A Study of Cogging Torque Reduction Methods in Brushless DC Motor

Teeradej Srisiriwanna[1] and **Mongkol Konghirun**[2], Non-members

ABSTRACT

The cogging torque is undesirable effect in the brushless dc (BLDC) motor, causing vibration and audible noises. It arises from the rotor permanent magnet interacting with the steel teeth on the stator. This paper studies the various reduction methods of cogging torque when designing a BLDC motor. These methods can be categorized according to three parts of motor structure, i.e., air gap length, rotor and stator parts. The finite element method magnetic (FEMM) is primarily used to analyze the cogging torque among these different reduction methods. In this paper, a 4-pole, 24-slot BLDC motor is focused with variations of air gap length, rotor, and stator parts in order to study its cogging torque reductions. Finally, the FEMM simulation results are presented to validate these reduction methods.

Keywords: Brushless DC Motor, Finite-Element Method Magnetic, Cogging Torque

1. INTRODUCTION

During the past few years, the brushless dc (BLDC) motor has been becoming popular in industrial applications such as air conditioners and blowers as the high efficiency is concerned. It also offers compact size, comparing with the same rating of induction motor. As its overall cost continued to decrease, it has the great opportunity to become a dominant force in the market of abovementioned industrial applications [1]. Unfortunately, one of main disadvantages of BLDC motor is the cogging torque, causing the undesirable effects to the motor, i.e., vibration and audible noises. The cogging torque arises from the rotor permanent magnet interacting with the steel teeth on the stator. It exists even there is no stator current flowing into the stator windings. Basically, it is caused by an uneven air-gap permeance resulting in the magnets constantly seeking a position of minimum reluctance. In a well-designed BLDC motor, the cogging torque should be minimized [2]. There is a number of reduction methods of cogging torques while designing a BLDC motor such as increase of air

gap length, larger number of slots/pole, thicker tooth tips to prevent saturation, minimizing slot opening, magnetic slot-wedge usage, magnet skewing, magnet pole shaping, addition of dummy slots, and lower magnet flux density[1]-[4].

The objective of this paper is to present the comparison of five methods for cogging torque reduction by means of analysis of finite element method. The air-gap length adjustment, slot opening, number of slots/pole, magnet flux-density and dummy stator slots are adjusted in order to see the effects of cogging torque reductions.

2. COGGING TORQUE REDUCTION METHODS

In [1], the cogging torque equation has been derived as

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

Where θ_g is the air-gap flux, R is the air gap reluctance and θ is the rotor position. In this section, the cogging torque reductions in each part of motor structure can be separately explained as follows.

2.1 Air-gap length [2]

The distance between rotor and stator refers to air-gap length. The air-gap length may be varied according to the size of motor. In [2], the suggested air-gap length range for very small motor, medium size motor, and large motor are 0.12-0.25mm, 0.38-0.5mm, and0.63-0.88mm, respectively. The cogging torque can be simply reduced by means of increasing air-gap length, resulting in lowering the dR/dθ in (1), thereby reducing the cogging torque. However, when increasing air-gap length, its reluctance is increased. As a result, the ϕ_g is finally lowered. In turn, the cogging torque is lowered as well. To keep the same permeance coefficient at operating point in the demagnetization curve, the magnet width is required to be increased to keep the ϕ_g constant.

2.2 Rotor structure [1]

In this part, there are three methods related to the permanent magnet that can reduce the cogging torque as follows:

• Magnet pole shaping. The rate of change in air gap flux density at magnet edges has effect on cogging torque. Generally, this method can reduce the

cogging torque by designing either magnet width or magnet length decreased. In this method, the desired torque decreases because less magnet flux is available to the stator winding.

• Skewing. This method is basically making the $dR/d\theta$ zero over of each magnet face. In theory, the cogging torque can be completely eliminated. In reality, it may not perfectly reach zero, but be significantly reduced. Skewing can be implemented on either the magnets or the slots. Both have disadvantages. Skewing the magnets increases the magnet cost. Skewing the slots increases the copper losses due to increased slot length, resulting in the longer wire.

