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DC PERMANENT MAGNET BRUSHLESS MOTOR PERFORMANCE EVALUATION WITH DIFFERENT ROTOR MATERIAL USING FEMM

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Abstract

This paper presents the performance evaluation of a 4 pole, 6 slots DC permanent magnet brushless motor. In order to obtain efficiency, EMF induced, copper losses, torque & cogging force, computer simulations were performed on this machine. Moreover different rotor materials have been used and tested in order to obtain the highest efficiency. Real time brushless DC motor dimensions were taken in order to design the motor by using Finite Element Method Magnetics (FEMM). The material used for the motor and the air gap was varied in order to obtain the best performance of the motor. The software employed in this research is Programming Language Lua based script embedded with FEMM for evaluating the results obtained. It was also observed that different rotor materials gave better induced EMF results and the smaller the air gap size the better flux density results. The motor performance with reasonable precision is predicted by mathematical calculation method.

Keywords: Brushless Direct Current Motor (BLDC), Finite Element Method Magnet (FEMM), Lua programming.

1 INTRODUCTION

Permanent magnet brushless motors are employed in wide range of applications which include hybrid & electric vehicles, pumps with high-efficiency, servo motors, and etc. Various new applications are budding due to low noise, high efficiency and efficient control requirements where these machines are being used. Both sine-wave and square-wave drives are employed, with a large range of geometries of the motor, materials and winding configurations. Some of the problems of the brushed D.C motor are eliminated in the brushless design due to high maintenance (of brushes) and limited life span. The mechanical "rotating switch" or brush gear / commutator assembly is replaced by an electronic switch synchronized to the rotor's position which is mounted externally in this motor (Akinaga et al., 2011).

To obtain solutions to a variety of problems in science and engineering, computational methods such as Finite Element Method (FEM) can be applied. In electromagnetic, fluid dynamics and structural analysis problems involving steady state, transient state, linear and nonlinear conditions can be analyzed and solved using FEM method. It combines geometrical adaptability and materials of any composition without altering any of the formulation of the computer coding that has been implemented. The idea of this method is to divide the main problem domain into a large number of sub domains, called finite elements, each with a simple geometry resulting in the transformation of the initial problem from a small but difficult to a larger one that is easier to solve (Akinaga, 2011; Kostaridis, 2001).

In general Lua extension programming supports programming with data description conveniences. Lua programming is deliberately used to perform powerful and light-weight configuration language, for any type of program that needs data description facilities. Lua programming is applied as a library function and codes are in ‘C’ language. Lua programming being an extension language, has no concept of a “main” program and it can only work when embedded in host client, which is known as the embedded program. The host program can raise function to perform a piece of code, and also can write and read Lua programming variables. It can also register ‘C’ functions to be called by a Lua code. All the way through the use of ‘C’ programming functions, Lua programming can be improved to manage wide range of special domains, thus creating tailored programming language giving out a syntactical framework (Baltzis, 2008; TeCGraf, 2000).

2 METHODOLOGY

FEMM environment is divided into several subsections. There are two problems solving addressing to Magnetics and Electrostatics Problem. A set of data files that describes the problem is taken by each solver and the relevant mathematical equations are solved to get values for the preferred field all through the solution domain stated by David Meeker. For the purpose of this study, electromagnetic problem is chosen for modeling the Brushless D.C motor. The FEMM interactive shell is divided into Magnetics Preprocessor and Magnetics Postprocessor. The preprocessor area is where the magnetic model is developed and integrated with the command *femme.exe* and the finite element solutions are generated in the solver (*fkern.exe*). Figure 1 shows the mechanism followed to design the BLDC motor.

