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Design of Slotless BLDC Motor for Eliminating Cogging Torque

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ORIGINAL ARTICLE
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Abstract *– Design of a cogging torque free motor is presented in this paper. Cogging torque is a disturbing phenomenon in electrical machines that causes certain problems in performance of them. This unwanted component in output torque could be reduced or eliminated by some methods i.e. skewing the stator slot, skewing the permanent magnets (PMs) of rotor, employing fractional pitch winding and building slotless motor. In this paper, firstly these ethods are discussed and then the effect of skewing PMs is investigated which is distinguished by a design parameter i.e. offset. After that, slotless structure of a brushless DC motor (BLDC) is considered. In a slotless BLDC motor, cogging torque would be eliminated and there is no major component of cogging torque in slotless structure of a BLDC motor. These types of motors are very convenient due to excellent features such as zero-cogging torque, minimal vibration, high speed capability, excellent power-to-weight ratio, compact design, light weight and etc. At the end, finite element analysis (FEA) is employed to validate the topics.*

Keywords*: Slotless, Brushless DC Motor, Cogging Torque, Skewing, Fractional Pitch Winding, Finite Element Analysis, Ansys Maxwell*

INTRODUCTION

One of the main problems of electrical motors is cogging torque. This unwanted and disturbing torque reduces the nominal performance of electrical motors. Hence, researchers' attention has paid to overcome this problem. Cogging torque is caused by an uneven air-gap permeance resulting in the magnets constantly seeking a position of minimum reluctance. Several methods have been proposed to reduce cogging torque including skewing the stator slot, skewing the permanent magnets (PMs) of rotor, employing fractional pitch winding and building slotless motor [1-5].

Emergence of slotless motors leads to cogging torque free motors. Aim of this paper is to design a BLDC motor. These types of motors are becoming increasingly prominent because of their good merits over conventional motors. Main advantages of slotless brushless DC motors can be listed as: Zero-cogging torque for smooth operation, minimal vibration, high speed capability of up to 100,000 RPM, excellent power-to-weight ratio enabling the design of compact, light-weight devices, smooth high speed operation and lower audible noise [6-10].

This paper first discusses methods for cogging torque reduction. After that, equations and structure description of slotless BLDC motor are presented. Then, characteristics of motor are investigated using finite element analysis (FEA). Main output performance characteristics of a slotless BLDC motor are discussed and compared with a slotted BLDC motors.

COGGING TORQUE

Cogging torque is an unwanted phenomenon in electrical machines which is produced as a result of reluctance variations between stator tooth and rotor magnetic poles. In other words, this torque is occurred because rotor tends to align with stator in some specific directions. Simply, Cogging torque is the torque created when the rotor permanent magnets attempt to align themselves with a maximum amount of ferromagnetic material. Cogging torque is a pulsating torque with zero average value [1-5].

Cogging torque describes the interaction of the rotor magnets acting on the stator teeth or poles independent of any current. While this torque is often considered beneficial in step motors, it is considered detrimental in brushless permanent magnet motors [1].

Cogging torque produces noise and destructible pulsations in electrical machines and in some cases mechanical resonance would happen that leads to serious problems. However, certain amount of this torque is required in some specific industrial applications. Therefore, cogging torque is an important characteristic of machine which should be considered with a lot of care in design process.

Peak value for cogging torque is determined by some parameters like slot width to slot pitch ratio, permanent magnet energy and air gap length. Cogging torque characteristic could be corrected by changing the pole arc to pole pitch ratio. In practice, this disturbing torque is minimized by accurate selection of abovementioned parameters.

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Cogging torque can be represented by

$$T_{cog} = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta} \quad (1)$$

where ϕ_g is the air-gap flux by PMs, R is the air-gap reluctance, and θ is the position of the rotor [1]. Cogging torque has a periodic nature because air-gap reluctance varies periodically. In addition, cogging torque is independent of flux direction because the magnet flux ϕ_g is squared.

