Reduction of cogging torque of radial flux permanent magnet brushless DC motor by magnet shifting technique

Introduction. In spite of many advantages of radial flux permanent magnet brushless DC motors it suffers from the distinct disadvantage of high cogging torque. The designer must emphasize to reduce the cogging torque during the design stage. This paper introduces magnet shifting technique to mitigate cogging torque of surface mounted radial flux brushless DC motor. Methodology. Initially 200 W, 1000 rpm surface mounted radial flux permanent magnet brushless DC motor is designed with symmetrical placement of permanent magnets with respect to each other on rotor core. Cogging torque profile of this initial motor is obtained by performing finite element modelling and analysis. Originality. This design has been improved by shifting the position of permanent magnets with respect to adjacent permanent magnets. The effect of magnet shifting on cogging torque has been analyzed by performing finite element analysis. Results. It has been examined that the peak to peak cogging torque is decreased from 1.1 N·m to 0.6 N·m with shifting of permanent magnets respectively. References 19, tables 2, figures 11.

Key words: cogging torque, finite element analysis, magnet shifting, permanent magnet brushless DC motor.

Introduction. Permanent magnet brushless DC (PMBLDC) motors exhibit superior performance in comparison to conventional motors. They are inherently efficient, compact and having wide speed range and fast dynamic response [1, 2]. Because of the advancement in permanent magnet (PM) materials and semiconductor technology, PMBLDC motors have found various applications demanding precise speed and position control. This type of motors has potential to become workhorse of many industrial applications due to its attractive features. Noticeable torque ripple is one of the important limitations of PMBLDC motor. Vibration and acoustic noise is introduced by the torque ripple in the drive system which deteriorates overall performance. Torque ripple is high due to cogging torque and non-ideal commutation of exciting currents. Torque ripple can be reduced with decrease in cogging torque and modification in excitation pattern. Any modification in excitation pattern usually results into a reduction in efficiency. It is highly desirable to reduce cogging torque of permanent magnet motor during design to reduce torque ripple. Cogging torque is innate in PM motors due to presence of permanent magnets and slotted stator. Interaction between rotor PM magnetomotive force and slot reluctance originates cogging torque. Due to this interaction, the PMs constantly seek a position with low reluctance. The cogging torque does not depend on stator current which means that it occurs even though the stator winding is unexcited.

Reduction of cogging torque is of utmost importance as it improves the torque quality. Improvement in torque quality makes them suitable in various torque sensitive applications. Various methods are proposed in literature for cogging torque reduction of radial flux PMBLDC motor viz. skewing of either stator or rotor, magnet pole arc variation, shifting of slot opening, teeth notching, unequal teeth width, magnet shaping and sizing, pole arc to pole pitch ratio, fractional pole pairs, number of slots/pole, addition of dummy slots, variation in air-gap length, magnet pole shaping, lowering magnet flux density, choosing proper thickness of stator teeth tips, variation in width of slot opening, etc. [3-18]. Skewing of either stator or rotor results in undesirable axial thrust. Skewing of stator slot increases length of conductors thus increases copper losses. Also winding becomes difficult to wind. Skewing of PMs and/or stator slots increases manufacturing complexity and production cost. Step skew of PMs also increases manufacturing complexity. To eradicate the cogging torque by skewing, the skewing angle should be one slot pitch. The cogging torque can be decreased by varying the magnet pole arc width. It is found that PM covers almost \( m \) times that of slot pitch chosen, where \( m \) is an integer. Generally, the pole pitch of \( m + 0.17 \) or \( m + 0.14 \) produces minimum cogging torque. A small variation in pole arc width results in considerable reduction in cogging torque. The cogging torque harmonic components can be diminished by notching the stator teeth i.e. incorporation of dummy slots in stator teeth. Addition of dummy slot increases the frequency of interaction between slot and salient poles. This reduces the magnitude of cogging torque. However, introduction of notches removes some material from
The cogging torque has zero average value and is generated by propensity of PMs to align with stator teeths. There is periodical variation of air gap reluctance which makes cogging torque to vary periodically. Fourier series expresses cogging torque as under,

$$ T_{cog} = \sum_{j=1}^{\infty} T_{jk} \cdot \sin(j \cdot k \cdot \theta) $$

where \( j \) is the least common multiple of number of slots \( N_s \) and poles \( N_p \); \( i = 1, 2, 3; \) , \( T_{jk} \) is the coefficient of Fourier series.