• Lowering magnet flux density. Referring to (1), the cogging torque can be simply reduced by decreasing the air-gap flux. Thus, the lowering the magnet flux density by changing the magnet grades, directly reduces the air-gap flux.

2.3 Stator Structure [2]

In this part, there are four methods related to the stator structure that can reduce the cogging torque as follows:

• Proper thickness of stator tooth tips. If these stator tooth tips are too thin, then they are likely subject to magnetic saturation, increasing the cogging torque. The thickness of tooth tips should be the same width of slot opening.

• Slot opening. The width of slot opening affect to the cogging torque. Reducing the width of slot opening to reduce permeance variation between teeth of stator, the cogging torque will decrease as well.

• Increasing the number of slots/pole. When the number of slots/pole is close to 1, the number of slot becomes more important. Increasing the number of slots affects the decreasing cogging torque.

• Addition of dummy slots. It makes the bifurcate teeth in the tooth overhang to modulate the permeance variation to reduce the cogging torque. It has similar effect as the double number of slots. In this case, the cogging torque frequency would be double.

• Adding magnetic slot wedges. The stator slot openings are closed by wedges made soft magnetic composite materials. The effect of this cogging torque reduction method is similar to that of the minimizing slot opening between the teeth.

3. FINITE ELEMENT ANALYSIS [5]

The fundamental physical equations that describe the electromagnetic fields are given by Maxwell's equations as

$$\nabla . B = 0 \tag{2}$$

$$\nabla \times E = -\frac{dB}{dt} \tag{3}$$

$$\nabla \times H = J \tag{4}$$

Equations (2)-(4) are presented in terms of vector field variables E, B and H, but these equations are usually solved by using vector potential formulation.

The magnetic vector field B can be written in term of the vector potential as:

$$B = \nabla \times A \tag{5}$$

Also, the relationship between H and B is expressed as follow:

$$H = r.B \tag{6}$$

Vector potential equation for magnetic field is obtained by substituting equations (5) and (6) in equation (4), yields

$$\nabla \times (r.\nabla \times A) = J \tag{7}$$

To numerically solve equation (7), the finite element method is used. In this paper, the open source software FEMM version 4.2 is employed. This software is able to solve two-dimensional partial differential equations.
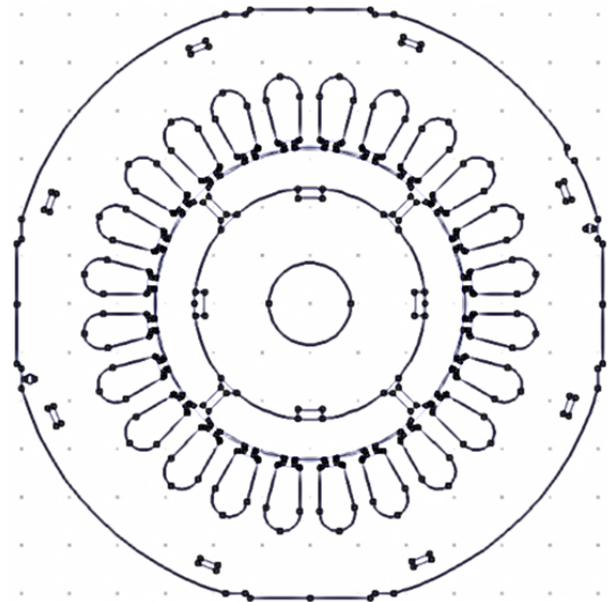

