I J C T A, 9(14) 2016, pp. 6895-6902

Cogging Torque Reduction in Brushless DC Motor by Applying Various Slot Modification Techniques in Stator Tooth

M. Arun Noyal Doss[1*], V. Ganapathy[2], R. Brindha[1], M SaiSrinivas Rao[3],
Shivva Rohith[3] and K. Karthik[3]

ABSTRACT

Cogging torque is one of the main drawbacks of Permanent Magnet (PM) Brushless Direct Current (BLDC) motor, which create the direct impact and affect the performance of the motor. This paper proposes a various stator slots modification technique of reducing the cogging torque in BLDC machine such as: Bifurcation, Dual bifurcation and Reduced Stator Slot width. These techniques are verified by 2-D Finite Element (FE) analyses and it is compared with conventional model of BLDC motor. The results of cogging torque and flux densities are compared and analyzed. Among these techniques the Reduced Stator Slot width technique is very effective in cogging torque reduction and it enhances the best performance.

Keywords: PM, BLDC motor, FE, Reduced Stator Slot width.

1. INTRODUCTION

BLDC motor has been widely accepted in the automation and industrial drives for its best performance applications due to its good features such as torque density and smooth operation. Cogging torque reduction is a need to enhance the performance of the motor. Ideally, the desired torque ripple minimization scheme should not only minimize the torque ripple due to cogging torque, but also minimize the other sources of torque ripple without sacrificing the average torque [1-2]. Several researches have been reported in literature [1-9] to reduce the cogging torque. In two ways the cogging torque can be reduced 1. Shaping of PMs and 2. Stator Slot Modifications.

The magnet pole arc design, skewing of rotor magnets or stator, step skew of the magnets, PM shifting, etc., are known common techniques for reducing the cogging torque in rotor side. The skewing of stator slots, slot pairing and dummy slots are well known and effective techniques for reducing the cogging torque. All the methods reported so far are capable of minimizing the cogging torque at the expense of added complexity of stator or rotor magnet construction and some loss of output torque. Practically, however, they do not completely eliminate the cogging torque, and some of the techniques may have adverse effect on the magnitude and harmonic contents of the back EMF of the motor. Hence, optimization is needed for high-performance PM motor design [1-2].

In this paper the techniques are modified slightly and applied to stator teeth are Single Bifurcation, Dual Bifurcation and Reduced Stator Slot Width methods. The variations in cogging torques and flux densities for different stator teeth shapes are simulated and the performances compared with the Conventional

---

[1&3] Department of Electrical and Electronics Engineering, SRM University.
[2] Department of Information Technology, SRM University.
[3] UG Scholar, Department of Electrical and Electronics Engineering, SRM University.
*E-mail: *arunoyal.d@ktr.srmuniv.ac.in*

motor. The result shows that the cogging torqueminimization may not be eliminatedcompletely but can only be minimized to aacceptable level dependingon the specific motor application. Table 1 describes the main specification of the BLDC motor.

2. COGGING TORQUE IN STATOR SLOT MODIFICATIONS

Cogging torque is also called detent torque, and it is one of the inherent characteristics of BLDC motor. Theoretically, cogging torque is caused by the reluctance change between the stator teeth and magnetic poles on the rotor, and it is mainly the magnetic poles corners, not the whole magnetic poles, are responsible for creating the cogging torque. Cogging torque is influenced by a variety of other design factors of BLDC Motor. Among these factors, air gap length, slot opening, and magnetic poles pitch play important roles [10]-[11].

Cogging torque drastically influences the control precision of PM motors used in speed and position control systems. Usually PMBLDC motor and PM synchronous motor (PMSM) are employed in these systems. A larger cogging torque will decrease the speed and cause oscillations in the rotor movement, and these effects are undesirable in precise control systems applications [1-2]. Cogging torque sometimes may cause excessive acoustic noise and harmful vibration to the motor as well as to its load (or driver), and in many cases, a mechanical resonant may occur so that a serious catastrophe is caused. Reducing harmful cogging torque of BLDC motor has become one of the most interesting researches in the motor design and application fields [5-6].

To simplify the theoretical analysis of cogging torque, the following assumptions are made:

1) End effect of the motor is negligible.
2) Flux leakage is negligible.
3) Permeability of the iron is infinite.
4) Permeability of permanent magnet is equal to that of the vacuum.

