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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.**

Вступ. *Незважаючи на багато переваг безщіткових двигунів постійного струму з радіальним магнітним потоком, вони мають явний недолік, що полягає у високому крутному моменті зубчатої передачі. Проектувальник повинен зосередитись на зниженні крутного моменту зубчатої передачі на етапі проектування. У цій статті представлена методика зсуву магніту для зменшення крутного моменту зубчатої передачі безщіткового двигуна постійного струму з радіальним потоком, встановленого на поверхні.* ***Методологія***. *Спочатку безщітковий двигун постійного струму з радіальним магнітним потоком потужністю 200 Вт, 1000 об/хв спроектований із симетричним розміщенням постійних магнітів відносно один одного на сердечнику ротора. Розподіл крутного моменту зубчатої передачі цього початкового двигуна отриманий шляхом аналізу методом скінчених елементів (МСЕ).* ***Оригінальність***. *Ця конструкція була вдосконалена за рахунок зсуву положення постійних магнітів по відношенню до сусідніх постійних магнітів. Вплив зсуву магніту на крутний момент зубчатої передачі було проаналізовано за допомогою аналізу МСЕ.* ***Результати***. *Досліджено, що піковий крутний момент зубчатої передачі зменшився з 1,1 Н·м до 0,6 Н·м, відповідно, при зсуві постійних магнітів.* Бібл. 19, табл. 2, рис. 11.
Ключові слова: **крутний момент зубчатої передачі, аналіз методом скінчених елементів, зсув магніту, безщітковий двигун постійного струму з постійними магнітами.**

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 stator teeth and gives rise to saturation. Hence, this technique is not appropriate for minimization of cogging torque. The cogging period is given by one complete mechanical revolution divided by least common multiple of stator slots number N_s and rotor poles number N_p. The peak amplitude of cogging torque reduces as the frequency of cogging cycles increases. The cogging torque decreases considerably as number of stator slots increases minutely thus resulting in fractional slot pitch. The distance between stator slot and PM denotes to length of air-gap. The length of air-gap is different as the size of the motor changes. The recommended length of air-gap range for very small size motor is 0.12 – 0.25 mm, medium size motor is 0.38 – 0.5 mm, and large motor is, 0.63 – 0.88 mm. The cogging torque can be decreased by increasing length of air-gap thus reducing $dR/d\theta$. However, increase in air-gap length decreases the air-gap flux Φ_g thus lowering the magnitude of cogging torque further. To keep Φ_g constant, the width of magnet pole arc is required to be increased. The rate of change of flux density at magnet edges affects the cogging torque. Thus, shaping the magnet edges lowers the magnitude of cogging torque. The cogging torque can be decreased by reducing the air gap flux density. This can be done by changing the grades of PM material. The width of stator teeth influences the cogging torque. If the stator teeth tips are too thin, saturation is established in it which increases cogging torque. The width of slot opening and thickness of stator teeth tips should be equal. Cogging torque is also affected by the slot opening width. If the width of slot opening is decreased, the rate of change of permeance between PM and stator teeth is reduced. This lowers magnitude of cogging torque.

The aim of this paper is to present a magnet shifting technique which reduces cogging torque of surface mounted radial flux permanent magnet brushless DC motors.

Magnet shifting technique is relatively easy to implement hence it has better feature as far as manufacturability is concerned. There is no adverse implication on initial cost of motor as cost of PM remains unchanged. Lower order harmonics have been suppressed on account of shifting of magnets from its original position. Magnets are placed accordingly with an objective of harmonic suppression of cogging torque. Initially, the basics of cogging torque and reference design of radial flux PMBLDC motor is discussed. Thereafter, the magnet shifting technique used to decrease cogging torque of initially designed motor is explained. Thereafter, Improved design of PMBLDC motor incorporating magnet shifting technique, simulation results and analysis have been presented. At the end, Conclusion of this paper is presented

Basics of cogging torque. Following equation expresses the cogging torque and factors affecting it

$$T_{cog} = -\frac{1}{2} \cdot \Phi_g^2 \cdot \frac{dR}{d\theta_m}, \quad (1)$$

where Φ_g is the flux crossing air-gap; R is the reluctance of gap; θ_m is the angular displacement of rotor.

