Brushless Direct Current Electric Motor Design with Minimum Cogging Torque

Muhammad Nizam
Mechanical Engineering, Post Graduate Program
Sebelas Maret University
Surakarta, Indonesia
nizam_kh@ieee.org

Hery Tri Waloyo
Mechanical Engineering, Post Graduate Program
Sebelas Maret University
Surakarta, Indonesia
hery.tw@student.uns.ac.id

Inayati
Chemical Engineering Department
Sebelas Maret University,
Surakarta, Indonesia
inayati_stmt@yahoo.com

***Abstract*— Cogging torque is one of the factors that influence electric motor efficiency. Many methods have been used to reduce the cogging torque. One of the methods is the determination of the number of slots and poles fraction. This study was intended to determine the number of slots and poles fraction to get a minimum of cogging torque. Research was done by ANSYS software. By varying the number of slots and poles, the data cogging torque and torque ripple were observed. It was found that the lesser difference between the number of slots and poles produced lower cogging torque. More numbers of slots would reduce the cogging torque. The smallest cogging torque was produced at difference in the number of slots and poles of 1 and 2. For slots more than four, the cogging torque produced were irregular.**

Keywords*— *design; cogging torque; brushless motor;

I. Introduction

Brushless Direct current Electric Motor (BLDC motor) is widely used in various fields and intended to replace conventional brushed motor. It is supported by the development of nano particles, electromagnetic materials, technology switching and in particular to support the very high-speed switching process [1]. BLDC motor works without using brushes to produce a commutation effect and so it has many advantages, such as do not require periodic treatments because of the absence of noise, minimizing carbon snarled, no arising of sparks. The researches of the electric motors are much highlighted by researchers in the field of transportation. Electric motors demand for vehicles are high to replace fossil fuels based vehicles [2]. In transportation, BLDC motors are required to have high torque required to fulfill the energy needs against the vehicles traction. In practice, the usage of three-phase BLDC motor is preferred compared to single phase because it does not have a dead point.

Designing a BLDC motors need to pay attention to some aspects and the most important is its efficiency. One factor which affecting its efficiency is the existence of cogging torque. Large cogging torque causes vibration and noise which reduces the efficiency. Axial motor with variation on the number of poles will affect the asymmetry of the back-EMF, cogging torque, torque and reduce the electromagnetic torque ripple [3]. Adding an additional gap can reduce cogging torque and electromagnetic torque ripple. After reaching a maximum gap addition, the cogging torque will be at steady state [4].

Calculation and simulation are needed to design a motor with minimum cogging torque. Methods that are widely used in process analysis and engineering is the Finite Element method (FEM). FEM can be applied in process analysis including construction, structure, thermodynamics, heat transfer, and fluid. Wide application areas can be analyzed using this method, thus it can be said that the FEM can be applied to any engineering analysis [5]. The development of computing and programming contributed to the increasing of field that can be solved [8]. FEM is effective to solve complex geometry, where the usual solution to the ordinary derivative equation cannot provide a solution [9]. Complex issue of boundary value problems on a single dimension or two dimensions or even three dimensions can be solved with better [10]. Simulation to initiate the design process can be performed by using 2D or 3D. For the initial design of the limited parameters used 2D simulations. More detail simulation can be done using 3D simulation. A disadvantage of 3D simulation is time consuming and simulation tools used are very complex [11,12].

II. Basic Theory

A. DC motor

DC Motor is composed of rotating part or rotor and fixed part or stator. Stator has fixed pole that is generated by permanent magnets or coils. Rotor produces rotates magnetic field by a coil and core or armature. An electric current flows in the rotor from the voltage source by using a brush which is usually made from carbon materials. Carbon brush form mechanically contact, connected to the copper link at the end of the rotor. Commutators are copper connector that connected to the coils of the rotor. In a rotation, carbon brush moves from one copper segment to the next forming current flow. Poles difference direction will cause the force acting on the rotor at tangential direction and affects the amount of torque produced.

B. BLDC motor

BLDC motors can be classified as synchronous motor. The rotational speed of its rotor is equal to the change in the magnetic polarization. In BLDC motor, pole change was done on the stator component. Its stator consists of coils and cores. Rotor is static magnets, which are generated by permanent magnets. The position sensor is used to find out the position of the motor poles. Inverter is used to regulate the amount of current should be provided. Semiconductor switches are used to get the effect of pole change. BLDC Motor used in this paper was a motor with three phase electricity. To get a good power, Y electrical circuit type was used. Electrical interaction can be simply modeled by the equation 1-4.