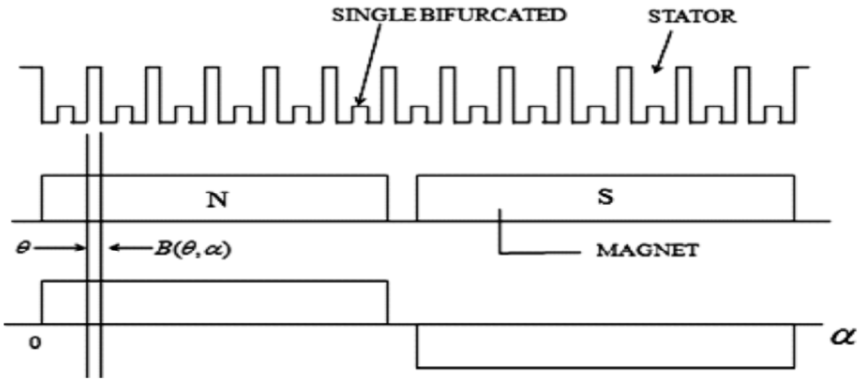
The distribution of the magnetic field in the air gaps of Single, Dual Bifurcation in stator teeth and Reduced Stator Slot Width models of BLDC motors are schematically shown in Figure 1.

Table 1
Specification of BLDC Motor

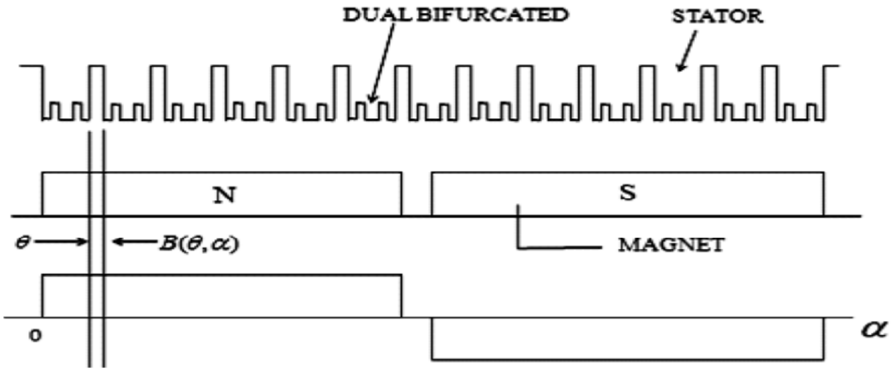
Power Rating of motor	375W(0.5HP)	Pole arc coefficient	0.7
Flux density in air gap B_g	0.1-0.9Wb/m^2	Inner radius of rotor (mm)	15
Average Flux density B_{av}	0.10 - 0.65Wb/m^2	Outer radius of rotor(mm)	55
Electric Loading	10000ac/m	Outer radius of stator(mm)	80
Residual flux density	0.96 T	Air gap(mm)	0.1
Coercive force(kA/m)	145.36	Width of slot opening(mm)	1.0– 1.5
Rated Speed	2000-4000rpm	Residual flux density(T)	0.96
Number of poles	8	Number of slots	60

3. STATOR SLOT MODIFICATION TECHNIQUES

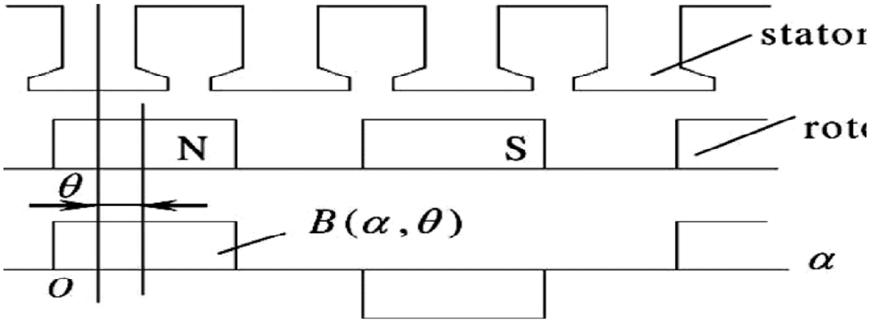
The conventional model of BLDC motor has been designed for an 8-pole 60-slots motor and the construction view is shown in Figure 2. The maximum value of the normal flux density of conventional motor is 0.6 Wb/m^2. The cogging torque of the conventional motor is shown in Figure 3.