In one mechanical revolution of rotor, cogging torque has \( j \) periods and \( N_s \) and \( N_p \) are directly related with it [19].

Equation (1) depicts that elimination of cogging torque can be achieved either by forming \( \Phi_g \) zero or by forcing \( dR/d\theta \) zero. It is not practical to reduce magnetic flux since it affects the torque productivity which is required to drive the motor. Hence, cogging torque can be reduced adequately with design modification because of air-gap reluctance variation. It is practically impossible to completely eliminate cogging torque.

Equation (2) shows that the cogging torque can be characterized as a Fourier series and is superposition of all sinusoidal harmonic components. In PM motors without any cogging torque reduction techniques, each magnet pole’s cogging torque is added. This happens because each magnet pole is symmetrically placed with respect to the stator slots. The torque due to each PM is cophasel torque due to adjacent PM. Because of this, there is summation of each magnet pole’s harmonic components. If the PM motor is designed such that cogging torque of magnet poles are out of phase with respect to others, some of the harmonic components of (2) are cancelled out. This results in to decrement of cogging torque of PM motors.

**Reference design of radial flux PMBLDC motor.**

The surface mounted PMBLDC motor of 200 W, 1000 rpm is analytically designed and is considered as reference motor for the analysis. The sizing of reference PMBLDC motor is carried out by assuming various design variables i.e. specific magnetic and electric loadings, stator current density, flux densities of stator and rotor cores, space factor, stacking factor, winding factor etc. Design variables are assumed considering performance requirements and availability of materials.

Cross sectional view of reference PMBLDC motor is shown in Fig. 1.a. The rotor poles are made of high energy NdFeB permanent magnet material of grade N42. Figure 1,b shows the design of surface mounted four pole rotor reference design. The design information of reference motor has been presented in Table 1.

Finite element (FE) analysis has been performed to attain cogging torque versus rotor angle characteristic of reference motor. The model of reference motor is prepared using FE software according to the calculated dimensions and appropriate materials are assigned to different sections of the motor. The waveform is obtained by rotating the rotor for discrete positions of 1° mechanical each and cogging torque values are obtained up to 15°. Figure 2 shows the cogging torque profile of reference motor. It is observed that reference PMBLDC motor has cogging torque (peak-to-peak, p-p) of 1.1 N-m.
Table 1

| Design parameter             | Value  |
|------------------------------|--------|
| Outer diameter of stator, mm | 87     |
| Outer diameter of rotor, mm  | 51     |
| Axial length, mm             | 50     |
| Inner diameter of stator, mm | 52     |
| No. of stator slots          | 24     |
| No. of phases                | 3      |
| No. of rotor poles           | 4      |
| No. of slots/pole/phase      | 2      |
| PM thickness, mm             | 5      |
| Air-gap length, mm           | 0.5    |
| Type of PM                   | NdFeB  |
| Stator core material         | M19    |
| Rotor core material          | M19    |

The average torque developed by the motor has been determined with 2-D FE analysis. Series of 2-D transient simulations have been performed. In this analysis, the rotor is rotated at rated speed of 1000 rpm and the stator winding is energized by appropriate switching of inverter switches. The value of electromagnetic torque at discrete rotor positions are obtained and plotted against these rotor positions. Figure 3 shows torque profile of reference motor. The average torque obtained using FE analysis is 1.91 N·m.

**Magnet shifting technique.** The cogging torques due to each magnet pole are in phase in PM motor and thus all of them are added. This results into substantial cogging torque effect. To reduce this summative effect, placement of PMs can be shifted in comparison to adjacent PM so that cogging torque of adjacent magnets is out of phase with each other. Figure 4 shows surface magnet rotor with PM shifted by $\theta_0$.