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \quad (1)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c. \quad (2)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \quad (3)$$

$$T_e = k_f\omega_m + J\frac{d\omega_m}{dt} + T_L. \quad (4)$$

Where v, i and e states inter-phase voltage, phase current and phase back-emf, which are in three phases named a, b and c. Electrical resistance is symbolized by R and L is the inductance. T_e and T_L are the electrical torque and load torque. J is the inertia of the rotor, the friction constants is k_f states, and ω_m is the rotor speed. Back-emf and torque can be calculated using equation 5-8.

$$e_a = \frac{k_e}{2}\omega_m F(\Theta_e) \quad (5)$$

$$e_b = \frac{k_e}{2}\omega_m F(\Theta_e - \frac{2\pi}{3}) \quad (6)$$

$$e_c = \frac{k_e}{2}\omega_m F(\Theta_e - \frac{4\pi}{3}) \quad (7)$$

$$T_e = \frac{k_t}{2}\left[F(\Theta_e)i_a + F(\Theta_e - \frac{2\pi}{3})i_b + F(\Theta_e - \frac{4\pi}{3})i_c\right] \quad (8)$$

C. Location of Permanent Magnet

Based on the arrangement of the rotor and stator, BLDC motors [6] are divided into two types, i.e, inner rotor and outer rotor. Each type has its advantages (fig.1). In inner rotor, heat dissipation process is easier because the stator coils are placed at outside. In outer rotor, coil stator is protected from the dangers that come from outside.

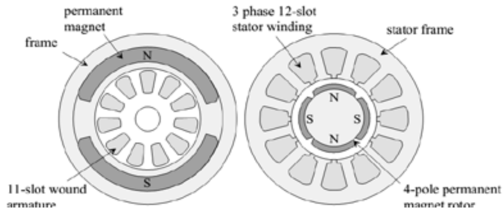

Fig. 1. Brushless slot-pole structure a) Outer rotor b) Innerrotor

Conventional motors using brushes have been widely abandoned due to its draw backs. BLDC motors have some advantages compared to the brushed motor such as better speed-torque characteristic, high dynamic response and efficiency, longer life time, minimum noise during greater snd its speed range[7].

D. Cogging Torque

Cogging torque is a force resulted from the interaction between the rotor and stator. During switching process by semiconductors, there are conditions where there is no current flowing in the stator. Cogging torque is not very desirable, especially at low speeds. At high speed, the impact of the cogging torque is dispensed by the moment of inertia of the motor. Cogging torque greatly affects the performance of BLDC motors because it can cause speed ripple and vibration. Cogging torque can only be minimized because in practice it is not possible to eliminate its existence. Cogging torque is closely related to the flux density so that the cogging reduction also reduces flux density.

The existence of the cogging torque can be minimized by several methods such as with skewing stator stack or magnets, fractional slots per pole, modulating drive current waveform, optimizing the magnet pole arc or width. Most methods for reducing cogging torque also resulted in reducing the power electromotive which consequently reduces the total torque that can be generated [7].

III. METHODOLOGY

A. Design of Study

Research was carried out by using ANSYS software. This study was aimed to observe the effect of the number of slots and poles of the cogging torque generated. Simulation was started by determining the variation of the number of slots and poles. Then, it was followed by setting the fraction of the number of slots and poles. Variation of the difference of one to four run, then cogging torque was examined for each variation. Finally, the torque ripple, which was influenced by cogging torque, was analyzed and it was varied at minimal cogging torque value.

B. Equipment and Materials

Research was done by the software, to model the electric motor related specified parameters. BLDC motors used in the simulation is three-phase. Variables of this research were the number of stator slots and poles. Parameters of the motor used in this study are shown in table I.

TABLE I. GLOBAL PARAMETER DESIGN

Parameter	Value	Unit
Rate Voltage	72	Volt
Rate Speed	1500	rpm
Rated Power	550	watt
Diameter luar stator	200	mm
Diameter dalam stator	100	mm
Diameter luar rotor	99	mm
Diameter dalam rotor	20	mm

Important parameter in designing stator slots is the shape of the stator. Fig. 2 shows the shape of the stator slot shape used in this study while table II presents the parameters of the slot.

