International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 8, No. 1, March 2017, pp. 297~304
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i1.pp297-304

Reduction in Cogging Torque and Flux per Pole in BLDC Motor by Adapting U-Clamped Magnetic Poles

M. Arun Noyal Doss[1], S. Vijayakumar[2], A. Jamal Mohideen[3], K. Sathiah Kannan[4], N. D. Balaji Sairam[5], K. Karthik[6]
[1-6] Department of EEE, SRM University, Chennai, India

Article Info

Article history:

Received Oct 18, 2016
Revised Dec 24, 2016
Accepted Jan 03, 2017

Keyword:

Cogging torque
Finite element analysis
Permanent magnets (PM)
U-Clamped

ABSTRACT

A Permanent Magnet BLDC motor is designed for reduction in cogging torque and flux per pole. The cogging torque causes direct impact in permanent magnet BLDC motor performance by causing torque ripple problems. This paper proposes a new method for reducing cogging torque by adapting to U-clamped magnetic poles. Finite Element Analysis (FEA) is used to calculate the cogging torque and the flux per pole for different shapes of magnetic pole. It can be shown that the cogging torque could be greatly reduced by adapting to U-clamped magnetic poles. At the same time it is found that the flux per pole is also considerably reduced. The effectiveness of the proposed method is verified by comparing the cogging torque and flux per pole for various designs available in the literature.

Corresponding Author:

M. Arun Noyal Doss,
Department of Electrical and Electronics Engineering,
SRM University,
Chennai, Tamil Nadu, India.
Email: arunnoyal@gmail.com

1. INTRODUCTION

In recent years, permanent-magnet BLDC motors have wide usage in home appliances, automotive field and industrial areas. Some advantages of BLDC motors are their high performance, high ratio of torque/volume, capability for high speed applications, electronic driven commutation etc. With the development of high-performance PM material, PM motors are widely used in speed and position control systems. However, in slotted motors, cogging torque, which may affect the control accuracy, is produced as a result of the interaction between rotor PMs and armature [1]. Thus techniques for reducing cogging torque plays an important role in motor design and many studies have been carried out on the prediction and reduction of cogging torque. In BLDC motors the main undesirable effect is the cogging torque. This torque is an oscillatory torque caused by the permeance variation between stator slots and rotor magnets.

Many methods have been developed to minimize the cogging torque. Some of them are using the shape change of laminations [2]-[3], some are using auxiliary slots and air gap profiles [4]-[5], and other are using skewing the rotor magnets and step skewing using FEA implementation [6]. Further stator slots skewing [7]-[8], adapting to different combination of slot numbers and pole numbers [9] and adapting to Iso-diametric and Semi-circled magnet [1],[10] are some of the other methods used. A FEA method based on a combination of electromagnetic field and circuit equation for magnetic field modelling and torque prediction is presented for decreasing the level of cogging torque for sufficient condition without skewing [11]. In their paper, some core shapes that reduce cogging torque are designed by using genetic algorithm [12]. The radial field topology has been using applied FEM in optimization of PM motors [13]. The predefined slot shape on the pole surface reduces the cogging torque, which is an evolution strategy for the optimal design process to determine the slot size [14]. The computer aided design (CAD) of radial flux surface mounted magnets was easy to fabricate and applied successfully. Hyper-cube sampling strategy is applied to optimize a magnet pole shape of the large scale PM motor. The influences of stator tooth width on cogging torque are analyzed theoretically and experimentally. The Optimization of Two Design Techniques for Cogging Torque Reduction Combined with Analytical Method by a Simple Gradient Descent Method is discussed. The last method is found to be effective, but it limits the choice of the number of slots discussed in.