(a) Single Bifurcated Stator Teeth



(b) Dual Bifurcated Stator Teeth



(c) Reduced Stator Slot Width

Figure 1: Distribution of Air Gap Magnetic Field

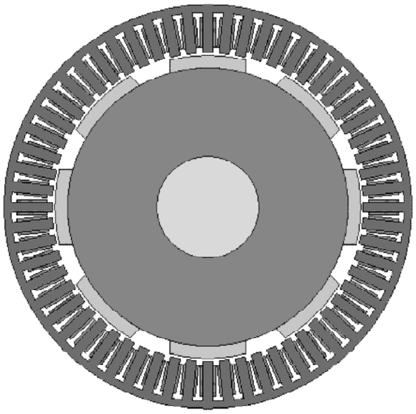


Figure 2: Constructional View of 8-Pole 60-Slot Conventional BLDC Motor

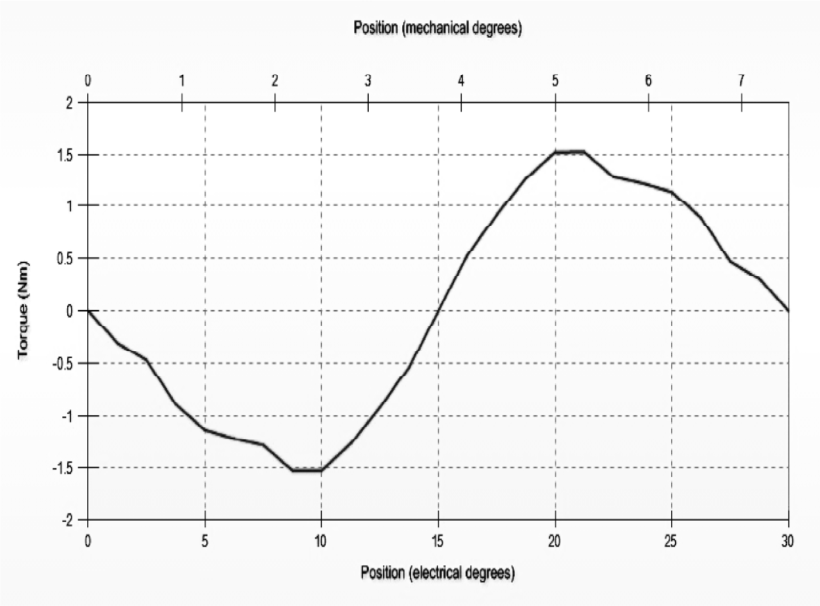


Figure 3: Cogging Torque of Conventional BLDC Motor

3.1. Single Bifurcated Stator Teeth Motor

Bifurcated slot teeth are alternate physical structures of the stator lamination [5-6]. The solid model of the single bifurcated slots is shown in the Figure 4. The empty slots in the stator teeth are used to change the reluctance of magnetic fields. The cogging torque is caused by the reluctance variation due to the stator slots and rotor magnets when the rotor rotates. The permeance variation helps to reduce the cogging torque. The bifurcated slot effect is similar to that of increasing the number of slots per pole. Two configurations are considered in the proposed motor. The first configuration has one bifurcated slots and the second has two under one tooth. The tangential equi-flux density distribution of bifurcated slot design is shown in Figure 5.

The maximum value of normal flux density of an 8-pole 60-slot motor with a single bifurcation is 0.45 Wb/m^2 and is shown in Figure 6. This Bifurcated BLDC motor is simulated in the MagNet software and the flux densities are shown in the Figures 5 and 6. When the auxiliary slots are provided to each of the slot tooth, the cogging torque is reduced significantly. The configuration with one auxiliary slot per tooth gives an average cogging torque reduction of 25%, which is shown in Figure 7, while the average back-EMF change remains at 1%.

