the magnetic air-gap. Therefore, the reduction of cogging torque becomes an increasingly vital subject in IPM motor. In this paper, to minimize the effect of cogging torque in IPM motor, four common techniques for cogging torque reduction such as skewing, notching, pole pairing and rotor axial pole pairing has been analyzed in order to compare the cogging torque effect. 3D finite element analysis (FEA) by JMAG software is carried out for each technique. The results showed the reduction of cogging torque up to 99%, followed by 81.90%, 43.2% and 39.01% compared to the initial model design.

**Keywords:** Interior Permanent Magnet motor (IPM); Permanent magnet (PM); cogging torque reduction; cogging torque

## INTRODUCTION

Permanent Magnet (PM) motors have been an invaluable part of the industry today as these motors can save nearly any industry a great deal of time and money under the right circumstance. In various PM motors, for an interior-type PM (IPM) motor used for variable-speed drives, a separation of PMs caused by the centrifugal force at high speed can be avoided since the PM is inserted into the rotor core [1]. Magnets for IPM motors are inserted inside the rotor rather than bounding the surface that leads to the advantages of robust design and high speed operation. The advantages of IPM motor over Surface mounted Permanent Magnet motors (SPM) is some of their inherent characteristics which IPMs combines the reluctance torque that is generated by rotor saliency and the magnetic torque due to the PM. Therefore, they have the benefits of high torque density, high efficiency, and their compactness, etc [2]. However, fluctuations of torque, which are the essential source of variation, noise and the fluctuations of speed in IPM motors are large. These speed variations can be divided into two factors which are torque ripple and cogging torque. The main reasons for torque ripple is the fluctuations of the field distribution and the armature MMF and the major sources are cogging, PWM current harmonics, non- ideal back-EMF waveforms, and converted related issues. Torque ripple is usually filtered out by the system inertia at high-speed levels, but at low speeds, it may result in undesirable speed variations, vibrations and acoustic noise that way effect the significant performance of the machine [3]. The minimization of cogging torque become an increasingly critical issue as it may cause vibration and acoustic noises. Cogging torque of the IPM motor arises from interactions between PM on the rotor with the stator slot opening even without powering the motor. Cogging torque or also called detent torque and 'no-current' torque is one of the inherent characteristics of PM motors. These cogging torque acts as a disturbance, superimposing over electromagnetic torque produced during machine operation even produces zero networks. Number of cycles for cogging torque can be derived from:

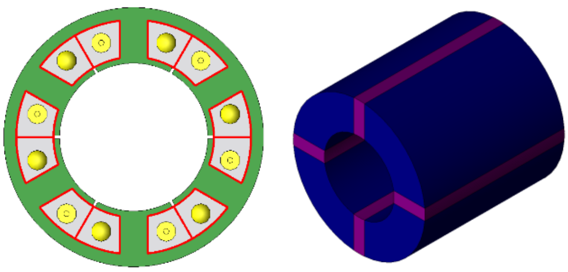
$$N_p = N_r/HCF\ [N_r, Ns]$$

$$N_e = N_p\ N_s/N_r$$

$N_e$ 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 Np leads to high cogging torque while higher values of Np lead to low cogging torque. For cogging torque reduction in PM machine, numerous methods are proposed and investigated, such as skewing the slots/poles [5]–[7] or the magnets [8], shifting the magnet [9], optimizing the pole arc coefficient [10], [11], slot openings [12] and the combination of the number of slots and poles], teeth paring , and teeth notching [13], [14], and so on. Variety of design factors and methods also influence the effect of cogging torque and among the factors, the length of the air gap, magnetic pole pitch and slot opening plays an important rule. Technique for reducing cogging torque plays an important role in the motor design and numerous studies have been carried out on the prediction and reduction of cogging torque. Hansel man D. C. have presented the effect of slot count, pole count and skew on Brushless DC (BLDC) motor for cogging torque, radial force and back EMF in year 1997 while in 2004, the techniques for designing the magnetic poles design, dummy slots, skewing for reducing cogging torque has been verified by Mohammad Islam et al. Then, the next 3 years, Fei. W. and Luk. P.C.K have designed the axial magnet pole pairing method aiming the cogging torque reduction. Based on these previous study, the cogging torque of IPM motor can be reduce since the IPM motors produces high cogging torque value. In this paper, several cogging torque technique in IPM motors are carried out using 3d FEA.

## REDUCTION METHOD FOR COGGING TORQUE

Several techniques used in this paper to minimize the cogging torque effect in IPM are rotor skewing, rotor pole notching, rotor pole pairing and rotor pole axial pairing. The performance of all IPM motors is compared by a conventional spoke-type 6S-4P IPM motor which is the basic model as shown in Fig.1. A six slot stator with concentrated windings is shown in Fig.1 (a) and circumferentially magnetized NdFeB magnets in a spoke-type array is inserted in the rotor as in Fig. 1(b).



