Analysis of Cogging Torque Reduction by Increasing Stator Slot Depth in Brushless DC Motor

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***Abstract* — Cogging torque is undesirable effect in the brushless dc (BLDC) motor, causing vibration and audible noises. It arises from permanent magnets of the rotor interacting with the steel teeth on the stator. This paper analysis cogging torque reduction method by varying stator slot depth in brushless motor. The finite element method (FEM) is used to analyze the cogging torque reduction method. In this paper, 70 W / 24 V and 2.2 kW / 230 V BLDC motors are analyzed by increasing stator slot depth in order to reduce cogging torque. The FE method simulation results are presented to validate this method.**

***Keywords* — cogging torque, finite element method (FEM), BLDC motor, permanent magnet, stator slot depth.**

I. INTRODUCTION

Permanent Magnet Brushless DC (PMBLDC) motors have advantages such as high efficiency, high power density and high reliability. These motors are inherently maintenance free because of the absence of a mechanical commutator. These advantages combined with the ease of control have made them very attractive motors increasingly being used in various domestic and industrial applications. Cogging torque is one of the important drawback of BLDC motor which results in shaft vibration and noise. The cogging torque is due to the physical structure of the machine and is produced by the magnetic attractions between the rotor mounted permanent magnets and stator teeth. It is circumferential component of the attractive force that attempts to maintain the alignment between the stator teeth and permanent magnets. In structural solution category researchers have proposed various design modifications to minimize cogging torque. Reduction of cogging torque has been done in many ways for a long time, such as Magnet shaping, Adding dummy stator slots, Shifting magnets, Skewing, Sizing, Teeth pairing etc.

The focus of this work is to minimize cogging torque in BLDC by increasing stator slot depth. For analyzing the performance of the motor, motor is modelled using Finite Element Analysis (FEA). The focus of this paper is to minimize cogging torque in BLDC by introducing structural design modifications. The performance of the machine is analyzed by varying the stator slot depth. The

Flowchart on the design process for reducing of cogging torque is shown in Fig. 1.

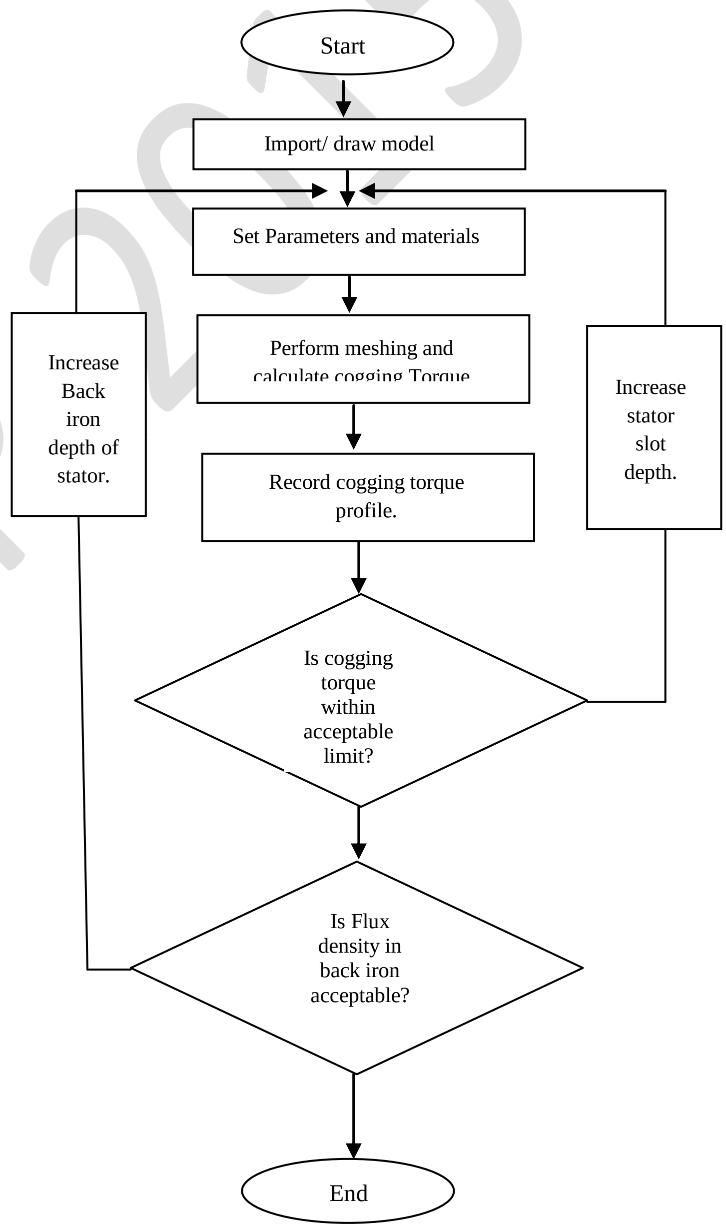

Fig. 1 Simulation step of cogging torque calculation

A. Cogging Torque

Cogging torque is generated due to interaction between the magnets of the rotor and the stator teeth. It is an undesirable quantity that affects smooth rotation of the rotor and generates noise and Vibration.