This paper is being based on Fourier expansion and energy method. An analytical expression of cogging torque is derived, which can be used to evaluate the effects of design parameters on cogging torque. The main idea in this paper is to reduce the cogging torque and to reduce the rate of change of flux density. The test motor is analyzed for different physical parameters and the results are given as normalized to the data that are provided by the manufacturer. FEA is used to calculate the cogging torque and flux per pole for different shapes of magnetic poles. Commercial software which performs 2D FEA Method is used for the numerical analysis part of the problem. The general dimensional view of a BLDC motor is shown below in Figure 1.

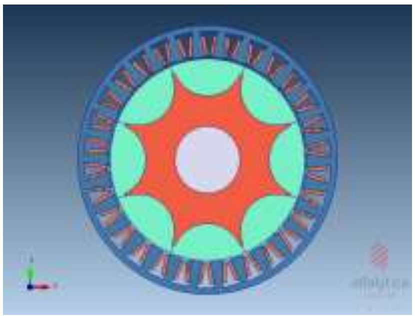


Figure 1. General Dimensional Of BLDC Motor

2. COGGING TORQUE

Cogging torque occurs in PM motors in the air gap between rotor and stator. It is the energy variation within a motor when there is no current in the windings. As the rotor rotates, the reluctance change in the air gap changes, due to the slots creating the cogging torque. While the magnetic flux is going through the rotor to stator, there is a variation in the reluctance. The path of the magnetic flux exists from magnets to rotor, and then follows through air gap and stator; lastly it returns to the magnets. Reluctance of the air gap is different from the air gap in the steel which is used in rotor and stator. The cogging torque can be calculated from the stored energy in the air gap. Since the cogging torque is formed in the air gap as a force, the stored energy in the air gap can be calculated by using the Virtual Work Method (VWM). According to VWM, the cogging torque is given by.

$$T_{cog} = -\frac{\partial w}{\partial \alpha} \tag{1}$$

where, ‘w’ is the stored energy and ‘α’ is the mechanical rotor position. The magnetic flux and stored energy varies for different rotor positions. Since the energy variation in iron is negligible in comparison to that in air and PMs, the magneto static energy can be expressed as follows [1].

$$W = W_{pm+airgap} \frac{1}{2\mu_o} \int_v B^2 \, dv \tag{2}$$

Generally ‘W’ is dependent on the relative position between PMs and slotted armature. At any rotor position *‘α’*, the radial flux density can be described as

$$B(\theta, \alpha) = B_r(\theta) \frac{h_m}{h_m + g(\theta,\alpha)} \tag{3}$$

where, ‘$B_r(\theta)$’ is the distribution of residual flux density of PMs along the circumference of air gap, h_m the length of PM in the magnetization direction and $g(\theta,\alpha)$ is the distribution of air gap length. Thus the magneto static energy can be rewritten as follows [1].

$$W = \frac{1}{2\mu_0}\int_v B_r{}^2 dv \left(\frac{h_m}{h_m+g(\theta,\alpha)}\right)^2 dv \quad (4)$$

where $g(\theta,\alpha)$ and h_m are the effective length of air gap, and the length of PM in magnetizing direction respectively. If the Fourier expressions of $Br^2(\theta)$ and $(h_m/(h_m+g(\theta,\alpha)))^2$ are known, the magneto static energy and cogging torque can be obtained. The Fourier expansions of $Br^2(\theta)$ and $(h_m/(h_m+g(\theta,\alpha)))^2$ can be expressed as shown below.

$$B_r{}^2(\theta) = B_{r0}+\sum_{n=1}^{\infty} B_m cos2np\theta \quad (5)$$

$$\left(\frac{h_m}{h_m+g(\theta,\alpha)}\right)^2 = \mathrm{G_o} + \sum_{n=1}^{\infty} G_n\, cosnz(\theta+\alpha) \quad (6)$$

where p is the number of pole pairs. Substituting (4), (5) and (6) in (1), the cogging torque can be expressed as follows:

$$T_{cog}(\alpha) = \frac{\pi z L_{Fe}}{4\mu 0}(R_2^2 - R_1^2)\sum_{n=1}^{\infty} nG_n B_{r\frac{nz}{2p}}\, sinnz\alpha \quad (7)$$

where L_{Fe} is the axial stack length of armature, R_1 the outer radius of armature, R_2 the inner radius of stator yoke, n the integer that enables $nz/2p$ to be retained as an integer always.