Fig.1: *Modeling4pole/24slots BLDC motor by FEMM.*

3.1 FEMM modelling though LUA script

The FEMM also supports LUA scripting language. The LUA scripted library can be used to draw the
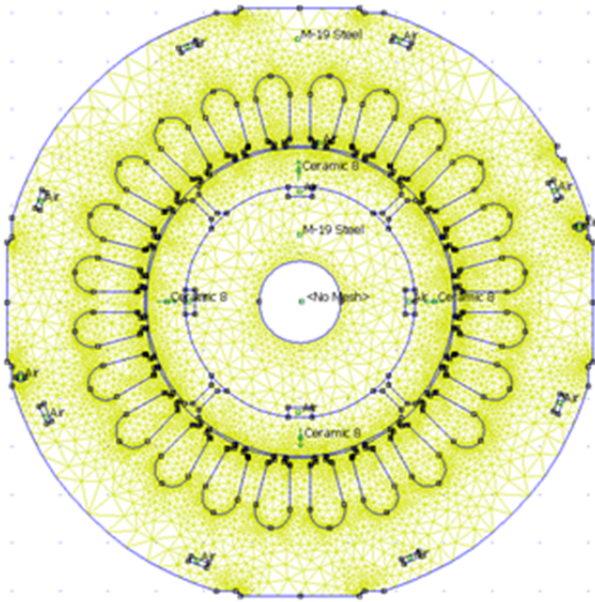
Fig.2: *FEMM mesh of BLDC motor.*

layout of the BLDC motor in FEMM through the process of drawing as shown in Fig.1. All motor parameters can also be specified in the LUA script.

After modelling, meshing of finite elements will solve problem differential equation in modelling of BLDC motor. The meshing yields approximately 30,000 nodes and 50,000 elements. To improve the accuracy of cogging torque calculations, the meshing around the arcs and corners has to be higher resolution as shown in Fig.2.

It is a well know fact that by increasing the meshing resolution, a higher accuracy in estimation can be reached but only to a certain extent. Where by the increase of meshing nodes of 20,000 to 140,000 produces an increase in accuracy of approximately 0.2%.[6]

3.2 Simulation steps

In the simulation, the model can be drawn in FEMM software or imported as an AutoCAD file. The material and mechanical properties are specified by setting the LUA script. The domain is meshed and the boundary conditions are determined by user. The software uses a triangular element to mesh the domain and linear functions to approximate the solution. There are approximately 35,000 nodes for entire BLDC motor model. After setting the meshing, the cogging torque for the initial rotor position is calculated by using the weighted stress tensor method. A flowchart of FEMM simulation is provided in Fig.3.

The meshing process and cogging torque calculation are performed before the rotor position is increased by a certain degree. These processes are repeated and results are recorded at each incremental
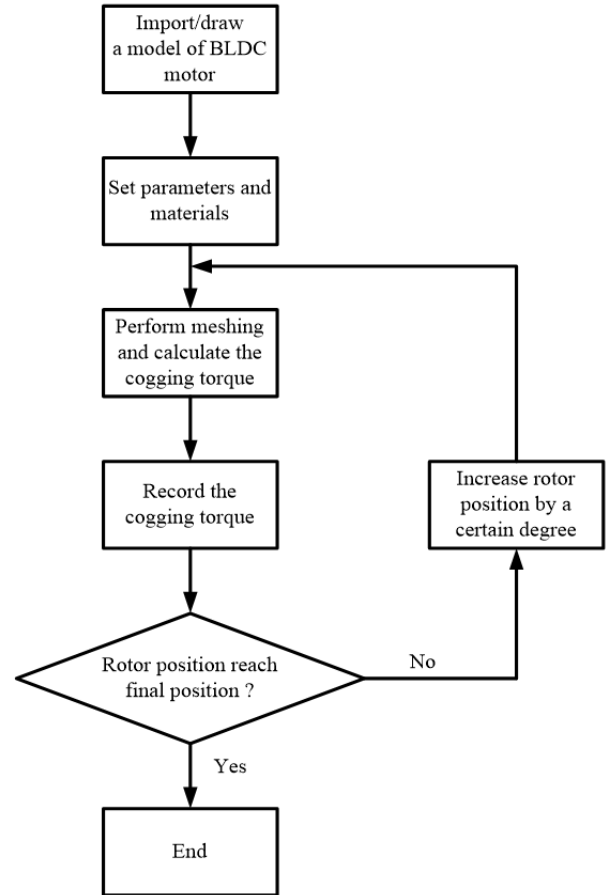

Fig.3: *Simulation steps on cogging torque calculation.*

rotor position until the final rotor position is reached. In this paper, the FEMM simulation is finished at 45 degree. The flux distribution of a 4-pole, 24-slot BLDC motors is shown in Fig.4.