The cogging torque influence of each PM is given by

$$ T_{cog} = \sum_{i=1}^{\infty} T_{PN,i} \cdot \sin(N_s \cdot i \cdot \theta), \quad (3) $$

where $T_{PN,i}$ is the per magnet coefficient;

$$ T_{cog} = N_p \cdot \sum_{i=1}^{\infty} T_{PN,i} \cdot \sin(N_s \cdot i \cdot \theta), \quad (4) $$

which is equivalent to that given by (2) and rewritten as

$$ T_{cog} = \sum_{i=1}^{\infty} T_{N,i} \cdot \sin(N_s \cdot i \cdot \theta). \quad (5) $$

Cogging torque produced by each magnet is in phase with the adjacent magnet hence it is imperative that each magnet’s position can be shifted with respect to the adjacent one. The sum of all cogging torques from each magnet gives net cogging torque in the motor and is given by
where $\theta_0$ is the angle through which each PM is shifted in comparison to adjacent PM.

The net cogging torque is reduced to

$$T_{cog} = \sum_{i=1}^{N_s} T_{N_s,i} \cdot \sin(N_s \cdot i \cdot (\theta - k \cdot \theta_0)),$$

$$T_{cog} = \sum_{i=1}^{N_s} T_{N_s,i} \cdot \sin(N_s \cdot N_p \cdot i \cdot \theta).$$

(6) (7)

Harmonics other than multiples of $N_p^{th}$ are cancelled, hence reducing the cogging torque.

**Improved design using magnet shifting technique.** The design is improved with application of magnet shifting technique to 200 W, 1000 rpm PMBLDC motor. The rotor of initial design is shown in Fig. 5,a and rotor of improved design with magnet shifting technique is shown in Fig. 5,b. Series of simulation exercise have been performed with FE technique to obtain cogging torque profile with relative magnet shifting from 1° to 3°.

**Comparison between initial and improved designs of radial flux PMBLDC motor**

| Sr. no. | Design details | Cogging torque peak to peak (N m) | Average torque (N m) |
|---------|----------------|---------------------------------|----------------------|
| 1       | Initial design  | 1.10                            | 1.91                 |
| 2       | Magnet shift 1° | 1.00                            | 1.89                 |
| 3       | Magnet shift 2° | 0.80                            | 1.89                 |
| 4       | Magnet shift 3° | 0.60                            | 1.89                 |
| 5       | Magnet shift 4° | 0.68                            | 1.88                 |
| 6       | Magnet shift 6° | 0.84                            | 1.87                 |

Comparison between average torque of reference design and improved design with magnet shift angle of 3° is shown in Fig. 7. It is seen that the torque ripple is also decreased in improved design incorporating magnet shifting technique.

The back electromotive force (EMF) profiles of initial design and improved design are shown in Fig. 8. It is observed that the back EMF waveform is slightly improved when magnet shifting technique is applied. The value of back EMF remains nearly equal in both the designs. The harmonic spectrum of back EMF of initial design and improved design is shown in Fig. 9. It is observed that Total Harmonic Distortion (THD) is reduced from 8.03 % to 6.54 %.
It is highly desirable to compare actual flux densities set up in various parts of motor with assumed flux densities in respective sections. Electromagnetic field analysis with FE software is carried out, on initially designed reference motor and improved designed motor with magnet shifting technique, to evaluate flux densities in various portions of the motor.

A numerical technique, FE method is flexible, reliable and effective method in the analysis of power-frequency electromagnetic devices. FE analysis software uses this technique to perform electromagnetic field analysis in electromagnetic devices. The motor model is divided into FEs using self adaptive meshing. The Maxwell equations are used to evaluate flux densities and field intensities in each FE. The results obtained for each FE is integrated to obtain the flux density in various parts of the motor.

Conclusions.

The magnet shifting technique is introduced in this paper to analyze its effect on cogging torque of permanent magnet brushless DC motor. The surface mounted permanent magnet brushless DC motor of 200 W, 1000 rpm is designed initially by mounting four permanent magnets symmetrically with respect to each other and considered as a reference design for the analysis. Design is improved by shifting position of permanent magnets by 1°, 2°, 3°, 4° and 6° mechanical degree with respect to each other. Finite element analysis is carried out to find cogging torque of both reference design and improved design. As the magnet shift angle increases, the cogging torque reduces. It has been analyzed that cogging torque (p-p) is reduced to 54.5 % for magnet shift angle of 3° with marginal reduction in average torque. Thus, it is examined that magnet shifting technique is an effective technique to reduce cogging torque of radial flux permanent magnet brushless DC motor.

Conflict of interest. The authors declare that they have no conflicts of interest.

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