The cogging torque has zero average value and 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,

$$T_{cog} = \sum_{i=1}^{\infty} T_{jk} \cdot \sin(j \cdot k \cdot \theta), \quad (2)$$

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 Φ_g zero or by forcing $dR/d\theta_m$ 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.

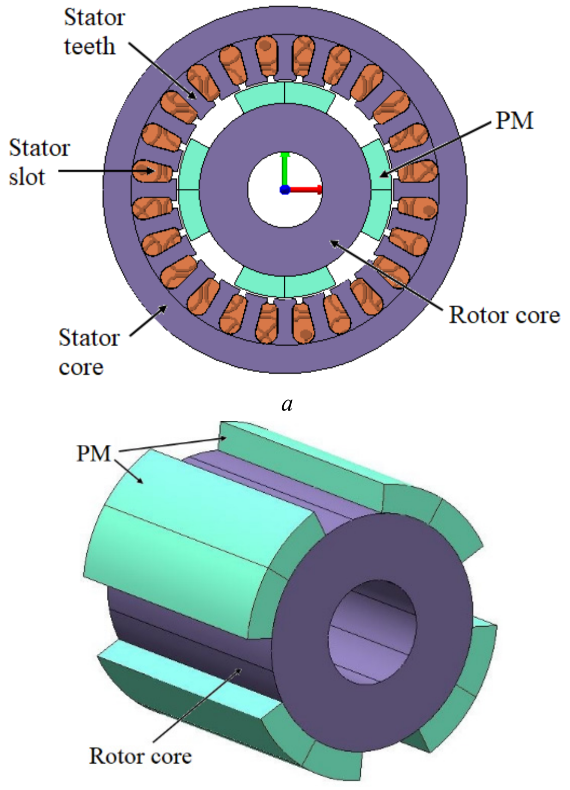

Fig. 1. Reference radial flux PMBLDC motor:
a – cross sectional view; *b* – 3-D view of rotor

Table 1
Design information of radial flux PMBLDC motor

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

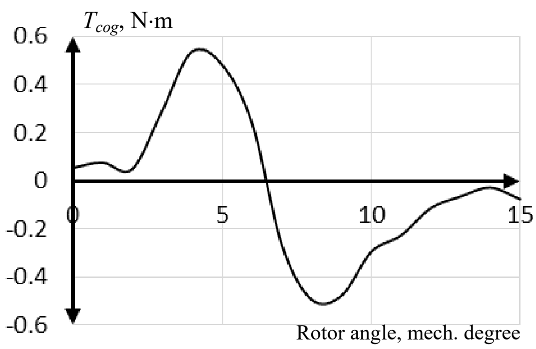

Fig. 2. Cogging torque versus rotor angle characteristic of reference PMBLDC motor

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.

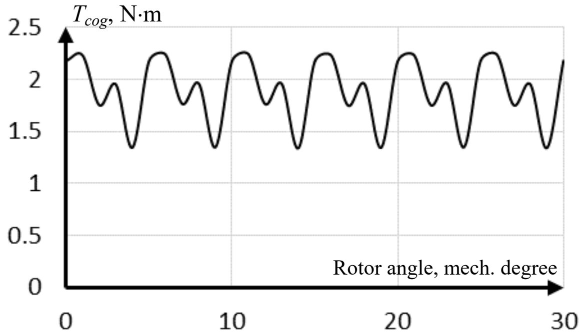

Fig. 3. Average torque profile of reference PMBLDC motor

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 θ_0.