4. SIMULATION RESULTS

In this paper, a4-pole, 24-slot BLDC motor is used as reference design. Its specifications and materials are given in Tables 1 and 2, respectively.

This section discusses the simulation results of three main methods for reducing the cogging torque of this reference design of BLDC motor. Firstly, the simulation results of reduced cogging torque by means of the air-gap length from 0.5 mm to 0.8 mm is shown in Fig.5. As expected, the increase of air-gap length results in the reduction of cogging torque. The cogging torque is reduced due to lowering the $dR/d\theta$ and the ϕ_g. In this Fig., the cogging torque waveform is repeated every 15 mechanical degree per slot. Secondly, the reduction of cogging torque in terms of rotor structure by lowering magnet flux density is studied. Three magnet grades are selected as shown in Table 3. Clearly, the cogging torque is reduced when using the magnet with lower flux density (or lower grade) as seen in Fig.6. The peaks of cogging torque
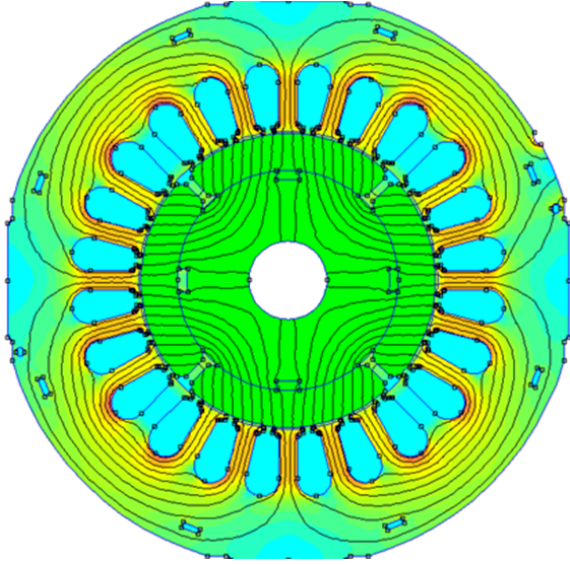
Fig.4: *Flux distribution of 4-pole, 24-slot BLDC motor.*

Table 1: *Specifications of reference BLDC motor.*

Name	Rating Values	Unit
Rated Power	1	kW
Rated Voltage	220	V
Number of Poles	4	-
Rated Speed	1500	rpm
Number of Stator Slots	24	-
Outer Diameter of Stator	125	mm
Inner Diameter of Stator	65	mm
Minimum Air Gap	0.5	mm
Inner Diameter of rotor	48	mm
Length of Rotor	40	mm
Thickness of Magnet	8	mm
Slots opening	2	mm
Width of teeth	6	mm

Table 2: *Materials of Reference BLDC motor.*

Type	Material
Stator	M-19 Steel
Rotor	M-19 Steel
Magnet	Ceramic 8

for NdFeB40MGOe, SmCo27MGOe, and Ceramic8 are 0.66 N.m, 0.28N.m, and 0.03 N.m, respectively. Thirdly, the reduction of cogging torque in terms of stator structure by lowering slot opening, increasing slot/pole, and use of dummy slots are evaluated. In Fig. 7, the slot opening is reduced from 2 mm to 1 mm, resulting in the reduced peak of cogging torque from 0.033N.m to 0.015Nm. Basically, this method is significantly decreasing the cogging torque by lowering the variation of reluctance between teeth. Next, the number of slot per pole is increased from total