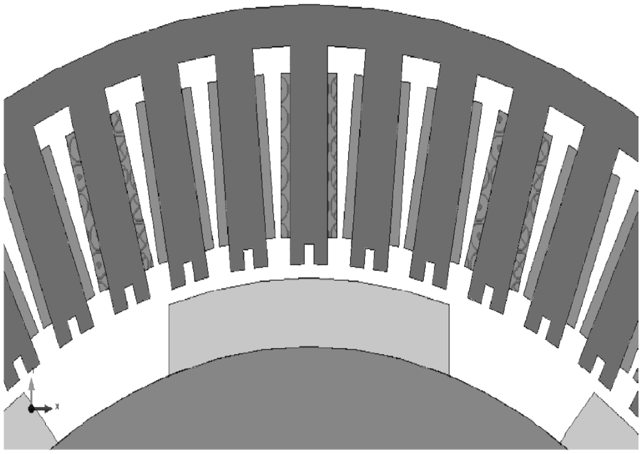


Figure 4: Model of Single Bifurcated Motor

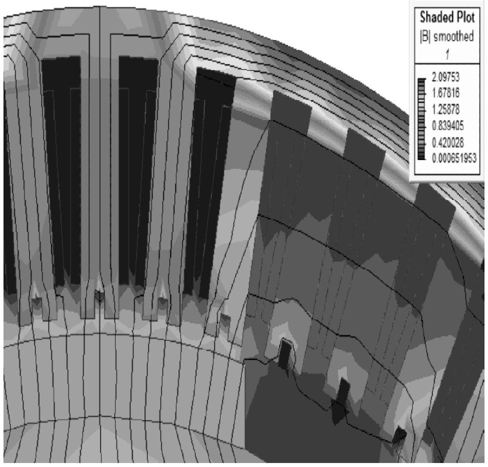


Figure 5: Tangential Flux Density of Single Bifurcated Motor

3.2. Dual Bifurcated Stator TeethMotor

The dual bifurcation technique is derived from the single bifurcation technique. The dual bifurcation is applied to the stator teeth and the solid model of dual bifurcation is shown in Figure 8. The flux line flows in the magnetic area of the stator teeth are shown in the tangential flux density. The tangential equi-flux density distribution of dual bifurcated stator slot teeth is shown in Figure 9. The bifurcated slot in the stator teeth is in the shape of a square. The shaded normal flux density of dual bifurcated motor is shown in Figure 10. In the dual bifurcation technique, the slot teeth have two auxiliary (dummy) slots and the empty slots under the teeth create reluctance change between the slots and rotor magnets, modulating the permeance variation which helps to reduce the cogging torque. The configuration with two auxiliary slots per tooth gives the average cogging torque reduction of 50%, while the average back-EMF change remains at 2%. The cogging torque reduction in dual bifurcated motor is shown in Figure 11. From the graph it is observed that the cogging torque varies between -0.41 to 0.41 Nm which is significantly lower than that obtained from the other stator slot modification methods.