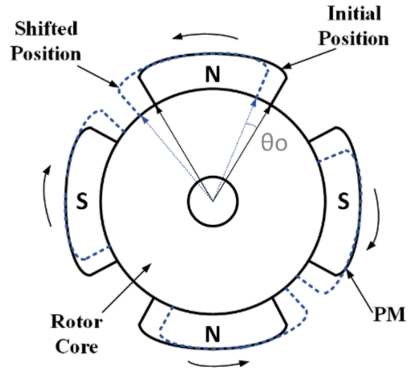

Fig. 4. Shifting of PM in surface mounted radial flux PMBLDC motor

The cogging torque influence of each PM is given by

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

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

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

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

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

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

$$T_{cog} = \sum_{k=0}^{N_p - 1} \sum_{i=1}^{\infty} T_{PN_s i} \cdot \sin\left(N_s \cdot i \cdot \left(\theta - k \cdot \theta_o\right)\right), \qquad (6)$$

where θ_o is the angle through which each PM is shifted in comparison to adjacent PM.

The net cogging torque is reduced to

$$T_{cog} = \sum_{i=1}^{\infty} T_{N_s N_p i} \cdot \sin\left(N_s \cdot N_p \cdot i \cdot \theta\right). \qquad (7)$$

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°.

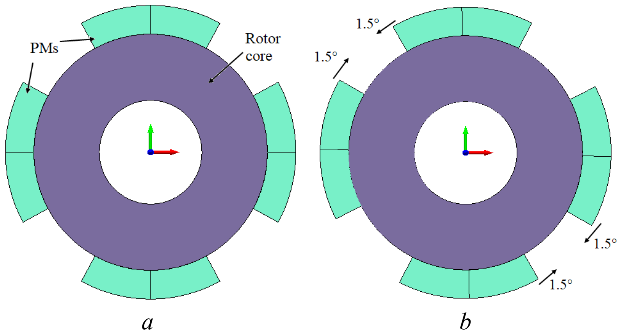

Fig. 5. Sectional view of rotor (*a*) reference design with regular PMs (*b*) improved design with shifted PMs

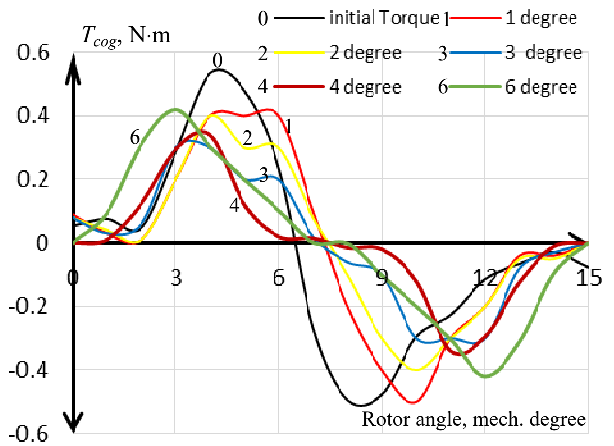

Fig. 6. Comparison between cogging torque profiles of reference design and improved design

The reference design of PMBLDC motor has cogging torque (p-p) of 1.1 N·m. With an objective of cogging torque reduction, magnet shifting is performed from 1° to 6° in the step of 1°. Figure 6 shows simulation results of cogging torque response on account of magnet shifting and its comparison with cogging torque profile of reference motor. It is observed that the improved design having magnet shifting of 3° has the minimum cogging torque (p-p) of 0.6 N·m. Cogging torque (p-p) has been reduced from 1.1 N·m to 0.6 N·m. Table 2 shows variation of cogging torque with variation in magnet shift angle. It is observed that cogging torque has been reduced significantly as magnet shifting angle is increased up to 3°. The cogging torque is increased for magnet shift angle of 4° and 6°. The reduction in average torque is marginal in improved designs.

Table 2

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	Improved design	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.

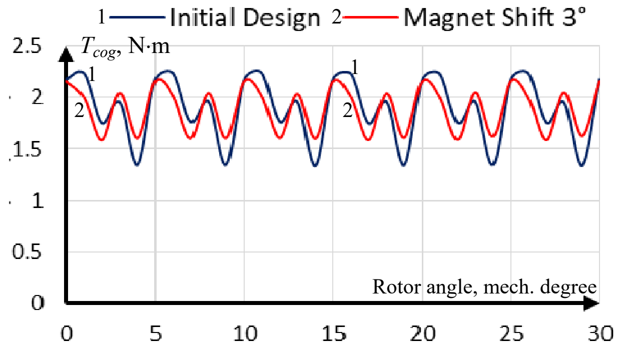

Fig. 7. Comparison between average torque profile of reference design and improved design

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 %.