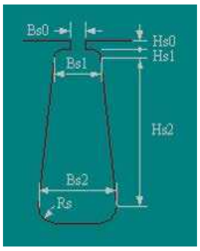

Fig. 2. Stator slot structure

TABLE II. STATOR SLOT PARAMETER

Parameter	Value	Unit
Hs0	1.3	mm
Hs1	2	mm
Hs2	25	mm
Bs0	0.5	mm
Bs1	10	mm
Bs2	18	mm
Rs	3	mm

IV. SIMULATION RESULTS AND DISCUSSION

This section describes the BLDC motor performance test with at varied number of slots and poles. By using the software, determination of the number of stator slots and poles are possible to be done. Tests were done to observe the effect of the fractions number of stator slots and poles on the generated cogging torque. Cogging torque will cause torque ripple. The simulation results are described as follows:

A. Restrictions on the Number of Slots and Poles

In the simulation, the size (Table II) and the shape of the stator slot structure as shown in fig. 2 were kept constant. By increasing the number of stator slots, while the slot opening size is kept constant, the size of the stator core slots will be smaller. Tests were done on a BLDC motor with stator core slots so that the maximum number of slots was limited to the maximum. Simulations using three-phase motors were very suitable for traction purposes. The electric motor was designed plan will be used to drive an electric car. Due to the use of three-phase motors, the numbers of stator slots were multiplication of three. The number of allowable slots and pole with predetermined parameters are shown in Table III.

TABLE III. MAXIMUM AND MINIMUM POLE NUMBER AT SPESIFIC SLOT NUMBER

Slot Number	Poles Number	
	Min	Max
3	2	4
6	2	10
9	2	16
12	2	22
15	2	28
18	2	34
21	2	40
24	2	44
27	2	50

The minimum number of slots allowed was 3 and then the multiple of 3. At number of 27, it was found that the size of the slot stator core has reached a minimum size so that the maximum number of slots was limited to this size.

B. Cogging Torque

Cogging torque is the interaction between the stator core at no-current and a permanent magnet during the commutating process. Simulation on the effect of the fraction of the number of slots and poles in the electric motor was done by using ANSYS software. In each experiment, the variation of the fraction of the number of stator slots and poles resulted cogging torque data as function of electrical degree as shown in Fig. 3.

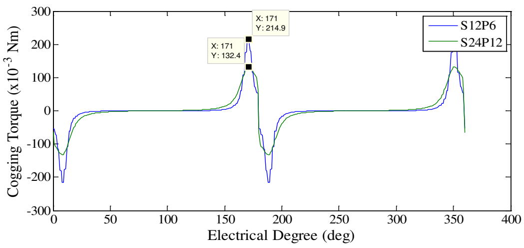

Fig. 3. Cogging Torque at Poles = 0.5 x Slot

Figure 3 shows the cogging torque which was generated when the number of poles was half of the number of slots. As seen from that figure, there are two full cogging torque waves in one full rotation. Both graphs almost were coincide but they had different maximum values. In motor with 12 slots and 6 poles (S12P6) the maximum cogging torque value was 214.9 x 10^{-3} Nm. While motor with 24 slots and 12 poles (S24P12) produced lower cogging torque value of 132.4 x 10^{-3} Nm. From the results, it can be seen that increasing the number of slots reduced the cogging torque.

The tests on cogging torque in BLDC motor was then continued on group of the number of poles and slots difference from 1, 2, 3 and 4. During these tests, the difference between the number of poles and slots fraction one was calculated by adding and subtracting by 1 (+1 or -1) from the number of stator slots. Result on the cogging torque at the number of poles is at one more than number of slots is shown in Fig. 4. After a 90-degree, waves reached the same point and they were repeated periodically.

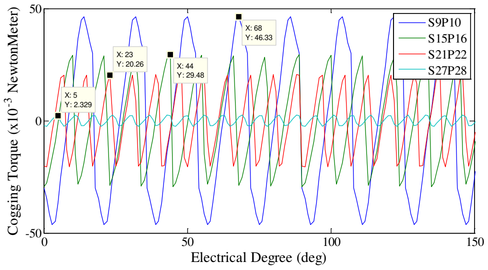

Fig. 4. Cogging Torque at Poles = Slot + 1

Figure 5 shows the results when the test was done for the difference of +2. From that figure, it can be seen that it needed 180 degrees to reach the same value and repeated periodically.