3. ECCENTRIC MAGNET POLES AND COGGING TORQUE FOR VARIOUS SHAPES OF MAGNETIC POLES

It can be seen from (7) that cogging torque is only dependent on Br(nz/2p) if the parameters such as R_1 and R_2 are given. Since Br(nz/2p) is determined by the shape of magnetic poles, the cogging torque can be reduced by adapting suitable shapes of magnetic poles. The shape of the conventional magnetic pole is shown in Figure 2(a). Its inner and the outer contour have the same centre O, and the radial thickness does not change with position. Figures 2(b) and 2(c) show an eccentric magnetic pole for Iso-diametric and Semi-circled magnetic poles. Its inner and outer contours have different centres, i.e. the centre for outer contour is point O while that of the inner contour is point O′. It can be seen that radial thickness of the magnetic pole h_m' changes for different positions. The distance between points O and O' is defined as the eccentric distance h [1],[10]. If h_m is equal to eccentric distance, the magnetic pole is called U-clamped. In this paper, in order to reduce the cogging torque the conventional magnetic, Iso-diametric magnetic poles and Semi-circled magnetic poles are replaced by U-clamped ones. Figure 2(d) shows the U-clamped magnetic pole. In this machine the material used for Stator is CR10 cold rolled steel, for Rotor M43 armature 24 cages, for Permanent magnet it is neodymium ferrite boron (NdF_eB) and for Shaft it is steel. The U-clamped magnet middle part is h_m and the edge is h_m'. It has 8-poles 30 slots, 8-poles 48slots and 8-poles 60 slots and is explained below. The h_m distance is higher than h_m' in semi-circled magnets. The main objective of this method is to demonstrate that cogging torque can be reduced to a generally acceptable level by appropriate selection of motor design. The proposed U-clamped model has been derived from the Semi-circled PM model. For different eccentric distances, the distributions of the radial flux densities are different. If h is zero the expression of $B(\theta)$ can be written as follows:

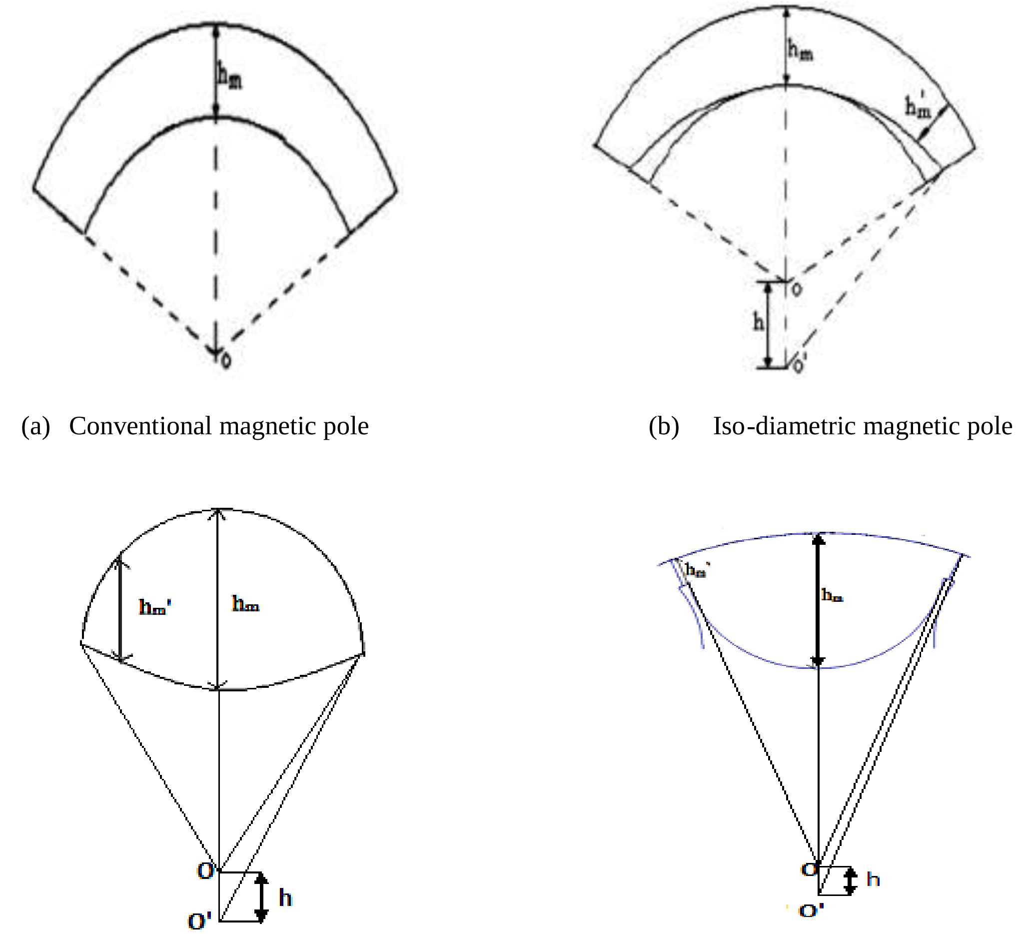
$$B(\theta) = B_r(\theta)\frac{h_m}{h_m+g} \quad (8)$$