slots of 24 to 36 with the same dimensional 4-pole BLDC motor as shown in Fig. 8. When slot per pole is increased, the slot opening is actually reducing to 0.8 mm with 36-slot. The cogging torque is obviously reduced as shown in Fig. 9. The frequency of cogging torque is also increased according to increase of the slots per pole. Next, the study of dummy slots added on the stator tooth is performed. Three different stator teeth with dummy slots are shown in Fig. 10. The widths of one and two dummy slot per stator tooth are 2 mm (same as slot opening) and 1 mm, respectively. Its simulation result of cogging torque is shown in Fig.11. According to this result, the peak of cogging torque would not be obviously different while the frequency of cogging torque is increased as dummy slots increased. Since the number of 24 total slots is quite high, this method may not be effective for this particular reference BLDC motor than any other BLDC motor with low number of total slots.
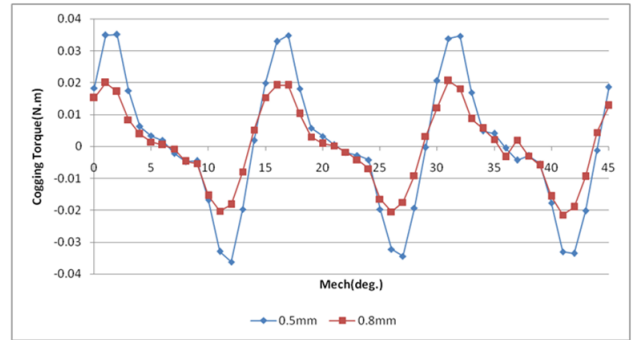

Fig.5: *Cogging torque waveforms with air-gap length 0.5mm and 0.8mm.*

Table 3: *Type of Magnets.*

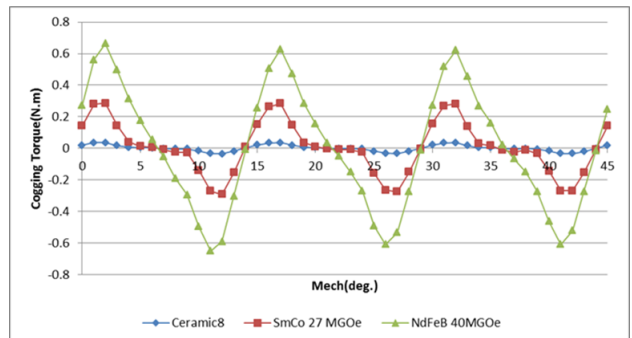| Type of Magnet	Flux Density(T)
NdFeB 40 MGOe	1.290
SmCo 27 MGOe	1.070
Ceramic 8	0.391

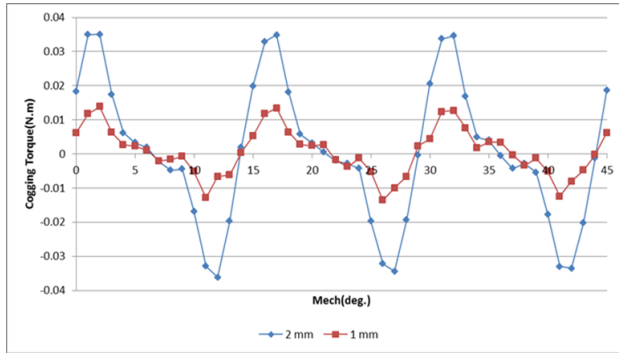**Fig.6:** *Cogging torque waveforms among three magnet types.*

Fig.7: *Cogging torque waveforms with slot opening of 2 mm and 1 mm.*
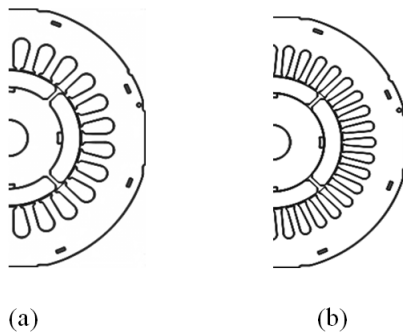