(a) (b)

**Figure 1:** Basic model a) Stator with coil winding b) rotor with magnet

The motor specification for the initial motor design model are listed in Table 1 and Table 2 shows the specification of each motor design techniques for cogging torque reduction. To examine and quantify the 3-D effects exhibited in the machine under consideration, all the 3-D design models were created using a commercial FEA package. The JMAG Designer version 14.0, of commercial FEA package released by the Japan Research Institute (JRI) is used as 3D-FEA solver for this design. There are two steps in designing which is geometry editor and JMAG designer. The circumferential magnetized NdFeb magnet in a spoke-type array is inserted in the Nippon Steel 35H250 type rotor.

**Table 1:** Design Parameter for basic motor design of 6S-4P IPM motor

| Parameters | 6S-4P IPM Motor |
|---|---|
| Stator pole/ slot numbers | 6 |
| Rotor pole numbers | 4 |
| Outer radius of stator (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 |

**Table 2:** Design Parameter for skewing, Notching, Pole Pairing and rotor pole axial pairing of 6S-4P IPM motor.

| Parts | 6S-4P IPM Motor | |
|---|---|---|
| | ***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 |

Materials and condition for all motor models are as shown in Table 3. Rotation motion, torque and arrangement of FEM coil is set under condition setting. Arrangement of the FEM coil are linked with a three phase circuit (Fig 5) and a rated speed of 4800rpm is used for magnet and rotor rotation in this paper.

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**Table 3:** Materials and conditions

| **Parameters** | **6S-4P IPM Motor Design** | | | |
|---|---|---|---|---|
| | **Skewing** | **Notching** | **Pole Pairing** | **Rotor pole axial pairing** |
| Rotor pole inner arc length (mm) | 15.9 | 15.9 | 3.9, 25.8 | 10.0, 17.7 |
| Rotor pole outer arc length (mm) | 32.9 | 32.9 | 10.2, 49.0 | 28.0, 33.0 |
| Permanent magnet width (mm) | 4.2 | 4.2 | 4.2 | 2.0, 10.0 |
| Skewing angle (Θ) | 2.8 | - | - | - |

## COGGING TORQUE REDUCTION ROTOR DESIGN

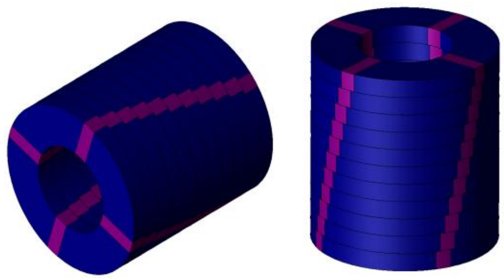
IPM motor focuses on the variations of rotor, air gap length, and stator parts in order to study its cogging torque reduction. The cogging torque reduction techniques are normally chosen with the conditions of easy implementation, minimum cost and machine performances. This paper deals with the optimal shape design of IPM motor and the design parameters are derived by an analytical method and the rotor shape is optimized by using FEA. There are four methods related to the permanent magnet that can reduce the cogging torque, which is 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.

### *A. Skewing*

Skewing of either the rotor or the stator stack is a widely applied method for reducing cogging torque and torque ripple in permanent magnet motors. The basic idea behind skewing is to influence the interaction between the stator slots and the rotor magnets. This method is basically making the dR/dθ zero over of each magnet face. In theory, the cogging torque can be completely eliminated. In reality, it may not perfectly reach zero, but be significantly reduced. Skewing can be implemented on either the magnets or the slots. Both have disadvantages. Skewing the magnets increases the magnet cost. Skewing the slots increases the copper losses due to increased slot length, resulting in the longer wire. The skewing angle for the skewed model is between two adjacent steps which is equal to

$$\Theta_{skewing} = 2\pi/nN_cQ \qquad [3]$$

Where n is the number of skewing steps, Q is the number of stator slots, and Nc is the period of cogging torque as mentioned in equation 2. In this paper, skewed model with an angle skew of 2.8° as shown in Fig. 4(a) and Fig. 4(b) has been designed and analyzed.

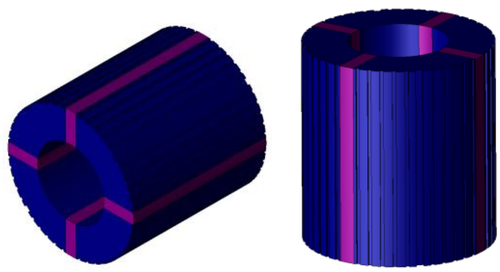


(a) (b)

**Figure 2:** Skewing rotor model a) Isometric view b) Rotor top view

### *B. Notching*

Notches are dummy slots in either stator or rotor of the machine. This technique can be effectively applied to minimize the cogging torque effect in IPM motor by decreasing the air-gap flux. Air-gap flux is directly reduced as the magnet flux density is lowered by changing the magnet grades. The number of the notches in the rotor pole is chosen as 11, as shown in Fig.3 (a) and 3(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.