In Equation (1), where the first to third terms correspond to the co-energies of the self-inductance, the permanent magnet and that is due to mutual flux respectively [1]. The instantaneous electromagnetic torque T, which is derivatives of the co-energy with respect to rotor position, as shown in equation 2 [3].

$$W_C = \frac{1}{2}Li^2 + \frac{1}{2}(R+R_m)\phi_m^2 + Ni\phi_m \text{ .... (1)}$$

$$T = \frac{dW_C}{d\theta}, \quad \text{i constant............................... (2)}$$

Where R and R_m are the reluctances seen by the magneto motive force and magnetic field, respectively while $\O_m$ is the magnetic flux of the magnet [3]. By substituting (1) into (2), the torque is calculated as:

$$T = \frac{1}{2}i^2\frac{dL}{d\theta} - \frac{1}{2}\phi_m^2\frac{dR}{d\theta} + Ni\frac{d\phi_m}{d\theta} \text{ .... (3)}$$

In equation (3), the second term is proportional to the square of the magnetic flux. Whereas the negative sign represents that the inductance and reluctance are inversely proportional, (i.e. L = N^2/R_m). Since the coil inductance is constant, independent of rotor position θ. [3].

$$T_{cog.} = -\frac{1}{2}\phi_g^2\frac{dR}{d\theta} \text{ ....(4)}$$

In equation (4), Where $\O_g$ is the air-gap flux, R is the air-gap reluctance, and θ is the position of the rotor. This supports the basic fundamental that cogging torque is the interaction between the rotor magnets and the stator teeth. The cogging torque can be minimized either by making air gap flux zero or the rate of change of the air gap Reluctance dR/dθ, equals to zero. Air gap flux can not be reduced, therefore the cogging torque can be minimized by making the air gap reluctance to be constant as possible with respect to rotor position.

In equation (5), the period of cogging torque in mechanical degrees is determined by dividing 360°, the overall circular mechanical degrees in space by the least common multiple of the magnetic pole number N_P and the slot number N_S of BLDC motor. That is why the cogging torque had better be minimized during the motor design process. [3].

$$\theta_{Cog-period} = \frac{360}{lcm(N_{P,}N_s} \text{ ....(5)}$$

1) Cogging Torque Analysis for 70 W, 24 V BLDC motor:

Fig. 2 shows the FEA model for 70 W, 24 V radial flux PMBLDC motor with stator slot depth of 14.9 mm and 15.9 mm. the stator slot depth is increased from 14.9 mm to 15.9 mm and cogging torque profile is obtained.

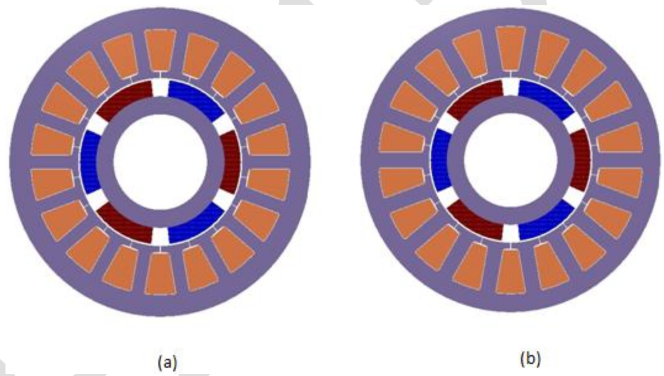

Fig. 2 (a) 14.9 mm stator slot depth (b) 15.9 mm stator slot depth

Peak to peak cogging torque is influenced by variation of stator slot depth, shown in fig. 3.Minimum peak to peak cogging torque is observed when stator slot depth is 15.9 mm. it is concluded that by increasing slot depth from 14.9 mm to 15.9 mm, reduction in cogging torque is from 0.578 N.m to 0.114 N.m without affecting other performance parameters.

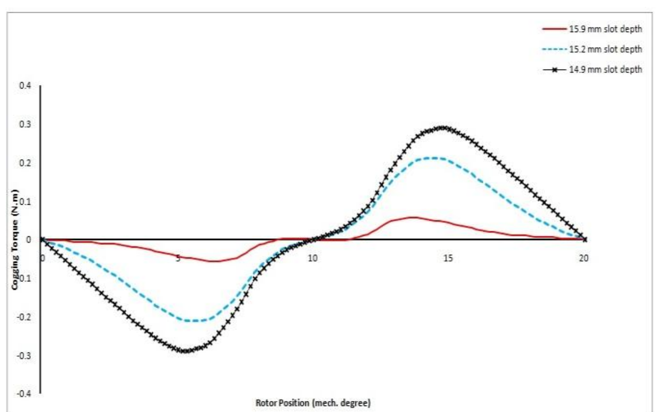

Fig. 3 Cogging Torque profile of 70 W radial flux motor

Fig. 4 shows the field plot for stator slot depth of 15.9 mm. it is observed that the flux density in different section of the magnetic circuit is as per the assumption.