If h is not zero, $B(\theta)$ can be obtained as follows

$$B'(\theta) = B_r(\theta)\frac{h_{m'}}{h_{m'}+g'(\theta)} = B_r(\theta)\frac{h_{m'}}{h_m+g(\theta)} = \frac{h_{m'}}{h_m}B_r(\theta)\frac{h_m}{h_m+g(\theta)} = B_{r'}(\theta)\frac{h_m}{h_m+g(\theta)} \quad (9)$$

where h_m' and $g'(\theta)$ are the effective length of PM in magnetization direction and the effective length of air gap with semi circled magnetic pole respectively i.e.,

$$B_{r'}(\theta) = \frac{h_{m'}}{h_m}B_r(\theta) \quad (10)$$



(a) Conventional magnetic pole

(b) Iso-diametric magnetic pole

(c) Semi-circled permanent magnetic pole

(d) U- clamped magnetic pole

Figure 2. Eccentric magnetic pole

Thus the residual flux density $B_r(\theta)$ for motor with an eccentric magnetic pole is equivalent to $B_{r'}(\theta)$ in a motor with a concentric magnetic pole. The Fourier expansions of $B_r'^2(\theta)$ can be expressed in the following form.

$$B_r'^2(\theta) = a_0 + \sum_{n=1}^{\infty}(a_n \cos 2\mathrm{np}\theta) \quad (11)$$

In this paper, an 8-pole prototype motor is studied whose parameters are given in Table I. For simplicity, only the $B_r'^2(\theta)$ under one pole is considered. The Fourier coefficients with different eccentric distances are adapted. It can be seen that most of the Fourier coefficients get reduced with the increment of Eccentric distances, and some Fourier coefficients increase with the increment of eccentric distances. The Fourier coefficients reduce the cogging torque with the increment of eccentric distances. Hence this method is used to reduce the cogging torque effectively.

In addition to the CAD task of specifying the geometry of each object and the process of breaking up the model into a sufficiently refined mesh of FEA is directed. Most FEA systems provide a variety of mesh generation options, ranging from totally automatic to totally user-controlled. A variety of merge and validation options are available in mesh generation. In the FEA method of analysis, the model is divided into a mesh of elements. The mesh analysis is shown in Figure 3. The FEA is the solution of the set of equations for the unknown number of coefficients. In 2D, the elements are shaped like triangles defined by three vertices (nodes). The accuracy of the solution depends upon the nature of the field and the size of the mesh elements.