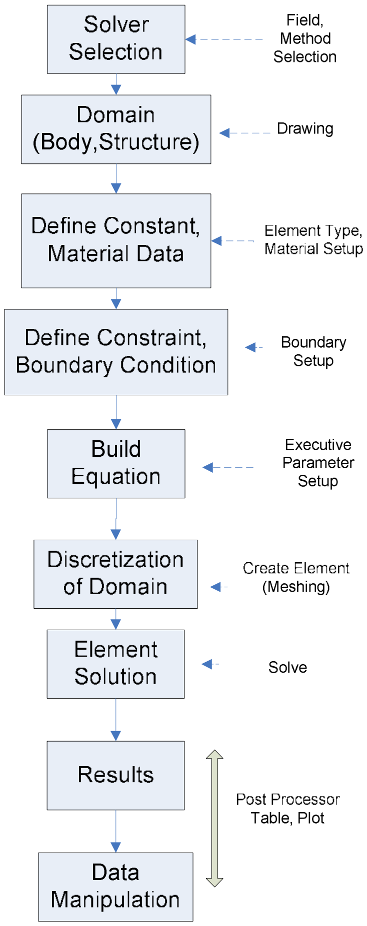


Figure 1. Mechanism in FEM Software

3 DESIGN OF BLDC MOTOR

Brushless DC Motor dimensions are taken from a real motor size. The motor was designed using FEMM software and script based on the programming language Lua. This is to provide adequate rated power, with convenient surplus power and with load current as low as possible. The design of the brushless DC motor is shown in Figure 2. Two different rotor materials have been tested for the BLDC motor design, which are Alnico and NdFeD PM materials. The variation of the rotor material is to select the best rotor material with the best performance. Table 1 shows the materials that have been selected for the design.

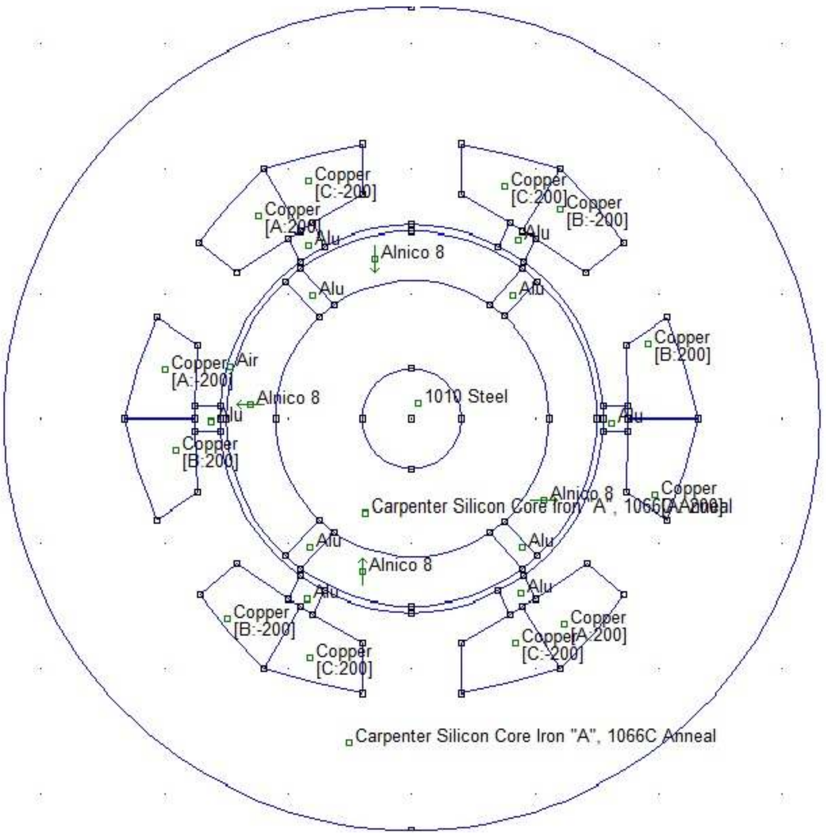


Figure 2. Design of BLDC motor

Table 1. Brushless DC motor materials

Part	**Materials**
Permanent magnet	Alnico 8 / NdFeD
Coil	Copper
Back Iron	Carpenter Silicon Core Iron
Shaft	Steel 1010

4 BLDC MOTOR PERFORMANCE CALCULATION

The Weighted Stress Tensor method of programming, which is distinct from the Maxwell's Tensor method, computes the torque and the results obtained are normally more precise than the conventional Maxwell's Tensor method. Lua programming routine integrated with the FEMM is used to obtain the flux density of the steel in each element of the mesh. These flux density values obtained were then used to compute the iron losses in each of the finite element. Then an amalgamation of the obtained values results in producing the iron loss in average of the motor at a particular position. This step is repeated along an electrical cycle to attain the total iron loss. The output mechanical power is then computed from the product of the average torque in one electric cycle and the motor speed. The static FEM model performs the simulation, which takes into consideration the effects due to dynamic losses, which reduces the mechanical power by the total iron losses. By applying Simpson's composite rule the average torque is computed using equation (1).

$$T_{av} = \frac{1}{2\pi}\int_{0}^{2\pi} T_m\,(\theta) d\theta$$

$$P'_{mech} = T_{av}\omega_m \qquad (1)$$

$$P_{mech} = P'_{mech} - P_{iron}$$

The copper losses are easily computed by (10).

$$P_{copper} = 3R_{ph}I^2{}_{rms} \qquad (2)$$

Where R_{ph} is the coil resistance per phase. The efficiency is then computed by dividing the mechanical power output by the electrical power input (3) (i.e. electrical power input equals the sum of mechanical power output plus the copper and iron and copper losses).

$$\eta = \frac{P_{mech}}{P_{mech} + P_{copper} + P_{iron}} \qquad (3)$$

The heat flux through the design can then be determined using the integration capabilities of FEMM. Figure 3 shows the heat flux between two points on the stator; the red color indicates the most flux heated points on the design, which shows that the design has a good agreement until 1.2 T.