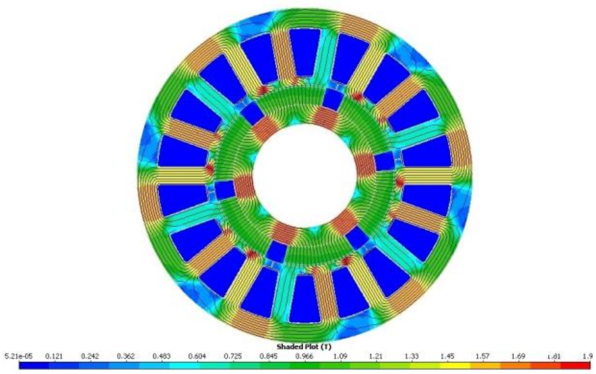

Fig. 4 Instantaneous field plot of 70 W radial flux motor for 15.9 mm stator slot depth

2) Cogging *Torque Analysis for 2.2 kW, 230 V BLDC motor*

Fig. 5 shows the FEA model for 2.2 kW, 230 V radial flux PMBLDC motor with stator slot depth of 21.4 mm and 22.4 mm. The stator slot depth is increased from 21.4 mm to 22.4 mm and cogging torque profile is obtained.

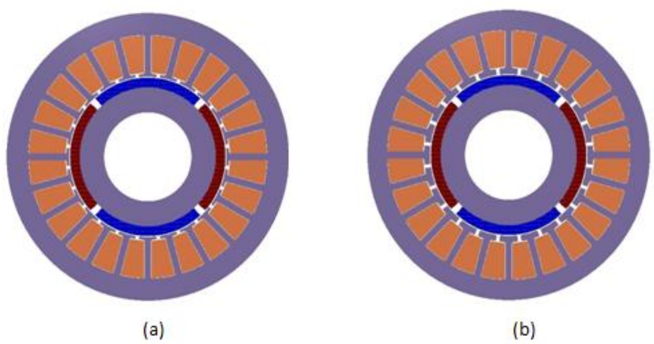

Fig. 5 (a) 21.4 mm stator slot depth (b) 22.4 mm stator slot depth

Peak to peak cogging torque is influenced by variation of stator slot depth, shown in fig. 6. Minimum peak to peak cogging torque is observed when stator slot depth is 22.4 mm. it is concluded that by increasing slot depth from 21.4 mm to 22.4 mm, reduction in cogging torque is from 10.24 N.m to 4.72 N.m without affecting other performance parameter.

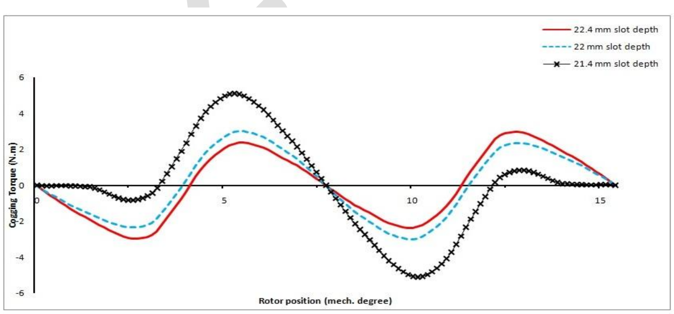

Fig. 6 Cogging Torque profile of 2.2 kW radial flux motor

Fig. 7 shows the field plot for stator slot depth of 22.4 mm. it is observed that the flux density in different section of the magnetic circuit is as per the assumption

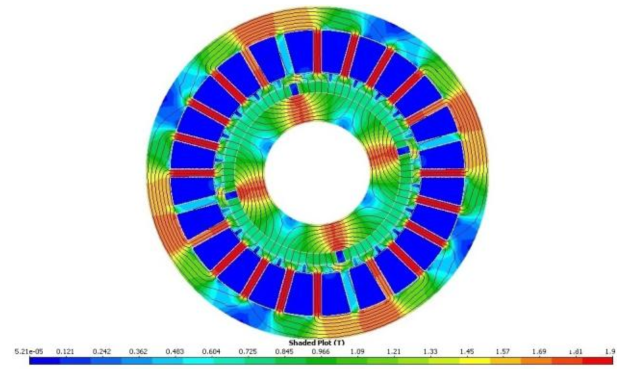

Fig. 7 Instantaneous field plot of 2.2 kW radial flux motor for 22.4 mm stator slot depth

II. CONCLUSIONS

In this paper, 70 W / 24 V and 2.2 kW / 230 V radial flux PMBLDC motors are analyzed. Effect of stator slot depth on cogging torque is investigated. Cogging torque is reduced from 0.578 N.m to 0.114 N.m (i.e. 80.2%) and 10.24 N.m to 4.72 N.m (i.e. 53.9%) in 70 W and 2.2 kW motors respectively. The result confirms that stator slot depth variation approach can significantly reduce the cogging torque and helps to improve the torque quality of BLDC motors.

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