Table 1. Parameters of prototype

Number of poles	8	Air gap(mm)	1
Outer radius of pole(mm)	76	Width of slot opening(mm)	1.4
Inner radius of rotor (mm)	20	Residual flux density(T)	0.96
Outer radius of rotor(mm)	60	Coercive force(Ka/m)	145.36
Outer radius of stator(mm)	80	Pole arc coefficient	0.7

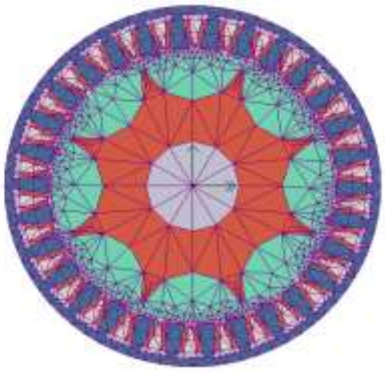


Figure 3. Initial 2D mesh

The primary purpose of electromagnetic FEA is generally to identify regions of intense saturation since these indicate the points through which the flux flows inside the device when the excitation is applied. A concentration of flux lines shows the regions of higher flux density. The contour plot displays the magnetic flux functions as contour lines as shown in Figure 4. The value of the flux function is constant along a contour line so that the contour lines are also magnetic flux lines. Each contour line corresponds to a different magnetic flux line. The difference in value from one line to the next is always the same. The difference in the value of flux functions between two neighbouring contour lines is the amount of flux flowing between the lines. Flux density is the next step involved in the post-processing unit, which depends on the flux function. Flux density plots generally include a colour code key with which the user can interpret the flux density values numerically. Additional information on the numerical values of flux density is available in tabular form for different portions of the device. For static and time-harmonic solutions, any entry in the Flux Linkage page can be graphically represented as shown in Figure 5.

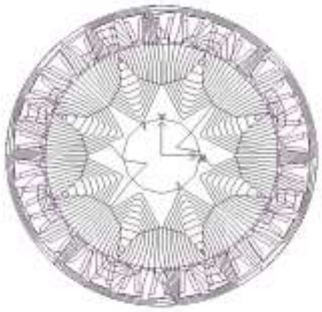


Figure 4. Contour flux function

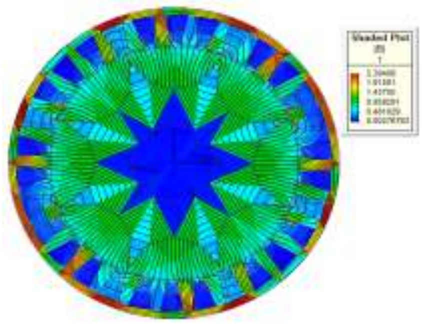


Figure 5. Shaded flux density

4. COGGING TORQUE AND FLUX PER POLE FOR DIFFERENT SHAPES OF MAGNETIC POLES

This section discusses the cogging torque for different shapes of magnetic poles such as conventional, Iso-diametric, Semi-circled and U-clamped magnetic poles. The conventional, Iso-diametric and semi-circled magnetic poles are investigated in the evaluation of cogging torque [1],[10]. In the proposed paper the U-clamped 8-pole machine with three prototypes 30, 48 and 60 slots are analysed and performance comparisons are carried out. In this paper Maxwell tensor method is used to calculate the cogging torque. In