A. Cogging Torque Reduction/Elimination

There are some methods for reduction/elimination of cogging torque based on applications and considering technical and economic aspects:

- Skewing the stator slots
- Skewing the permanent magnets of rotor or optimizing the magnet pole arc
- Employing fractional pitch winding
- Building slotless motor

Amongst abovementioned methods, the two earlier are more common. Besides, there are some new methods that could reduce cogging torque [5].

For further clarification, a brief description is presented about these methods [1].

The first method is to skew the stator slots. The net change in reluctance can be minimized, despite the slot openings, if the slot openings are spread out over the surface area of the magnet as depicted in Figure 1. In Figure 1, the slots are skewed so that each magnet sees a net reluctance that stays the same or nearly the same as slots pass by. In this way, changes along the axial dimension are used to diminish the effect of changes along the circumferential dimension. As a result, the dR/dθ experienced by the entire magnet decreases and the cogging torque decreases [1].

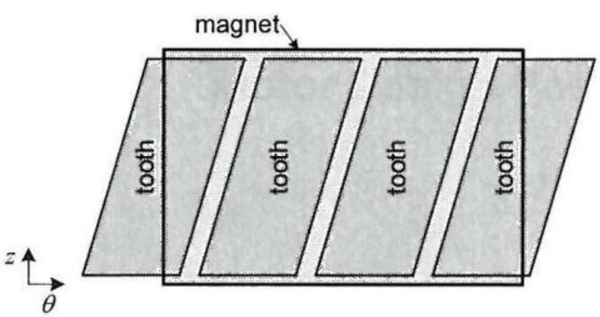

Fig. 1. Skewed stator slots [1]

The second method is related to permanent magnets on rotor. It is a well-established fact that the magnet skewing and its pole arc can have a large effect on the magnitude of the cogging torque. By doing this, the reluctance seen by magnets will change and cogging torque will reduce according to well adjusting PMs' shape and position.

The third method is associated with employing fractional pitch winding. Since each magnet produces cogging torque as it passes by stator slots, the relationship between the number of magnet poles and the number of stator slots influences cogging torque. In integral slot motors, each magnet appears in the same position relative to the stator slots. As a result, the cogging torque created by all magnets are in phase with each other, and the net cogging torque is equal to the product of the number of magnet poles and the cogging torque created by one magnet. That is, the cogging torque from each magnet simply adds to create the net result. On the other hand, in fractional slot motors, each magnet appears in a different position relative to the stator slots. As a result, the cogging torques created by all magnets are out of phase with each other, and the net cogging torque is reduced since the cogging torque from each magnet adds together and at least partially cancels the cogging torque from other magnets. This fact is one of the primary reasons for choosing a fractional slot motor [1].

The last way to minimize cogging torque is building up a slotless BLDC motor which is discussed in the next section.

SLOTLESS BLDC MOTOR

Slotless BLDC motors are developed for eliminating cogging torque in conventional slotted BLDC motors (Figure 2). Regarding Figure 2, as each magnet in the motor rotates past the stator teeth, the reluctance experienced by the magnet under the slot openings changes because of the longer flux path length into the slots terminating on the shoes. Therefore, the slot openings create a varying reluctance for the magnet flux, thereby creating cogging torque. If the stator teeth did not have shoes, the reluctance variation and resulting cogging torque would be much greater. Thus, the primary purpose for shoes is cogging torque reduction [1].

Shoe design represents a fundamental tradeoff. The narrower the slot opening, the smaller the cogging torque becomes. In the limiting case, if there was no slot openings, cogging torque would be zero. Therefore, slotless BLDC motors are devised for applications where zero cogging torque is the major concern.