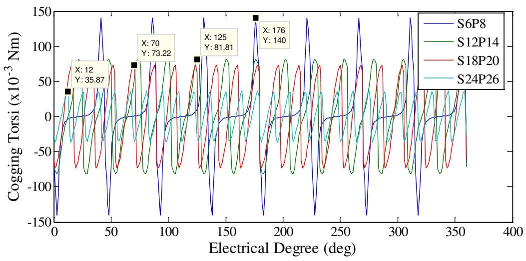

Fig. 5. Cogging Torque at Poles = Slot + 2

From varied tests, it was found that when the difference was odd number (1 and 3) the repetition occurred after 90 degrees period. The complete results are presented in table IV. The number of similar peaks and valleys shows that full waves cogging torque formed were repeated.

From the data in Table IV it can be seen that the more number of slots produced bigger cogging torque waves. When the difference was even (2 and 4), the repetition of the cycle must cover 180 degrees. Complete data can be seen in Table V which shows that the of cogging torque wave increased by increasing the number of slots, except for 24 slots and 28 poles and for 24 slots and 20 poles because these configuration had lesser waves. These phenomena occurred because of the greater number of slots and the difference reduced the total energy produced as results of the interaction torque generated each slot and the permanent magnet.

TABLE IV. THE PERIOD AT 90 DEGREE REPETED

Variation	Number of waves			comparison
	peaks	troughs	sum	
P=S+1				
S9P10	5	5	5	1
S15P16	8	8	8	1.6
S21P22	11	11	11	2.2
S27P28	14	14	14	2.8
P=S-1				
S9P8	4	4	4	1
S15P14	7	7	7	1.75
S21P20	10	10	10	2.5
S27P26	13	13	13	3.25
P=S+3				
S9P12	2	2	2	1
S15P18	3	3	3	1.5
S21P24	4	4	4	2
S27P30	5	5	5	2.5
P=S-3				
S9P6	1	1	1	1
S15P12	2	2	2	2
S21P18	3	3	3	3
S27P24	4	4	4	4

Number of cogging torque waves affected the magnitude of the torque ripple. The longer cogging torque periods produced smaller peak value. The magnitude of the peak value of cogging torque for each group of slots and poles difference can be seen in fig. 6 - 9.

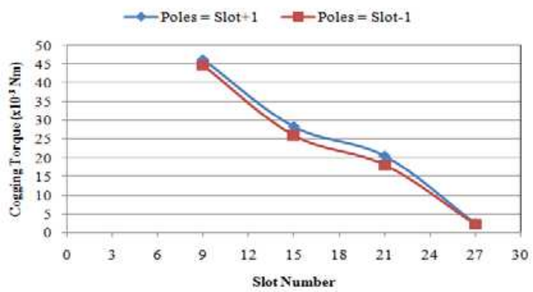

Fig. 6. Cogging torque at slots-poles difference of 1

Fig. 6 shows the cogging torque generated on the number of poles and slots with difference of 1. That figure shows that in the same number of stator slot, the cogging torque produced was nearly the same. With the increasing number of stator slots, large cogging torque became smaller. Cogging torque with the negative difference was always smaller than the positive difference at the same number of stator slots.

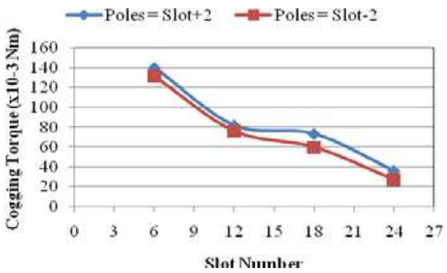

Fig. 7. Cogging torque at slots-poles difference of 2

The magnitudes of the cogging torque with the slot and pole number fraction difference of 2 were almost identical for all varied configuration. The magnitude of the cogging torque in the negative pole number was smaller than the cogging torque magnitude at positive pole for each variation, as shown in Fig. 7.

TABLE V. THE PERIOD AT 180 DEGREE REPEATED

variation	Number of waves			comparison
	peak	trough	sum	
P=S+2				
S6P8	4	4	4	1
S12P14	7	7	7	1.75
S18P20	10	10	10	2.5
S24P26	13	13	13	3.25
P=S-2				
S6P4	2	2	2	1
S12P10	5	5	5	1.25
S18P16	8	8	8	2
S24P22	11	11	11	2.75
P=S+4				
S6P10	5	5	5	1
S12P16	7	7	7	1.4
S18P22	10	10	10	2
S24P28	7	7	7	1.4
P=S-4				
S6P2	1	1	1	1
S12P8	2	2	2	2
S18P14	7	7	7	7
S24P20	1	1	1	1

Figure 8 shows not all variations of slots and poles with difference of 3 produced cogging torque with adjacent values, as happened for the difference of one or two. The biggest differences were in slot 21 where the cogging torque produced was 33.54% higher.