Fig.8: *Half structure of BLDC motor with total slots of (a) 24and (b) 36.*
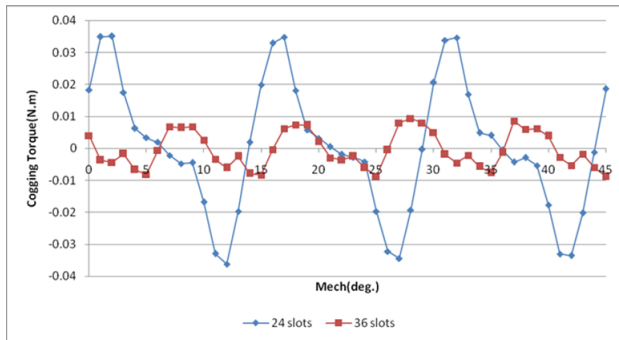

Fig.9: *Cogging torque waveforms with 24-slots and36-slots.*
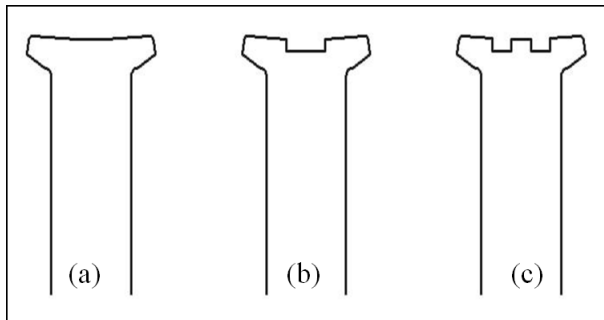

Fig.10: *Stator teeth (a) reference design (b) one dummy slot per tooth and (c) two dummy slots per tooth.*
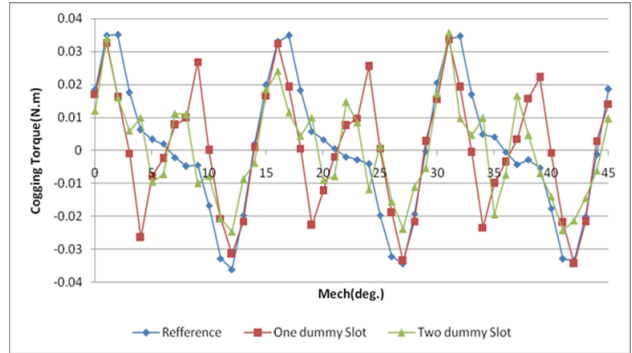

Fig.11: *Cogging torque waveforms with adding dummy slot method.*

In case of lower number of slots, e.g., 4-pole, 12-slot BLDC motor as shown in Fig. 12, the dummy slot method is then studied to reduce cogging torque. The number of slot per pole is now decreased from 6 to 3with the same dimensional 4-pole BLDC motor. The width of teeth and slot opening is 8.52 mm and 2.84 mm, respectively. The simulation result of cogging torque waveforms without adding dummy slots is shown in Fig.13.It is expected that the cogging torque of 12-slot BLDC motor is higher than 24-slot BLDC motor.
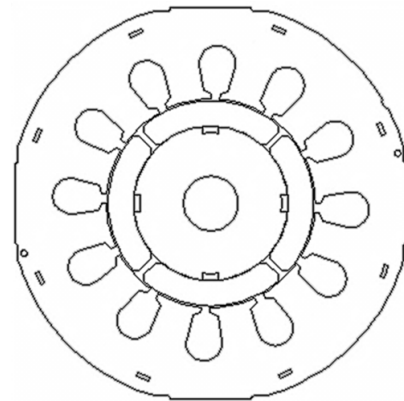