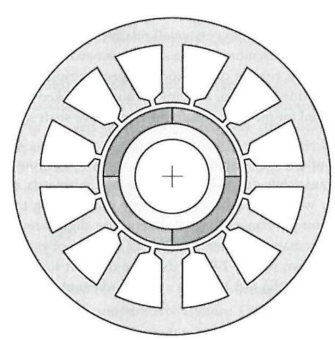

Fig. 2. Structure of conventional slotted BLDC motor [1]

Figure 3 shows a diagram of slotless BLDC motor. Separated permanent magnets are united to rotor core and distributed windings are fixed on the stator core. Flux path and magnetic circuit of slotless BLDC motor is shown in Figure 4. From geometric and material parameters of model, air gap magnetic flux is calculated. In magnetic circuit model taking into account one pole pair in Figure 4, the magnetic flux Φ can be expressed as

$$\Phi = \frac{2R_m}{2R_m + 2K_r R_g}\Phi_r = \frac{1}{1+K_r\frac{R_g}{R_m}}\Phi_r \qquad (2)$$

where R_m and R_g are the magnet and air gap reluctance, respectively, Φ_r is the flux source, and K_r is the reluctance factor which increases air-gap reluctance slightly to compensate for the missing steel reluctance [7]. The air gap flux can be written as

$$\Phi_g = K_l \Phi = \frac{K_l}{1+K_r\frac{\mu_r g A_m}{l_m A_g}}\Phi_r \qquad (3)$$

where

$$K_l = 1.5 p \beta \frac{g}{D_w} \qquad (4)$$

is the flux leakage factor considering magnet flux without passing into the stator core, and p, β, D_w are pole pair number, polar arc to polar pitch ratio, inner diameter of winding part, respectively [7, 8]. Figure 5 shows a simplified model of magnetic circuit for slotless BLDC motor.

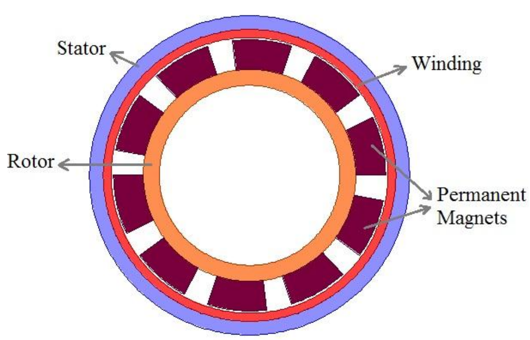

Fig. 3. Structure of slotless BLDC motor

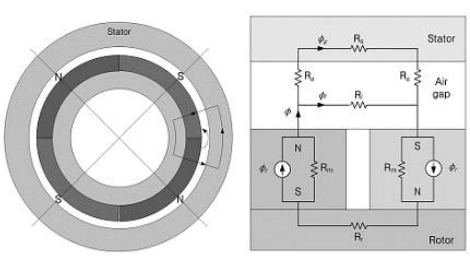

Fig. 4. Flux path and magnetic circuit of slotless BLDC motor

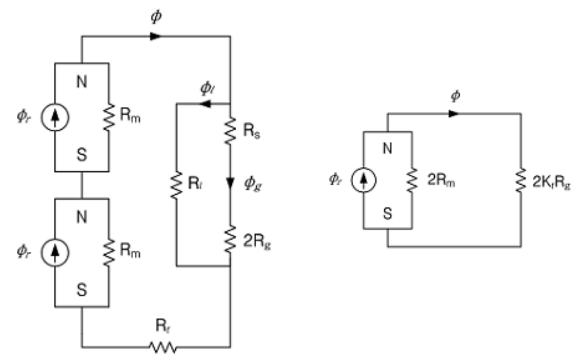

Fig. 5. Simplified magnetic circuit model for slotless BLDC motor

RESULTS AND DISCUSSION

In this section, finite element analysis (FEA) is occupied to investigate the discussed issues. Ansys Maxwell is used for this purpose. Firstly, a brief description is presented about the FEA and Ansys Maxwell. Then, the effect of skewing the PMs is analyzed and after that slotless structure for BLDC motor is considered.

A. FEA Validation

The FEA found its way into electrical engineering almost 30 years ago. The advantage of numerical methods like the FEA is to analyze the arbitrary shapes, arbitrary boundary conditions and complicated or distributed sources.