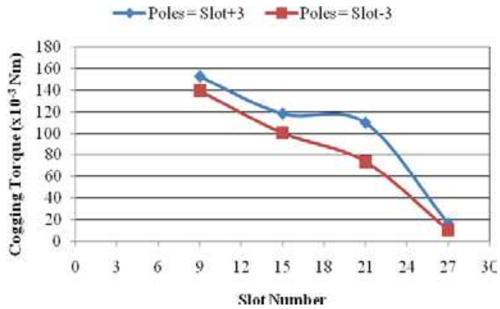

Fig. 8. Cogging torque at slots-poles difference of 3

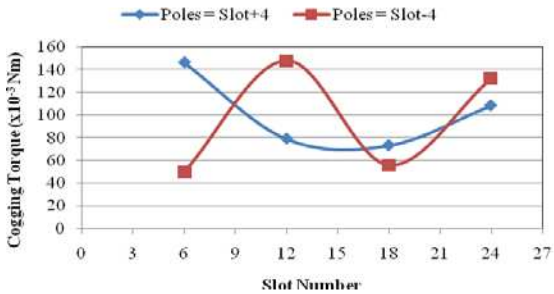

Fig. 9. Cogging torque at slots-poles difference of 4

At the pole difference of 4(Fig. 9), obtained results did not have a specific pattern. With the same number of slots, the cogging torque formed was much different. Negative cogging torque was not always smaller as another variation. These happened because the period of the cogging torque waves generated was irregular as described above, so it affected on the peak value. The magnitudes of the cogging torque were compared based on the positive and negative difference and they were presented in fig. 10 and 11.

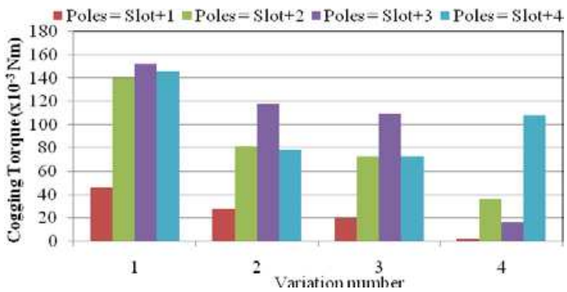

Fig. 10. Cogging torque positif slot differences

At the difference +1, the magnitude of the cogging torque was smallest for each variation. Almost in all variation, the margin of three slots had the highest cogging torque but at low value at variation 4. Lowest value of cogging torque was at the difference of +1 and were on variation 4 or 27 slots and 28 poles (S27P28). As well as in positive difference, the lowest value of torque was the variation 4 and the negative difference of 1 or S27P26.

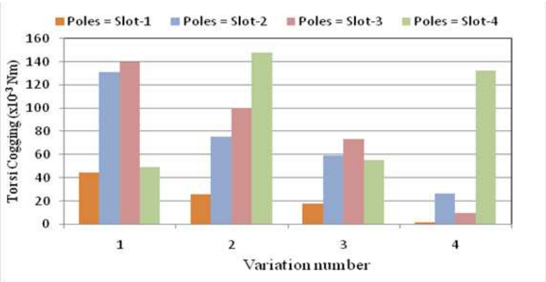

Fig. 11. Cogging torque negatif slot differences

From the data, it can be seen that the magnitude of the smallest cogging torque was at the difference between 1 and 2. In the following section the existence of torque ripple will be discussed.

C. *Torque Ripple*

The influence of the cogging torque presence is the torque ripple. Simulation of the torque ripple was done at certain motor speed. Average maximum speed of the motor was 1100 rpm, and simulation was done for low speed (300 rpm), medium (600 rpm) and high (900 rpm). Figure 12 and 13 present the torque deviation width, generated for each configuration.