FEA calculations, moving boundary method is used to take into account the relative position between the PMs and rotor armature, and the magnetic field distributions at different relative positions are obtained. In order to perform a comprehensive investigation on the effects of eccentric magnetic poles on the cogging torque, different slot numbers, i.e. 30, 48 and 60 are considered in the prototype motor. For 8-pole 30-slot, 8-pole 48-slot and 8-pole 60-slot PM motor, the Fourier coefficients which have effect on cogging torque are B_{r9k}, B_{r5k} and $B_{r10k.}$ The cogging torque waveforms are shown for U-clamp with 30 and 48 slots in Figure 6. and 60-slots in Figure 7. The cogging torque can change due to the magnet arcs. By adapting the U-clamp magnets the cogging torque has been reduced greatly. Also the flux per pole reduces slightly as the rate of change of flux density reduces which intern results in cogging torque reduction. The rate of change of flux density and eccentricity are compared with the various shapes of magnetic poles. Because the only source is the permanent magnet, the small change in the magnetic arc angle affects the result significantly as expected. In the test motor, the actual magnet arc angle is 79.76°. One degree-change in the magnet arc results in 18% of cogging torque reduction. The cogging torque is largely decreased in a U-clamped 8-pole 60-slot machine. When increasing the number of slots the slot pitch decreases then the widths of slot and tooth also decrease. This may result in reduction in periodicity of magnetic flux, and the rate of change of flux density which depends on the magnetic flux also reduces. The comparison of cogging torque results for various types of magnetic poles is shown in Table 2 and in Figure 8.

When changing the shape of magnetic poles, the cogging torque gets changed. The flux per pole also changes with a non-slotted armature corresponding to different eccentric distances as in [1]. It is shown that the flux per pole is also reduced when U-clamped magnetic pole is adapted. The rate of change of flux density reduces resulting in the reduction of cogging torque. It can be concluded that, by adapting U-clamped magnetic pole, the cogging torque can be reduced considerably while the flux per pole can be decreased marginally, which prove the effectiveness of the method proposed in this paper. Table 3 shows the improvement of efficiency when the cogging torque is reduced.

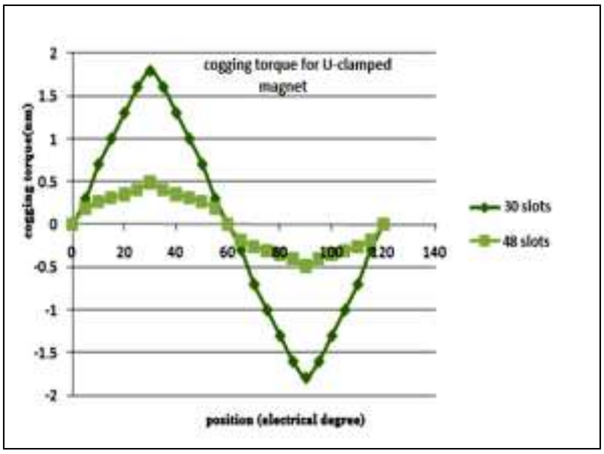


Figure 6. Cogging torque for 30 and 48 slots

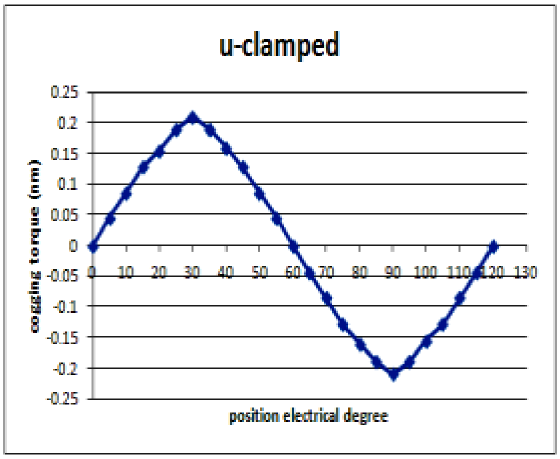


Figure 7. Cogging torque for 8-pole, 60 slot

Table 2. Cogging Torque for Different Magnetic Poles

Magnetic poles	Cogging torque Peak value (Nm)	Percentage to original
Conventional	6.85	100%
Iso-diametric	4.55	33.5%
Semi-circled	2.27	66.86%
U-clamped (30 slots)	1.76	74.30%
U-clamped (48 slots)	0.45	93.43%
U-clamped (60 slots)	0.21	96.93%