First implementation of FEA was in the analysis of DC motors, SR motors and etc. In this method, the space of interest is divided into small (but finite) regions called elements, which completely cover the space but does not overlap. Additionally it is required that an individual element does not cross a material boundary. Then it is assumed that over this small region, the unknown quantity can be described by a simple function, polynomials are usually chosen because the formulation involves differentiating and integrating these functions. The order of polynomial determines the order of the element.

Maxwell software which is based on FEA is one of the most important and efficient tools for FEA validation.

Desirable output quantities can be extracted using this software by doing below steps:

- Drawing the motor
- Assigning materials and boundary to the motor parts
- Performing mesh operation
- Setting up an analysis to solve
- Extracting output data and plots.

For this motor, stator and rotor core are composed of steel 1008. Surface-mounted permanent magnets are NdFeB with:

B_r: 1.23 T,
H_c: 890 kA/m.

Simulation is carried out for 70 msec.

B. Skewing the PMs

Cogging torque is reduced by skewing the edges of PMs. This is distinguished in the Maxwell software by a design parameter named offset. Offset determines the degree of skewing for PMs. Figure 6 shows BLDC motor with surface-mounted PMs. As shown in Figures 7 to 9, cogging torque is reduced by increasing the offset. However it has to be considered that when offset is increased, air gap flux density is reduced and as a consequence, output power of motor is decreased. Therefore there should be a trade-off between these two parameters. Table 1 compares the cogging torque of three cases with different offset. As shown in Table I, cogging torque is reduced about three times by skewing the PMs.

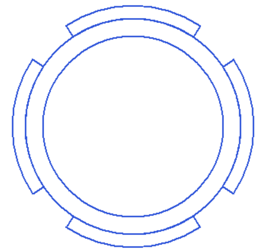

Fig. 6. Surface-mounted PMs

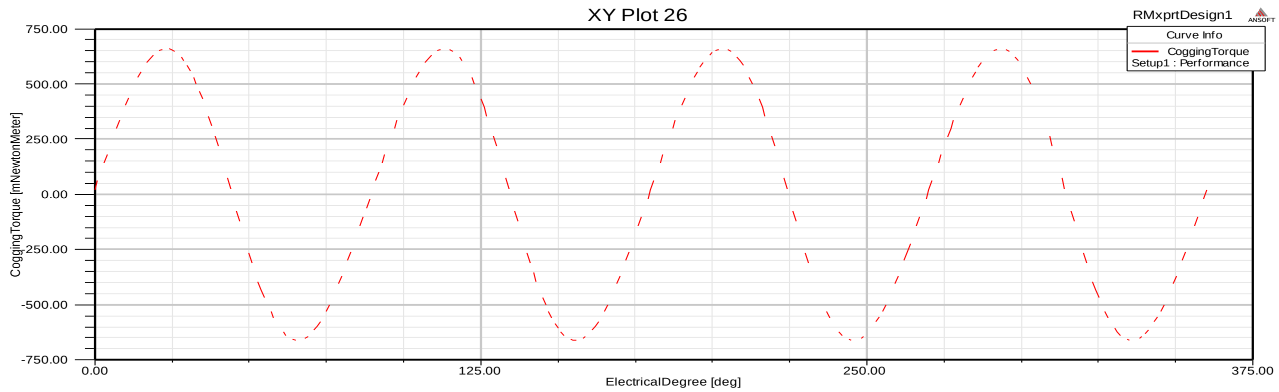

Fig. 7. Cogging torque diagram (Offset=0)