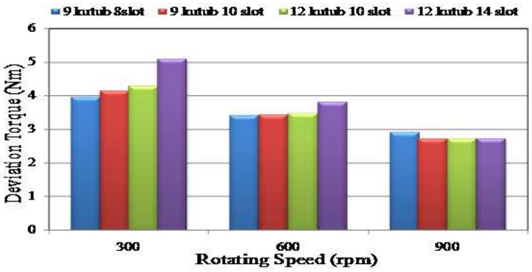

Fig. 12. Torque deviation

From fig. 12 it can be seen that higher motor speed produced narrower torque deviation width. It can be explained that the inertia of the moving objects reduced the influence of cogging torque. However, when the width of deviation was compared to the average torque, the results showed the opposite effects, as in depicted in fig. 13. It can be seen that the torque produced at higher speed was bigger.

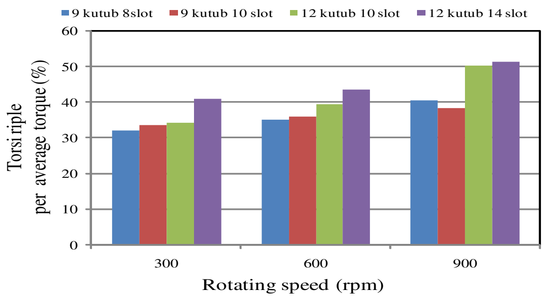

Fig. 13. Ripple torque in rate torque

V. CONCLUSION

The simulations on electric motor using ANSYS software were conducted to determine slots and poles, which produced minimum torque. Slots and poles configuration were varied for the simulation. From the results, it can be concluded that the magnitude of the cogging torque was strongly influenced by variations in the number of slots and poles. Increasing the number of slots produced smaller cogging torque. The greater the difference between number of slots and poles, the greater cogging torque produced. Minimum cogging torque was obtained by a margin of 1. For margin more than 4, the magnitude of cogging torque was irregular.

ACKNOWLEDGMENT

This work was supported by DP2M, Directorate of High Education, Ministry of Education and Culture Republik Indonesia, through "Penelitian Unggulan Perguruan Tinggi" grant Sebelas Maret University with the contract no: 351/UN27.11/PN/2014.

REFERENCES

[1] Beaty, H W., and Kirtley, J., *Electric motor Handbook*, New York: McGraw-Hill Companies, Inc., 1998.

[2] Jang, S.M.., Cho, H.W., and Choi, S.K.," Design and analysis of at high speed brushless DC motor for centrifugal compressor," IEEE Transactions on Magnetics, Vol. 43, No. 6, 2573-2575, June 2007.

[3] Zang,W. and Mingyao, L. Influence of Rotor Pole Number on Optimal Para meters in E-core Axial Field Flux-switching Permanent Magnet Machine, International Conference on Electrical Machines and Systems, Busan, Korea, 978-1-4799-1447-0/13, 2013

[4] C. Xia , Z. Chen , T. Shi , and H. Wang, Cogging Torque Modeling and Analyzing for Surface-Mounted Permanent Magnet Machines With Auxiliary Slots IEEE Transactions On Magnetics, vol.49, no.9, september 2013.

[5] Yedamale, P., Brushless DC (BLDC) motor Fundamental, Microchip Technology Inc., 2003.

[6] Choi J H, Kim J H, Kim D H, Design and Parametric Analysis of Axial Flux PM Motors with Minimized *Cogging* Torque, IEEE Transactions on Magnetics, Vol. 45, pp. 2855 - 2858 19, May 2009.

[7] Hanselman, D.C, Brushless Permanent Magnet Design, McGraw-hill Inc., 1994.

[8] Bathe, K. J., Finite Element Procedure, Prentice Hall Inc., 1996.

[9] Braess, D., FINITE ELEMENTS Theory, Fast Solvers, and Applications in Elasticity Theory , Cambridge University Press, New York, 2007.

[10] Becker, E. B., Carey, G. F., Oden, J. T., Finite Element An Introduction, Prentice Hall Inc., 1981.

[11] Wang, S., Kang, J. and Park, K., "Comparison of 2d and 3D FEA of a BLDC motor" The International Journal and Mathematics in Electrical and Electronic Engineering. Vol 19 No. 2 MCB University Press. UK., 2000

[12] Lowther, D. A. and Forgani, B., "A comparison of 2D and 3D analysis methods for the prediction of *cogging* torque in an electrical machine having skewed slots" The International Journal and Mathematics in Electrical and Electronic Engineering. Vol 20 No. 2 MCB University Press. UK., 2001