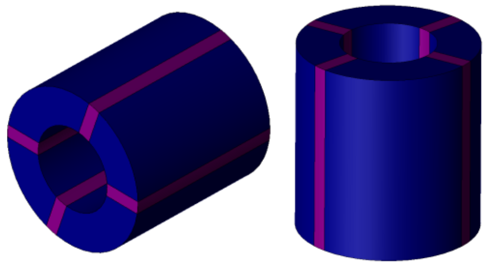


(a) (b)

**Figure 3:** Notching rotor model a) Isometric view b) Rotor top view

### *C. Pole Pairing*

Rotor pole pairing is a technieque of pairing the two different size or width in the rotor design. 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. The rotor with different pole widths assembled, as illustrated in Fig. 4, can be used to lessen the cogging torque effect. Width of these 2 poles could be optimized to minimize the cogging torque by this scheme.



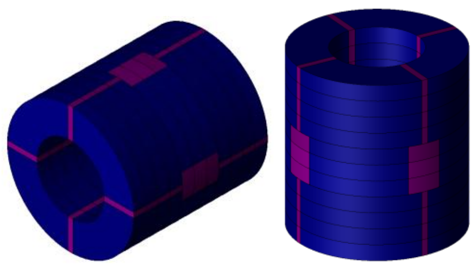
(a) (b)

**Figure 4:** Pole Pairing rotor model a) Isometric view

b) Rotor top view

*D. Rotor Pole Axial Pairing*

Rotor pole axial pole pairing is another technique of pole-pairing by altering the stack length of design, proportional to the magnitude of cogging. The phase of cogging torque can be reversed as magnet pole arc changes, thus, total cogging torque can be reduced by conjoining magnets having the same stack length but different pole arc. 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 IPM obtained should be carefully chosen so the cogging torque produced by axially pole arc paired magnets can be reduced. The rotor pole axial pairing model is as illustrated in Fig. 5(a) and Fig. 5(b) below.



(a) (b)

**Figure 5:** Rotor Teeth Axial Pairing model

a) Isometric view  b) Rotor top view

## NO LOAD ANALYSIS FOR COGGING TORQUE REDUCTION

Cogging torque characteristic effecting the torque pulsation which corresponds to unacceptable vibration, acoustic noise, poor position, performance degradation and running failure can be determined at no load condition which there is no supply from the stator. The cogging torque for 5 model design with an optimized stack length of 54mm are shown in Fig. 6 below.

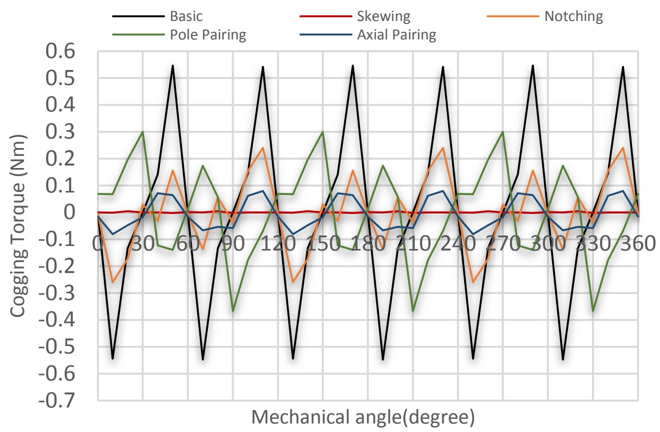



**Figure 6:** Cogging torque of Basic model, Skewed model, Notching model, pole pairing model and axial pairing model.

Fig. 6 demonstrates the peak to peak cogging torque value against mechanical angle. For the analysis result, cogging torque has been reduced as a result of the approach rotor-PM technique. Obviously, the cogging torque for the initial or basic model is the highest compared to other model as the peak to peak cogging torque value is 0.88Nm. Skewed model reduced the cogging torque about 99(%), followed by rotor teeth axial pairing 81.90(%), rotor pole notching 43.2(%), and rotor pole pairing 39.06(%).