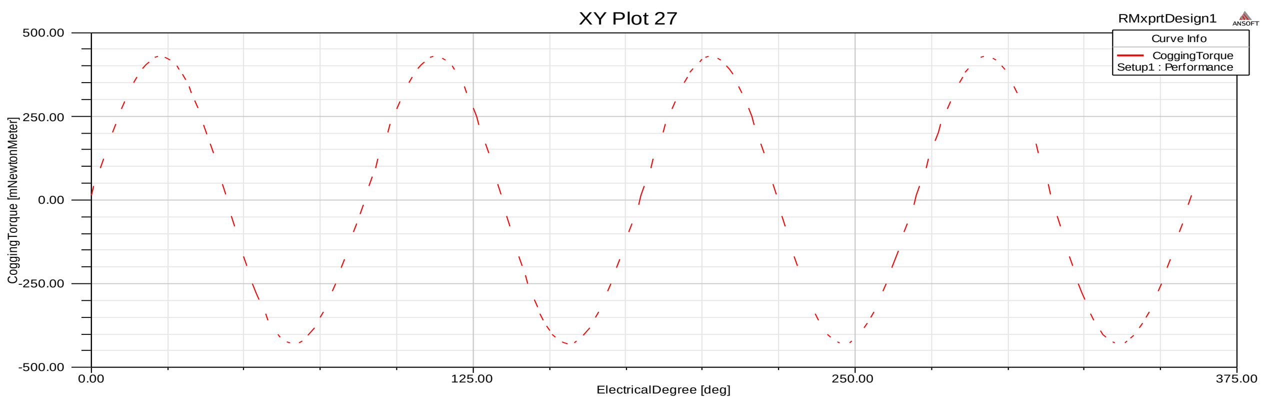

Fig. 8. Cogging torque diagram (Offset=2)

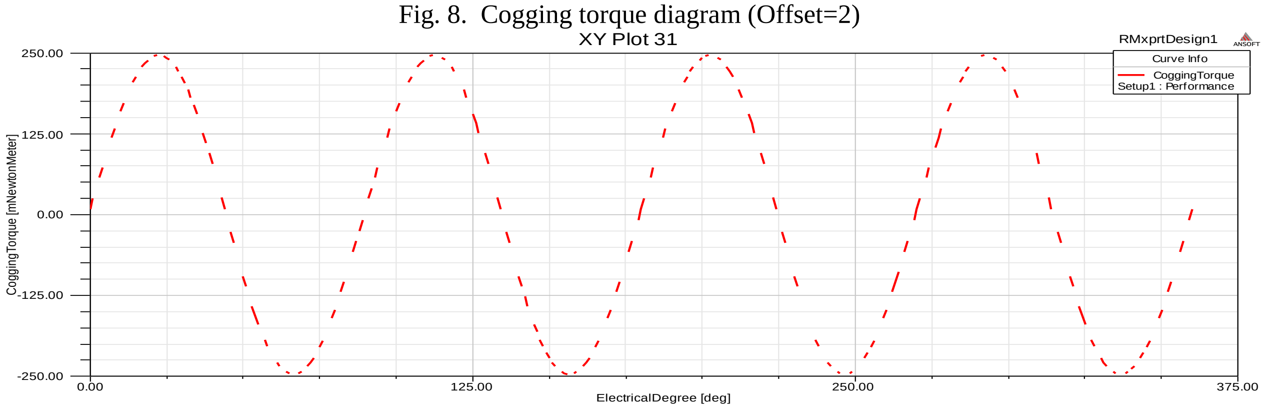

Fig. 9. Cogging torque diagram (Offset=4)

TABLE 1
Comparison of cogging torque for different offset

Offset (mm)	0	2	4
Cogging Torque (m N.m)	659.96	428.52	246.1

C. Building Up an Slotless BLDC Motor

In this section, FEA is employed to investigate the effect of slotless design in cogging torque. For this purpose, a comparison is carried out between two types of BLDC motors i.e. conventional slotted BLDC and slotless BLDC motor. Nominal parameters and dimensions of the two motors are identical except the fact that in slotless design, there is no slot. Main characteristics of the designed motor are listed in Table 2.

TABLE II
Main characteristics of motor

Parameter	Value
Power (kW)	1
Rated voltage (V)	220
B_{ys}, B_{yr} (T)	1.5
B_t (T)	1.5
B_r (T)	1.2
Number of slots (for slotted motor)	30

Mesh diagram produced by finite element analysis is shown in Figure 10. Flux lines and flux density of the proposed slotless BLDC motor are shown in Figures 11 and 12, respectively. As shown in these figures, first assumptions for motor are fulfilled.