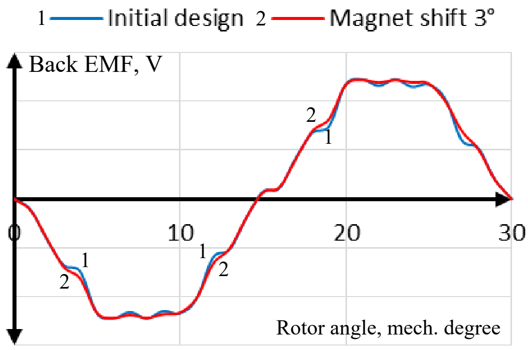

Fig. 8. Comparison between back EMF profile of initial design and improved design

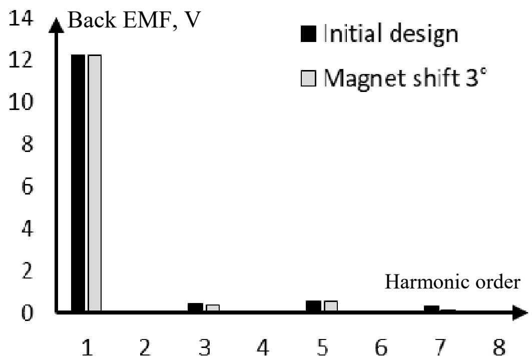

Fig. 9. Comparison of fast Fourier transform (FFT) analysis of back EMF

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.

Shaded field plot of reference design and improved design have been shown in Fig. 10, 11 respectively. Actual flux densities in different parts of the motor are close to assumed flux densities of reference and improved designs. Hence, both designs are validated.

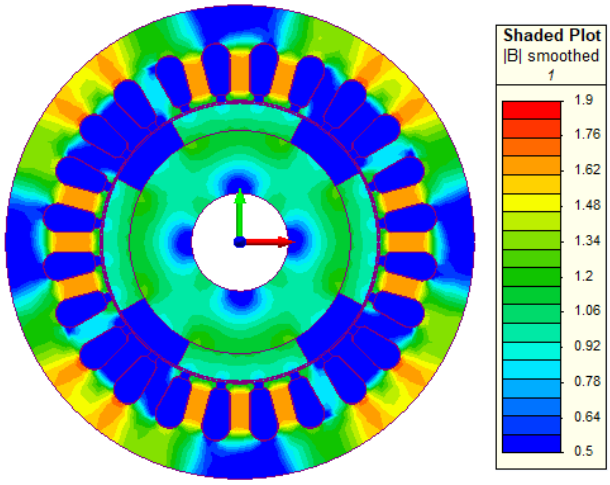

Fig. 10. Flux density distribution of reference design

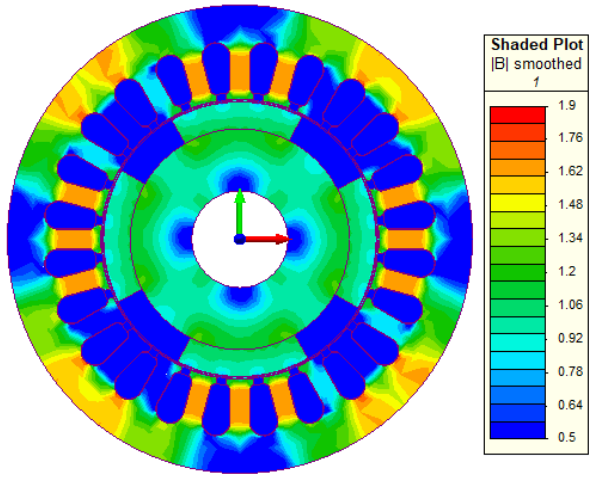

Fig. 11. Flux density distribution of improved design

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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