Table 3. Comparison of Efficiency and Cogging Torque

Methods	Cogging torque Peak to peak (Nm)	Efficiency
Conventional	6.85	84.26%
Iso-diametric	4.55	89.13%
Semi-circled	2.27	91.86%
U-clamp	0.21	94.67%

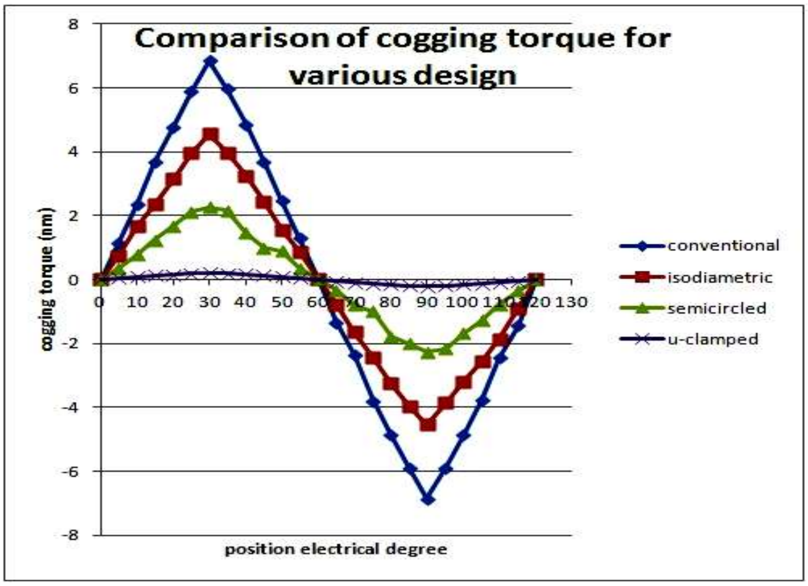


Figure 8. Comparison of Cogging Torque for different model

5. CONCLUSION

A Permanent Magnet BLDC motor is designed to reduce the cogging torque and flux per pole by adapting to a new design namely the introduction of U-clamped magnetic poles. The analytical expression for cogging torque, which can be used to analyze the effects of design parameters qualitatively, is derived in this paper. The comparison has been done with the various shapes of the magnetic poles. Based on this result, the U-clamped magnetic pole is found to have better efficiency compared with the different magnetic poles. Among the three prototypes of U-clamp models, the 60 slot machine is having a better performance, which is proved in this paper. Calculation of cogging torque by FE method proves that the cogging torque has been reduced considerably by adapting to U-clamped magnetic pole, in which the flux per pole also gets reduced a little, which validates the effectiveness of the proposed processing method.