Figure 13 shows cogging torque for slotted BLDC motor while no cogging torque is observed for slotless BLDC motor. It is obvious that cogging torque for slotted motor is 0.659 N.m while in slotless BLDC motor cogging torque is equal to zero. Figures 14 and 15 illustrate the output torque of motor for slotted and slotless BLDC motors, respectively. Average torque of slotted BLDC configuration is 6.0582 N.m and for slotless configuration is equal to 5.3943 N.m. Table III compares output and cogging torque of the two mentioned configurations. Average torque of sloless configuration is about 11 % less than the average torque of slotted one because of the structure difference. Therefore, it can be said that slotless configuration is a good candidate for precise applications which demand ripple-free torque.

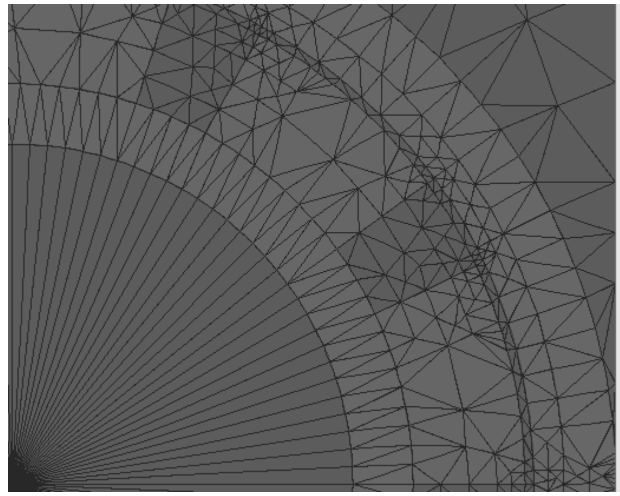

Fig. 10. Mesh produced by FEA

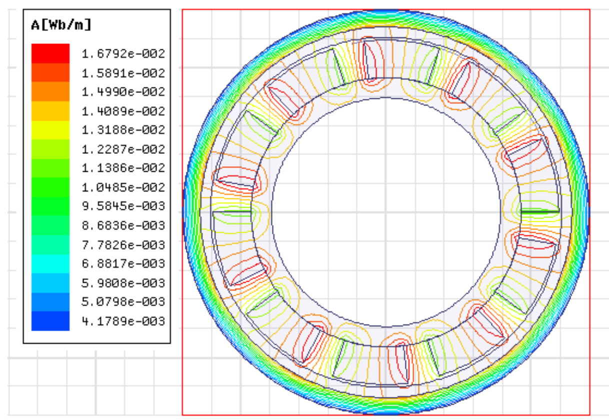