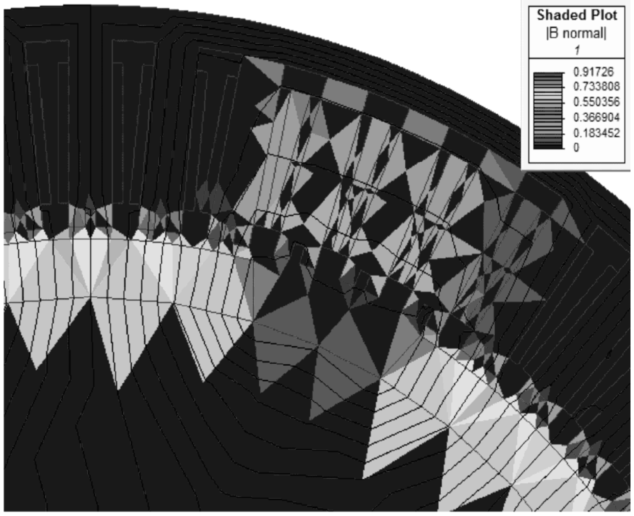


Figure 6: Normal Flux Density of Single Bifurcated Motor

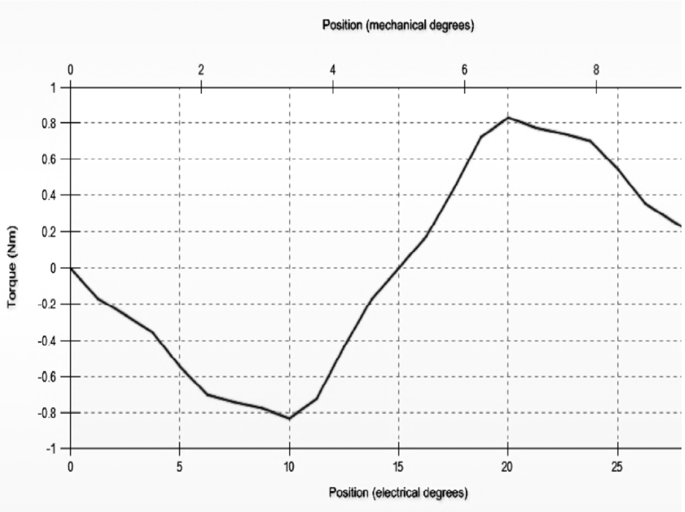


Figure 7: Cogging Torque of Single Bifurcated Motor

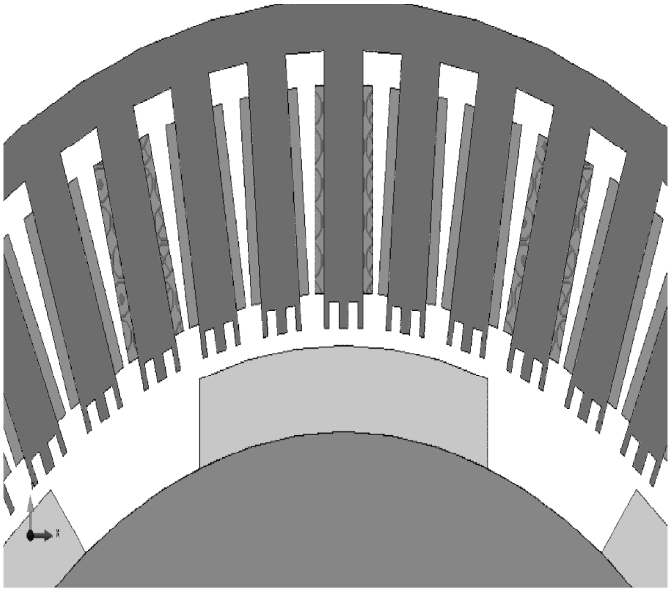


Figure 8: Solid Model of Dual Bifurcated Motor

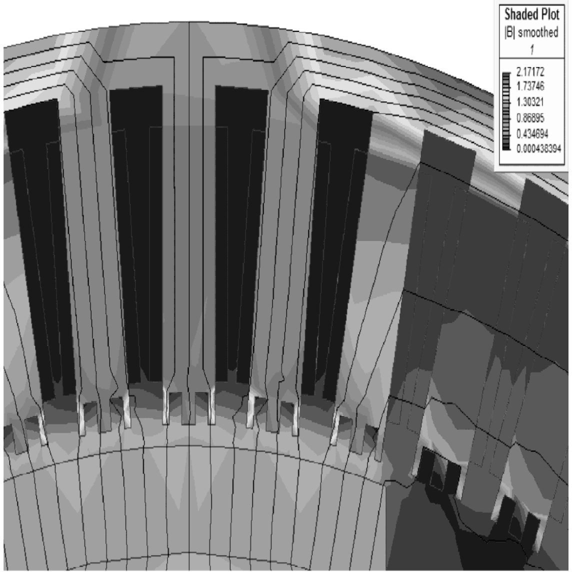


Figure 9: Tangential Flux Density of Dual Bifurcated Motor

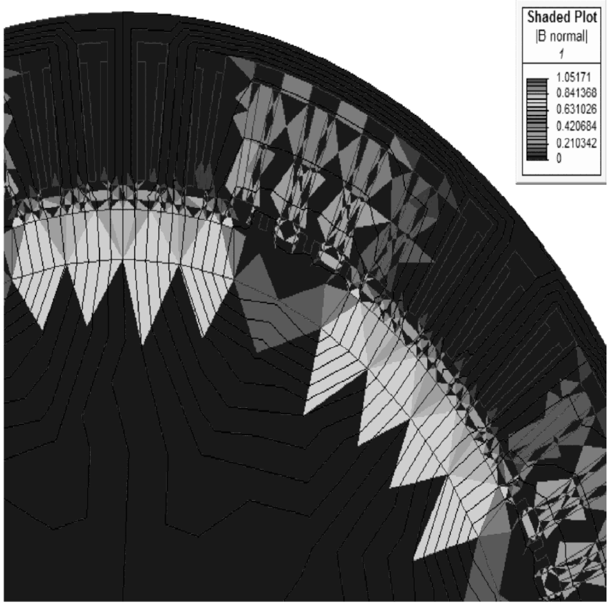


Figure 10: Normal Flux Densityof Dual Bifurcated Motor

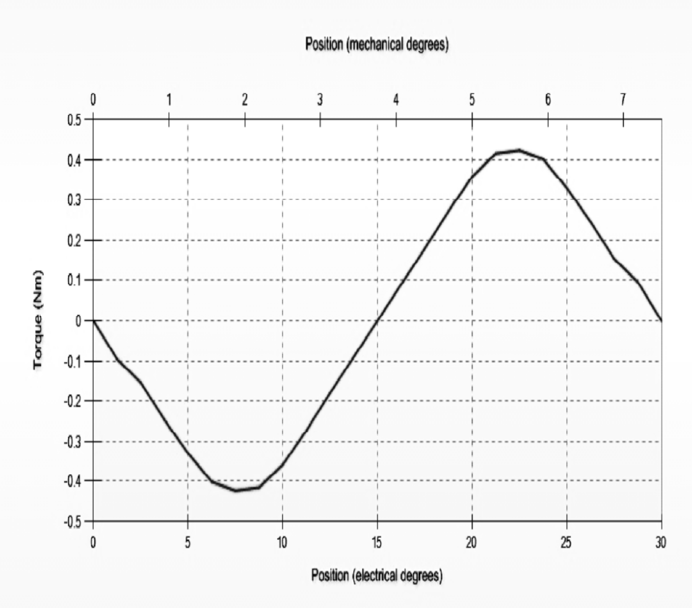


Figure 11: Cogging Torque of Dual Bifurcated Motor

3.3. Reduced Stator Slot Width Motor

When increasing the width of a tooth, the slot pitch is remains constant and it is maintained at the same value as in Conventional, Single and Dual Bifurcated motors, but as a consequence the width of slot gets reduced. These slot teeth are dumb-bell in shape. The solid model of the Reduced Stator Slot Width motor is shown in Figure 12.The 2-D and 3-D meshings are validated for the designed Reduced Stator Slot Width motor and they arediscretized for better clarity. The tangential and normal flux densities are highly reduced in this motor and shown in Figures 13 and 