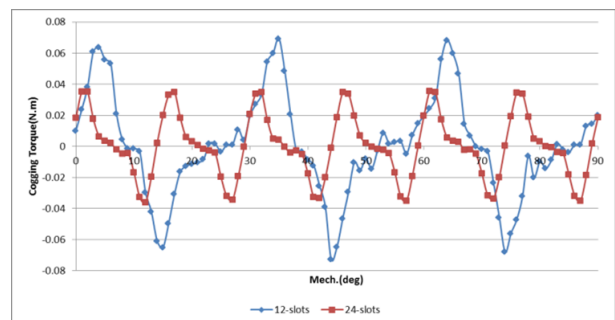**Fig.12:** *Modeling4-pole, 12-slots BLDC motor.*

Fig.13: *Cogging torque waveforms with 24-slots and 12-slots.*

Next, the 12-slot BLDC motor adds two dummy slots per tooth. The width of dummy slot is 2.84 mm (same as slot opening). The depth of dummy slot is 1.5 mm (same as depth of shoe).The distance between dummy slots is 2.84 mm (same as slot opening). The dummy slot structure is shown in Fig.14 and the modeling of this 4-pole, 12-slot BLDC motor is shown in Fig.15.Its simulation result of cogging torque is shown in Fig.16. It is evident that the peak of cogging torque would be significantly decreasedand the frequency of cogging torque is increased as the dummy slots increased.
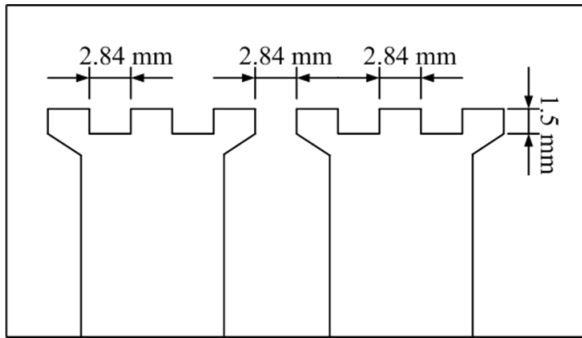

Fig.14: *Dimension of dummy slots on 4-pole, 12-slot BLDC motor.*
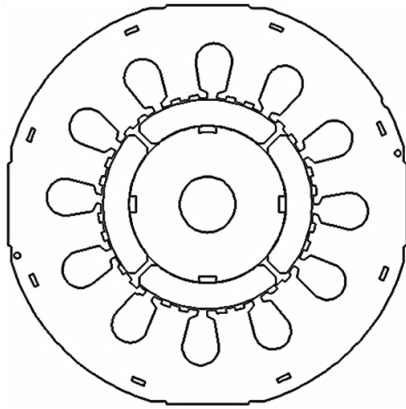

Fig.15: *Modeling4-pole, 12-slots BLDC motor with 2 dummy slots per tooth.*

Next, the variations of depth of dummy slot are simulated. In case of 12-slot BLDC motor which has cogging torque effects on the dummy slots, the depth of dummy slots is varied by three dimensions, i.e., 0.5, 1.5, and 2mm.The width of dummy slots is 2.84mm (same as slot opening). Cogging torque waveforms for 4-pole, 12-slot BLDC motor with variations of depth of dummy slots is shown in Fig. 17. The peak of cogging torque at depth of1.5mm is 0.02N.m.When adjusting the depth of dummy slots to 2 mm, the cogging torque waveform is similar one of 1.5mmdepth of dummy slots. In case of the 0.5mm depth of dummy slot, the peak of cogging torque is higher than one of
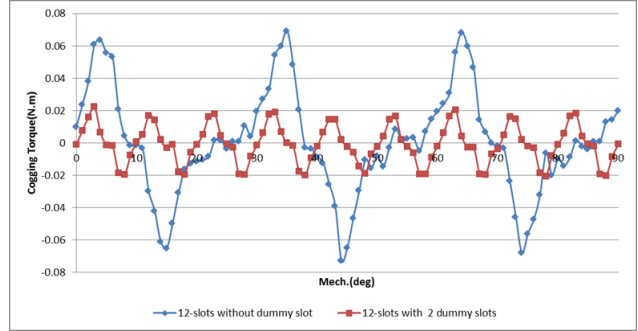