REFERENCES

[1] M. S. Islam, *et al.*, "Issues in Reducing the Cogging Torque of Mass-Produced Permanent-Magnet Brushless DC Motor," *IEEE Trans. Ind. Applicat.*, vol. 40, pp. 813-820, 2004.
[2] J. Mostafapour, *et al.*, "Improved Rotor Speed Brushless DC Motor using Fuzzy Controller," *Indonesian Journal of Electrical Engineering and Informatics*, vol/issue: 4(1), pp.78-88, 2016.
[3] H. Mirzaei, *et al.*. "Commutation Comparison of Direct Torque Control of BLDC Motor with Minimum Torque Ripple in Four- and Six-Switch Inverters," *International Review of Electrical Engineering (IREE)*, vol/issue: 8(3), pp. 971-980, 2013.
[4] Y. Yang, *et al.*, "*Reducing Cogging Torque by Adapting Isodiametric Permanent Magnet*," IEEE proc-electro, 2009.
[5] S. Saravanan, *et al.*, "Reduction of cogging torque by adapting semicircled permanent magnet," *ICEES*, 2011.
[6] D. Wang, *et al.*, "Integrated Optimization of Two Design Techniques for Cogging Torque Reduction Combined With Analytical Method by a Simple Gradient Descent Method," *IEEE Trans. Magn.*, vol/issue: 48(8), pp. 2265–2276, 2012.
[7] K. J. Hua, *et al.*, "Optimal core shape design for cogging torque reduction of brushless DC motor using genetic algorithm," *IEEE Trans. Magnetics*, vol/issue: 36(4), pp. 1927 -1931, 2000.
[8] T. Sutikno, *et al.*, "High-Speed Computation using FPGA for Excellent Performance of Direct Torque Control of Induction Machines," *TELKOMNIKA*, vol/issue: 14(1), pp 1-3, 2016.
[9] T. K. Chung, *et al.*, "Optimal pole shape design for the reduction of cogging torque of brushless DC motor using evolution strategy," *IEEE Trans. Magnetics*, vol/issue: 33(2), pp.1908-1911, 1997.
[10] P. R. Upadhyay and K. R. Rajagopal, "FE Analysis and CAD of Radial-Flux Surface Mounted Permanent Magnet Brushless DC Motors," *IEEE Trans. Magn.*,vol. 41, pp. 3952–3954, 2005.
[11] R. N. F. R. Othman, *et al.*, "Design of Hollow-Rotor Brushless DC Motor," *International Journal of Power Electronics and Drive Systems*, vol/issue: 7(2), 2016.
[12] J. Xintong, *et al.*, "Theoretical and Simulation Analysis of Influences of Stator Tooth Width on Cogging Torque of BLDC Motors," *IEEE Trans. Magn.*, vol/issue: 45(10), pp. 4601–4604, 2008.

[13] D. Lin, *et al.*, "Analytical Prediction of Cogging Torque in Surface-Mounted Permanent-Magnet Motors," *IEEE Trans. Magn.*, vol. 45, pp. 3296–3302, 2009.
[14] M. Fazil and K. R. Rajagopal, "Nonlinear Dynamic Modeling of a Single-Phase Permanent-Magnet Brushless DC Motor Using 2-D Static Finite-Element Results," *IEEE Trans. Magn*., vol/issue: 47(4), pp. 781–786, 2011.

BIOGRAPHIES OF AUTHORS

M. Arun Noyal Doss was born in India in 1982. He received his B.E degree in electrical engineering from Madras University in 2004, and the M.E degree in Power Electronics and Drives from Anna University in 2006 and PhD in electrical engineering from SRM University in 2014 and currently working as assistant professor in SRM University. His area of interest includes Power Electronics and Special Machines.

S. Vijaya Kumar was born in 1989. He completed his diploma in EEE from Board of technical education Tamilnadu, India at 2010. Doing his B.Tech in EEE by SRM university. Currently Working as associate in FORD IND PVT LTD. Area interested in power system operation and control.

A. Jamal Moideen was born in 1990. He completed his diploma in EEE from Board of technical education Tamilnadu, india. Doing his B.Tech in EEE by SRM university. Currently Working as associate in FORD IND PVT LTD.

K. Sathish Kannan was born in 1992. He completed his diploma in EEE from Board of technical education Tamilnadu, india. Doing his B.Tech in EEE by SRM university. Area interested in Switch and protection.

N. D. Balaji Sairam He completed his diploma in EEE from Board of technical education Tamilnadu, India at 2010. Doing his B.Tech in EEE by SRM university. Currently Working as associate in FORD IND PVT LTD. Area interested in power electronics and electrical Special machines design.

K. Karthik received his B.E degree in Electrical and Electronics Engineering from Anna University in 2012 and he is currently pursuing M.Tech in Power Electronics and Drives at SRM University. His areas of interests include Electrical machines, Power Electronics and Drives and his current research work is in designing Power Factor correction converter for BLDC motor drive