14. When the stator slot opening is small, there is a change in the flux density distribution. Though the flux density remains the same in many regions of the BLDC motor, maximum flux density indicated by yellow colour is attained in some parts of the stator (in addition to the permanent magnets). Red areas indicate undesirable high flux density and may result in hot spots that may damage the motor. By applying the Reduced Stator Slot Width, the slot opening is very small and the probability of development of hot spots increases.

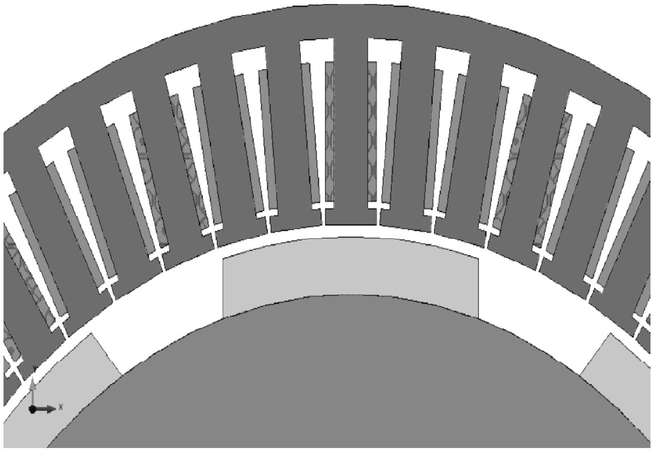


Figure 12: Solid Model of Reduced Stator Slot Width Motor

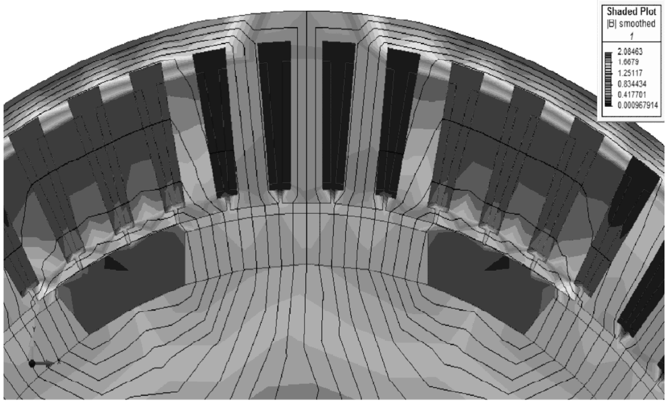


Figure 13: Tangential Flux Density of Reduced Stator Slot Width Motor

Hence, the change in flux density and the development of hot spots must also be considered while the slot modifications are done to reduce the cogging torque. So the flux density is decreases which makes the reluctance change, and hence results in cogging torque reduction. By modifying the shape of stator slots, it is found that the cogging torque is reduced and the cogging torque waveform of Reduced Stator Slot Width is shown in Figure 15.