Fig.16: *Cogging torque waveforms for 12-slot BLDC motor without dummy slot and 12-slotBLDC motor with 2 dummy slots per tooth.*

at 1.5 or 2.0 mm depth of dummy slots. It is clearly shown that the designing depth of dummy slot should be equal to the depth of shoe (i.e., 1.5 mm). By increasing the depth of dummy slot being 2mm, the peak of cogging torque is not reduced.
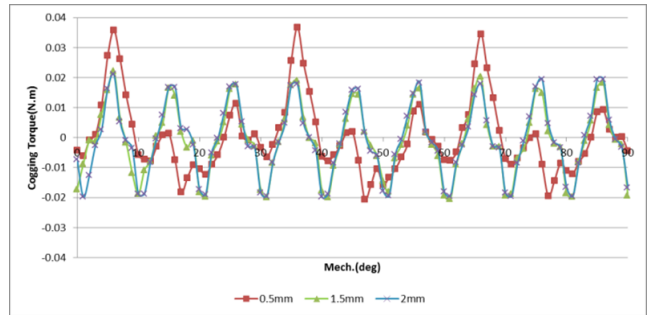

Fig.17: *Cogging torque waveforms for 12-slot BLDC motor with variations of depth of dummy slots.*

5. CONCLUSION

The cogging torque reduction methods have been studied through FEMM simulations in this paper. The results of the cogging torque reduction achieved by decreasing the width of slot opening from 2 mm to 1 and 0.8 mm, reducing the cogging torque by 57 and 77 percent, respectively. In this method, the cogging torque is effectively reduced more than any other method. As for the methods of reducing magnet flux density and increasing air-gap length, the performance of BLDC motor is lowered because the magnet flux level is decreased. Otherwise, to keep performance, the width of magnet has to be increased such that the magnetic operating point in demagnetization curve remains the same. In case of adding dummy slots in structure with many slots, it may not significantly affect the cogging torque reduction because the ratio of the width of dummy slot should be same as the width of slot opening. Thus, this method may not be suitable for structures with many slots, say 24 slots. In the designing BLDC motor with less

slots (e.g., 12 slots), the cogging torque could be reduced by means of dummy slots and depth of dummy slot.

References

[1] D.Hanselman, "Brushless Permanent-Magnet Motor Design." New York: McGraw-Hill, 1994

[2] J.R.HendershotJr, TJE Miller, "Design of Brushless Permanent-Magnet Motors" Oxford: CLARENDON, 1994

[3] N. Bianchi and S. Bolognani, "Design techniques for reducing the cogging torque in surface-mounted PM motors," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1259–1265, Sep./Oct. 2002.

[4] T. Li and G. Slemon, "Reduction of cogging torque in permanent magnet motors," *IEEE Trans. Magn.*, vol. 24, no. 6, pp. 2901–2903, Nov.1988.

[5] David Meeker,"Finite Element Method Magnetics." *User's Manual*: Oct 16, 2010.

[6] Paul Lefley, LidijaPetkovska, Saeed Ahmed, and GogaCvetkovski, "Finite Element Analysis of a Novel Single Phase Permanent Magnet Brushless DC Motor," *Power Electronics and Motion Control Conference (EPE/PEMC)*, 2010 14th International, Page(s): T4-96-T4-101.

Teeradej Srisiriwanna was born in Bangkok, Thailand. He got bachelor's degree from King Mongkut's University of Technology North Bangkok in 2007. He is currently studying a master's degree in in electrical engineering at King Mongkut's University of Technology Thonburi. His research interests motor drive.

Mongkol Konghirun received a B.Eng in Electrical Engineering from King Mongkut's University of Technology Thonburi, Thailand in 1995. And he received M.Sc. and Ph.D. degrees in Electrical Engineering from the Ohio State University, USA in 1999 and 2003, respectively. Presently, he is an Assistant Professor at department of Electrical Engineering, King Mongkut's University of Technology Thonburi. His research interests include electric motor drives and renewable energy.