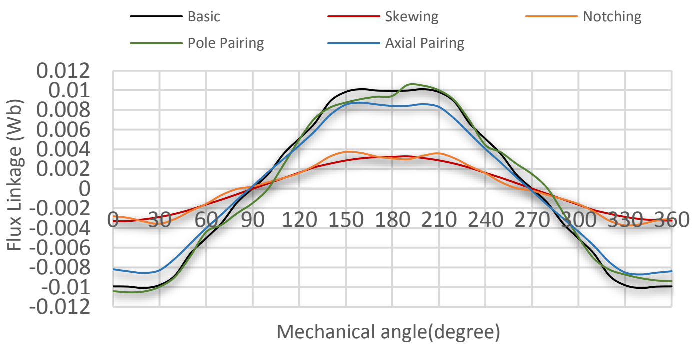



**Figure 7:** Coil arrangement

The coil arrangement test is used to set the armature coil position and normally performed to validate the operation principle of the 3-phase IPM motor. Therefore, each armature coil is tested separately with the counter-clockwise direction of winding. Every different coil is compared to define the armature coil phases according to the conventional 3-phase system, the

U, V and W phases. Fig. 7 illustrates the 5 model U-phase sinusoidal waveform of torque versus mechanical degree. Model basic and pole pairing are expected with the highest flux amplitude of approximately 0.011Wb followed by rotor pole axial pairing (0.0085 Wb), pole notching (0.004), and PM skewing (0.003 Wb). Skewed rotor-PM technique almost producing zero cogging torque or an optimal cogging torque and also improved the back EMF waveform as illustrated in Fig 8 but the flux linkage produces by skewing technique is low and thus increasing the leakage inductance and stray losses.

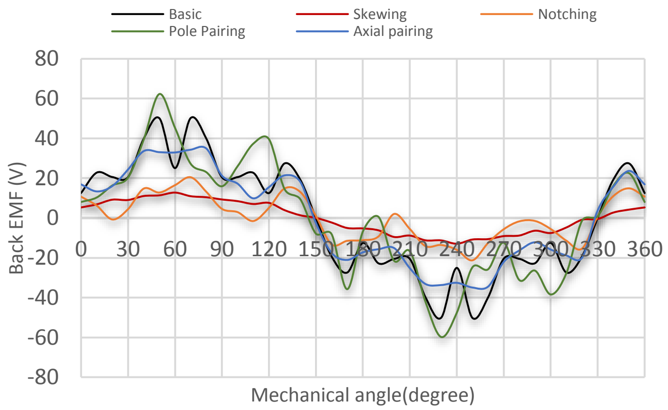



**Figure 8:** Back EMF phase comparison

Rotor pole pairing shows the best result among 4 techniques of cogging torque reduction based on the optimal value of cogging torque, flux linkage, back EMF and average torque as shown in figure 9.The Back EMF for 5 models are not following the requirement of sinusoidal shape, but can be improved by the optimization method for the future study.

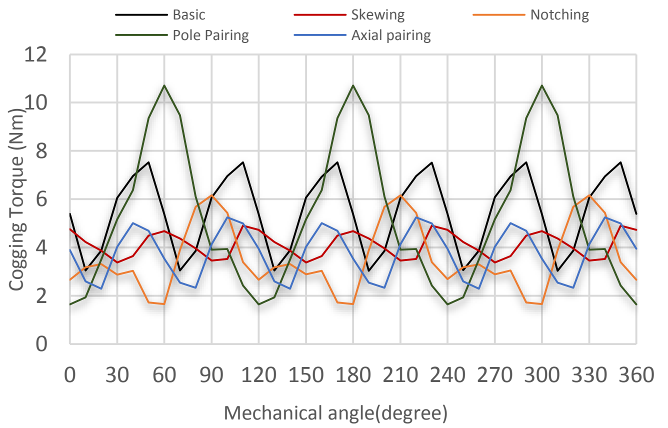



**Figure 9:** Average torque of Basic model, Skewed model, Notching model, pole pairing model and axial pairing model

These various techniques of rotor pole configuration technique effectively reduced the cogging torque. With this reduction achievement, it is expected that the torque ripple are reduced, low losses and the motor will offer a significant performance and efficiency by eliminating a high vibration or noise.

## CONCLUSION

Cogging torque has been a subject of recent investigations, in the pursuit of methods of minimizing torque ripple in various configurations of electrical machines. In this paper, the cogging torque effect of spoke-type 6S-4P IPM motor design has been investigated and discussed based on 3D FEA JMAG. Different rotor-PM pole design techniques, which are rotor skewing, rotor pole nothching, rotor pole pairing and rotor teeth axial pairing techniques, has been analyzed to compare the cogging torque effect and the best technique for cogging torque reduction techniques for IPM motor is rotor pole axial pairing techniques. With these excellent design approach has dramatically reduced the cogging torque of IPM motor. Hence, further improvement of cogging torque reduction technique in IPM motor for better power and torque performance should be carry out in future study.

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