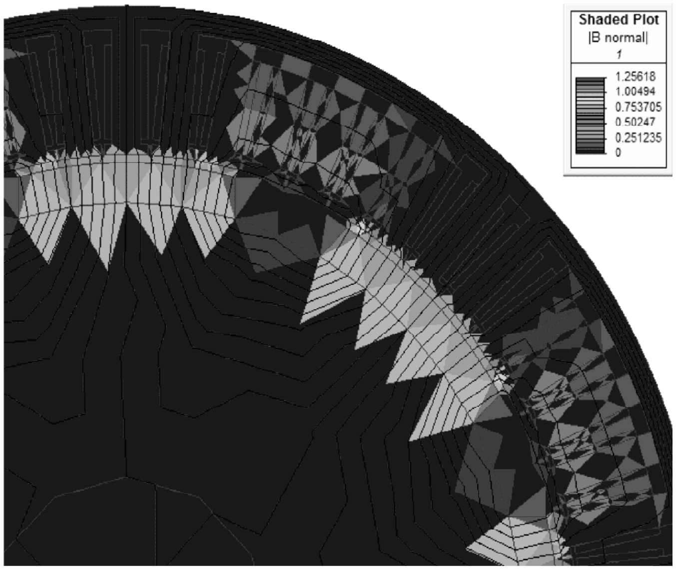


Figure 14: Normal Flux Density of Reduced Stator Slot Width Motor

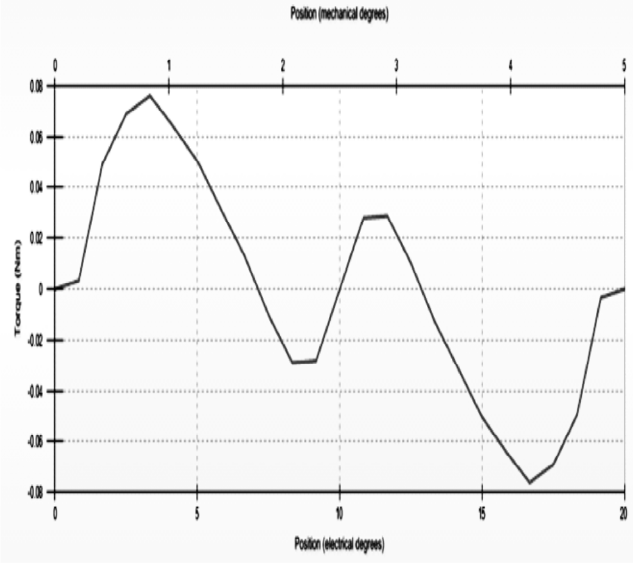


Figure 15: Cogging Torque of Reduced Stator Slot Width Motor

4. ANALYSIS OF RESULTS

The cogging torque reduction techniques based on the slot modifications are investigated for designs such as Conventional, Bifurcated, Dual Bifurcated and Reduced Stator Tooth Width.

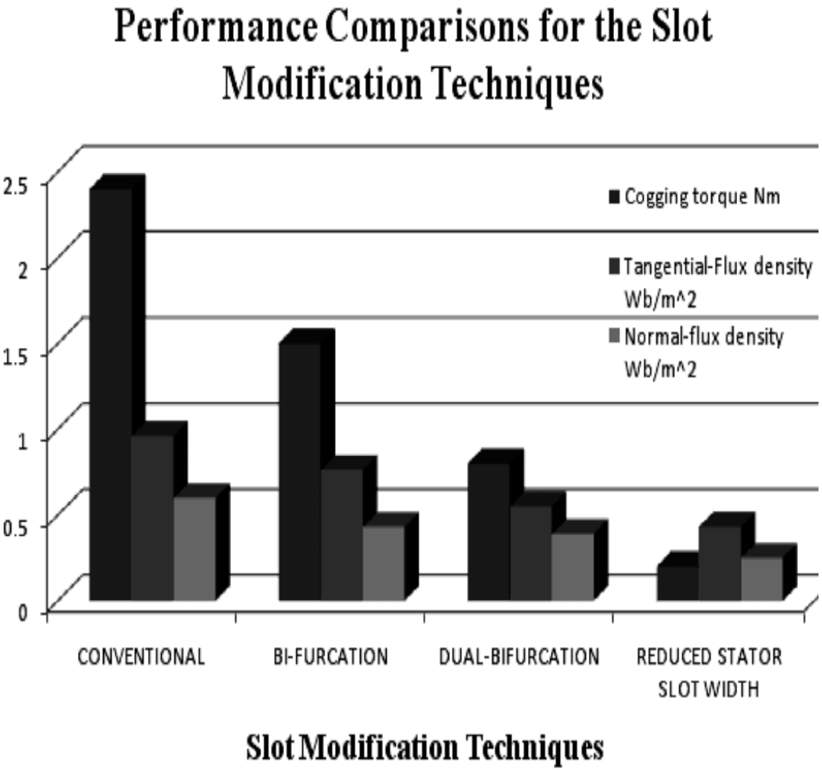


Figure 16: Comparisons of Cogging Torque and Flux Densities of the Slot Modification Techniques