In this study, Lua scripts is used in order to move the rotor in the Brushless DC motor geometry through prescribed angles vary from 0° to 360°. In each step movement of the rotor, the cogging force, the flux value and the electromotive force induced in the stator coils is calculated. The stator area is selected using contour mode, to calculate the force by block integration. Figure 4 shows the flow chart for Brushless DC motor analysis.

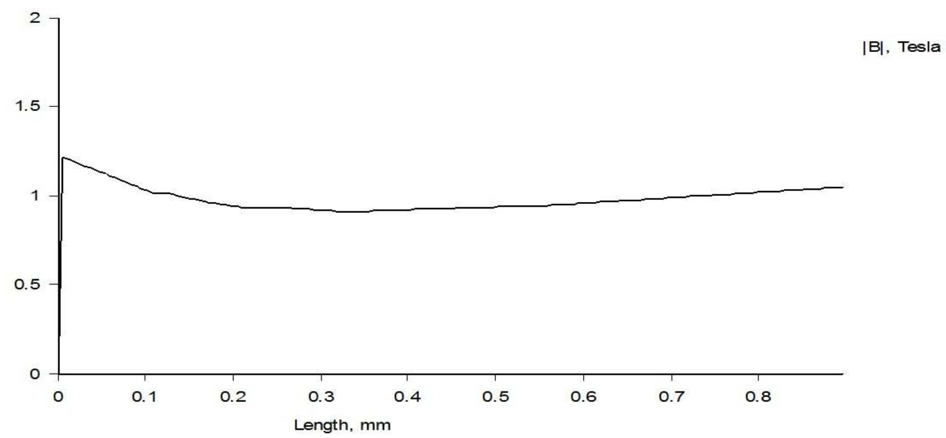


Figure 3. B-H curve between two points

A Lua Scripting Programming was performed in order to extract the torque values (T) of the Rotor for every 5° of rotational step angle. The rotor was programmed to rotate counter-clockwise by angle of 360° and the torque values were extracted in every step angle of 5°. In succession, the torque values would be used to calculate the work done (J) of the rotor for a complete 360° rotation and the result was plotted into a graph. The code developed consists of using interactive loops. First defining the initial condition and configuration for pre-processor step and, create a loop that defines the rotor position with a variation from 0° to 360°. It means that for each loop the rotor rotates 5° and the program calculate the torque for each step. For better understanding, Figure 5 shows the code developed for the brushless DC motor.