Fig. 11. Flux lines distribution

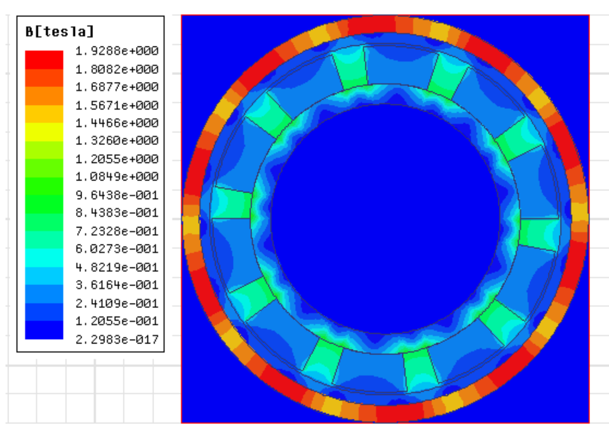

Fig. 12. Flux density of motor

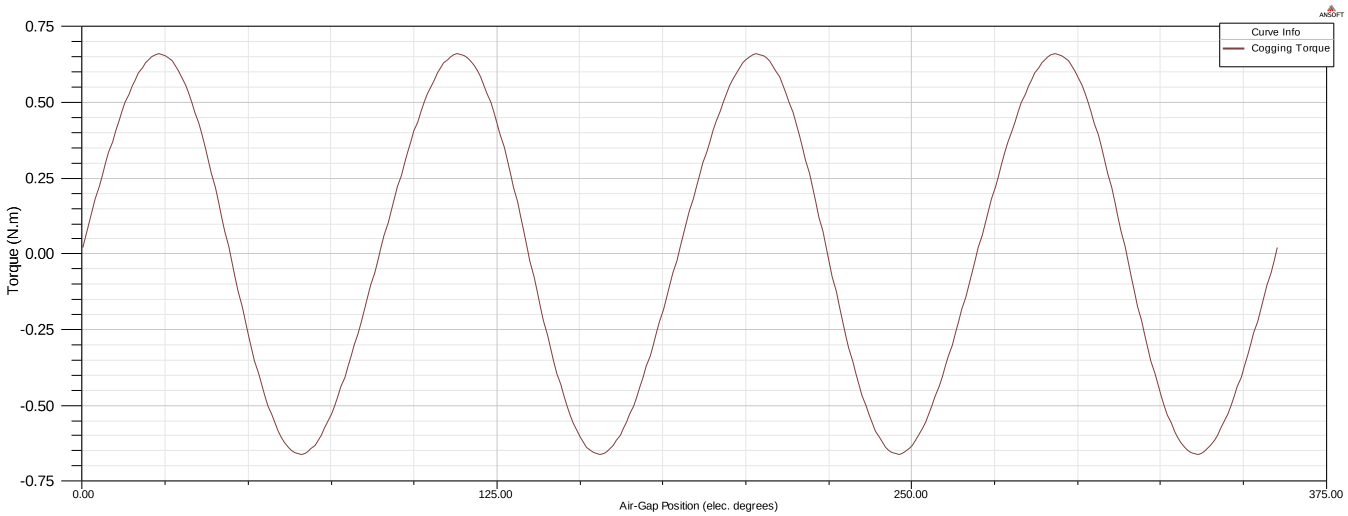

Fig. 13. Cogging torque of slotted BLDC motor

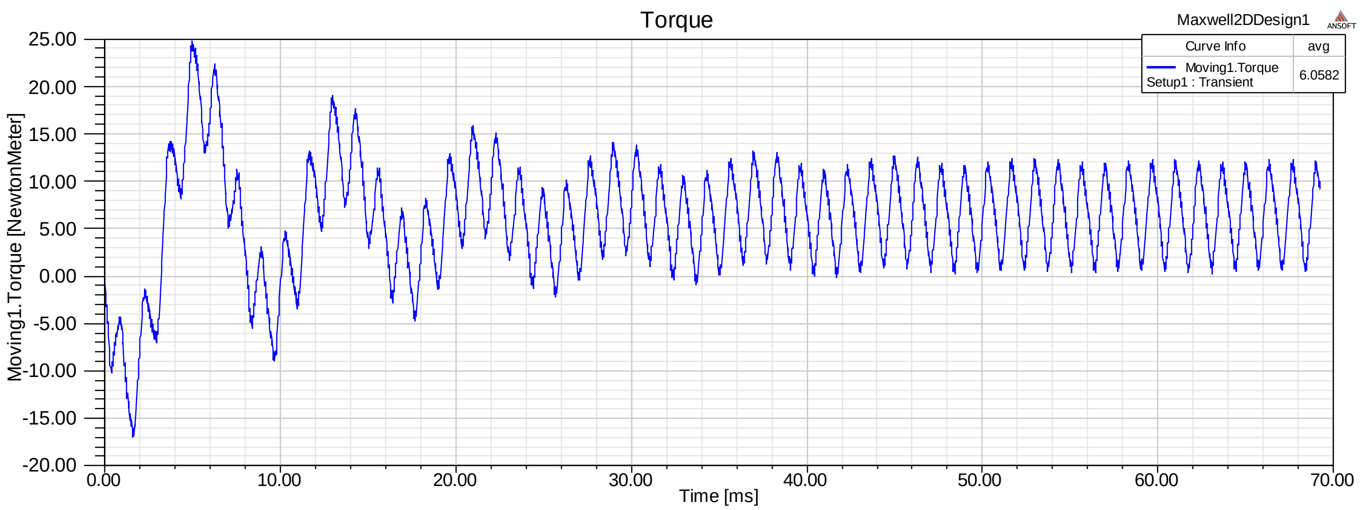

Fig. 14. Output torque of slotted BLDC motor

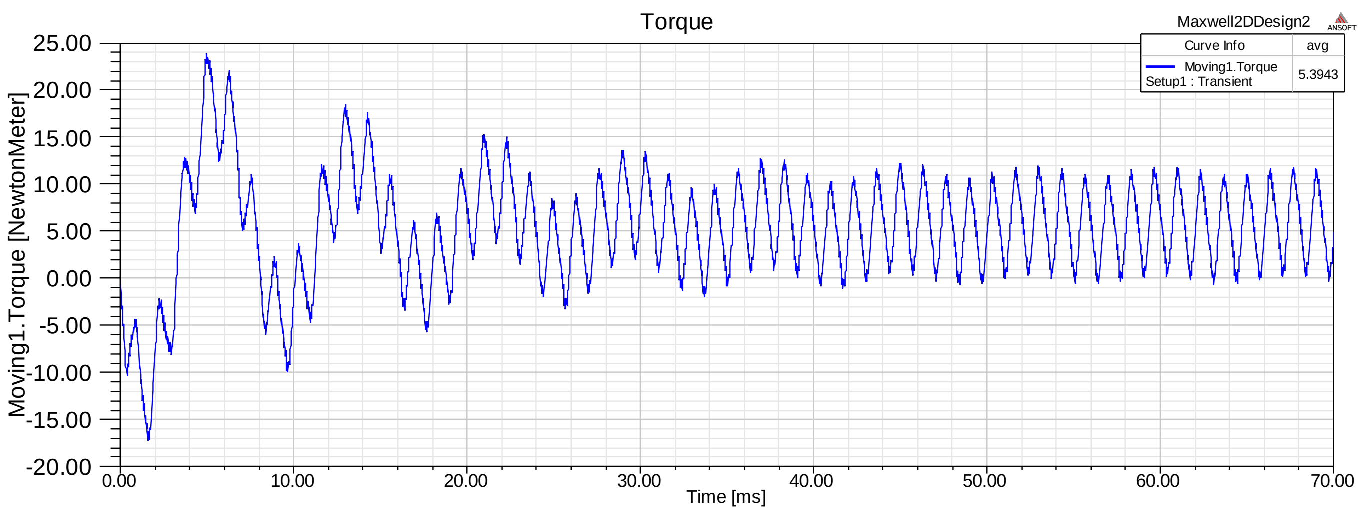

Fig. 15. Output torque of slotless BLDC motor

TABLE III
Comparison of BLDC motor configurations

Configuration	Average Torque (N.m)	Cogging Torque (N.m)
Slotted BLDC motor	6.0582	0.659
Slotless BLDC motor	5.3943	0

CONCLUSION

In this paper, methods for reducing cogging torque were investigated and after that a cogging torque free motor i.e. slotless BLDC motor was presented. There are some methods for cogging torque reduction/elimination such as skewing the stator slot, skewing the permanent magnets (PMs) or optimizing magnet pole arc of rotor, employing fractional pitch winding and building up a slotless motor. At first, these methods were discussed and slotless configuration of BLDC motor was surveyed. After that, the effect of skewing PMs was expressed by a design parameter i.e. offset. This parameter determines the degree of skewing for PMs. It was shown that increasing offset leads to cogging torque reduction. Then, slotless structure of a brushless DC motor (BLDC) was considered. Theoretically, a slotless BLDC motor has no major component of cogging torque. FEA results showed that cogging torque reduces to zero. Besides, while average torque of slotless motor has less magnitude in comparison with slotted configuration, but output torque of slotless configuration has less variation due to zero cogging torque.

Future works may be devoted to optimal design of magnet pole arc and using fractional pitch winding in BLDC motors in order to reduce cogging torque.

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