Table 2
Performance Comparisons for the Slot Modification Techniques of BLDC motors

Applied Techniques	*Tangential Flux density Wb/m²*	*Normal Flux density Wb/m²*	*Peak to Peak Cogging Torque (Nm)*
Conventional	0.96	0.6	2.4
Single Bifurcation	0.76	0.43	1.5
Dual Bifurcation	0.53	0.39	0.8
Reduced stator slot width	0.43	0.25	0.2

The performance comparisonsof the slot modification techniques of BLDC motors aregiven in Table 2. The profiles of flux density distribution in the air gap and the value of cogging torquefor different types of BLDC motors are evaluated and shown graphically in Figure 16

5. CONCLUSIONS

Permanent Magnet (PM) Brushless DC (BLDC) motors offer many advantages but exhibit some disadvantages. Cogging torque effects can raise problems with torque quality, speed precision and smoothness, and especially noise and mechanical problems created by torque ripple. In this paper, the stator slot modification technique is implemented and the CAD simulated results are carried out for various slot modification techniques. The stator slot modification is one of the effective techniques for cogging torque reduction. The cogging torque and flux densities of the slot modification techniques are compared with the Conventional motor. Among the mentioned techniques the proposed Reduced Stator Slot Width has the small slot opening (1.0 mm) compared to other technique. From the analysis of results, it is evident that there is a significant reduction of peak to peak cogging torque and flux densities in the Reduced Stator Slot Width motor as compared to the other slot modification methods.

REFERENCES

[1] M. ArunNoyal Doss; S. Jeevananthan; SubhransuSekhar Dash; M. JahirHussain (2013) ‘Critical evaluation of cogging torque in BLDC motor with various techniques’, *Int. J. Automation and Control*, Vol. 7, No. 3, pp. 135–146.

[2] Islam, M.S., Mir, S. and Sebastian, T. (2004) ‘Issues in reducing the cogging torque of mass-produced permanent-magnet brushless DC motor’, *IEEE Trans. Ind. Applicat.*, May/June, Vol. 40, No. 3, pp.813–820.

[3] Jiang, X., Xing, J., Li, Y. and Lu, Y. (2008) ‘Theoretical and simulation analysis of influences of stator tooth width on cogging torque of BLDC motors’, *IEEE Trans. Magn.*, November, Vol. 45, No. 10, pp.4601–4604.

[4] Lin, D., Ho, S.L. and Fu, W.N. (2009) ‘Analytical prediction of cogging torque in surface-mounted permanent-magnet motors’, September/October, *IEEE Trans. Magn.*, Vol. 45, No. 9, pp. 3296–3302.

[5] M. Arun Noyal Doss., Md. Rizwan and S.Jeevananthan., (2011) “Reduction of cogging torque in PMBLDC motor with reduced stator tooth width and bifurcated surface area using finite element analysis”, International Conference on electrical energy system at SSN, 2011, *pp. 106-110.*

[6] Donmezer, Y., and Ergene, L.T., (2009) ‘Cogging Torque Analysis of Interior-Type Permanent-Magnet Brushless DC Motor Used in Washers’, ELECTROMOTION 2009 – EPE Chapter ‘Electric Drives’ Joint Symposium, July 1-3, Lille, France.

[7] Arun Noyal Doss, M., Ganapathy, V., Marthandan, V., and Mahesh, D., 2013, “Modeling and Simulation of Brushless DC Motor for Minimizing the Cogging torque, Harmonics and Torque Ripples,” International review on modelling and simulation., **6**(5), PART-A, pp. 1452-1457.

[8] C. Breton, J. Bartolome, J.A. Benito, G. Tassinario, I. Flotats, J. Chalmers., (2000) ‘Influence of Machine Symmetry on Reduction of Cogging Torque in Permanent - Magnet Brushless Motors’, IEEE Trans. Mag., vol. 36, no. 5, Part 2, pp. 3819-3823.

[9] T. M. JahnsandW. L. Soong, (1996) ‘Pulsating torque minimization techniquesfor permanent magnet AC motor drives—A review’, *IEEE Trans. Ind. Electron.*, vol. 43, pp. 321–330.

[10] ArunNoyal Doss, M., Saravanan., and Jeevananthan, S., 2011 “Reduction of cogging torque by adopting Semicircled magnets,” International Conference on electrical energy system at SSN, pp. 128-132.

[11] J. R. HendershotJr and T. J. E. Miller, (1994) ‘*Design of Brushless Permanent Magnet Motors*’,. London, U.K.: Oxford Univ. Press.