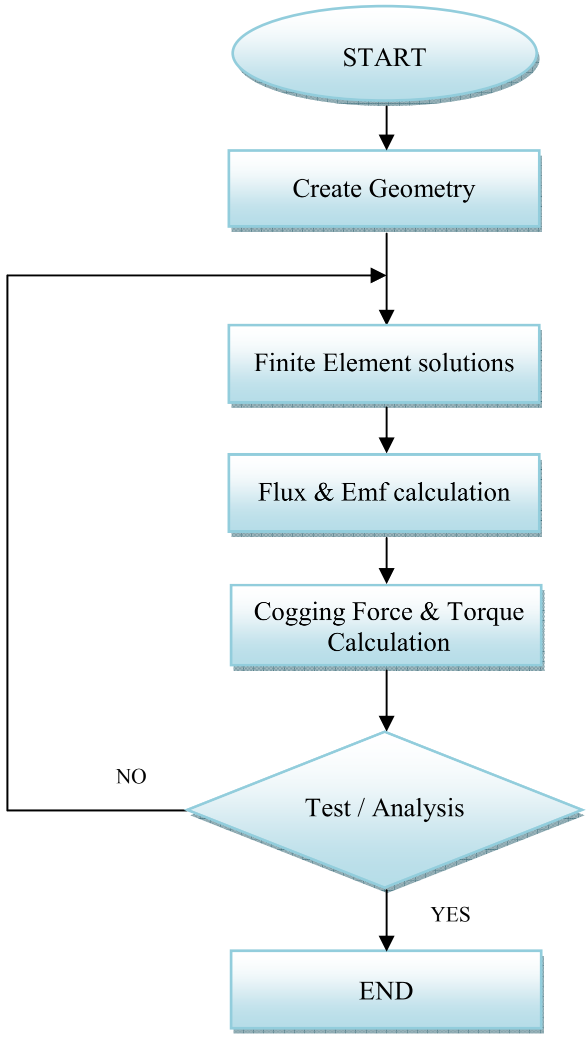


Figure 4. Flow chart for Brushless DC motor

```
mi_probdef (0,"centemeters","planar",1e-008, (10),(30),(0)); Define intial condition and
configuration for pre-processor step.

A=0; loop the program to run 360 times, in order to achieve the rotor to rotate by 360°

for A=0, 360 do

mi_selectgroup(2); The rotor was defined as Group 2.

 mi_moverotate(0,0,5); Rotate the selected block by 5 degree per program loop.

mi_analyze(); Analyze the pre-processing geometry model of brushless DC Motor Model
mi_loadsolution(); Load the solution for post-processing solution

mo_groupselectblock(2); Select the desired block(rotor).

 T = mo_blockintegral(22); Defined T as the torque values and calculate integral torque
value of the selected block.

 print(T); Display the obtained torque result.

end; End the program after it has looped for 360 times.
```

Figure 5. Using Lua script to calculate the torque

5 RESULTS AND DISCUSSION

Figure 6 depicts the distribution of flux density at nominal power in the BLDC motor (maximum flux density of 1.3 Tesla). The rotor materials of the brushless DC motor are Alnico 8 and NdFeD. It rotates 360° in a clockwise direction. Figure 7 shows flux linkage versus the angle in degree using Alnico PM material. When the brushless DC motor start runs in FEMM, the flux density distribution keep on changing for each 5°, with changing in flux linkage values. It shows the flux leakage for three phases between 0.33 *Wb* to -0.3*Wb*. Figure 8 shows the EMF induced versus angle in degree. The EMF induced in the stator coil of the brushless DC motor is always the interest in this analysis since the purpose of the brushless DC motor is to produce an electrical power. The electromotive force is calculated for each 5° of movement of by differentiating the flux curve.

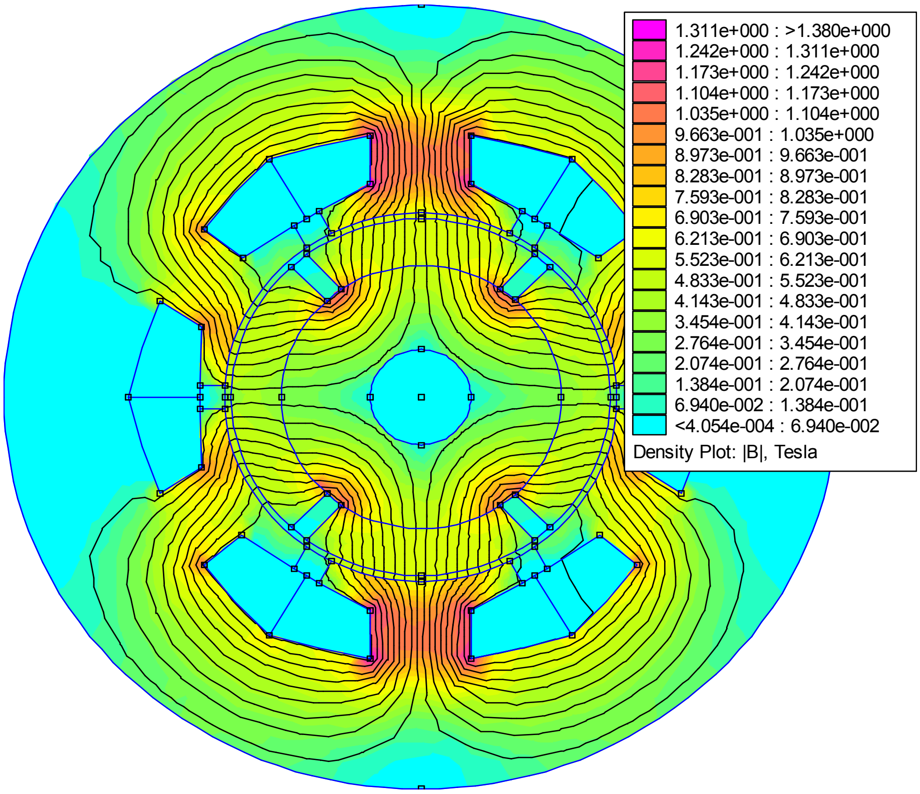


Figure 6. Flux density distribution at nominal power in the BLDC motor

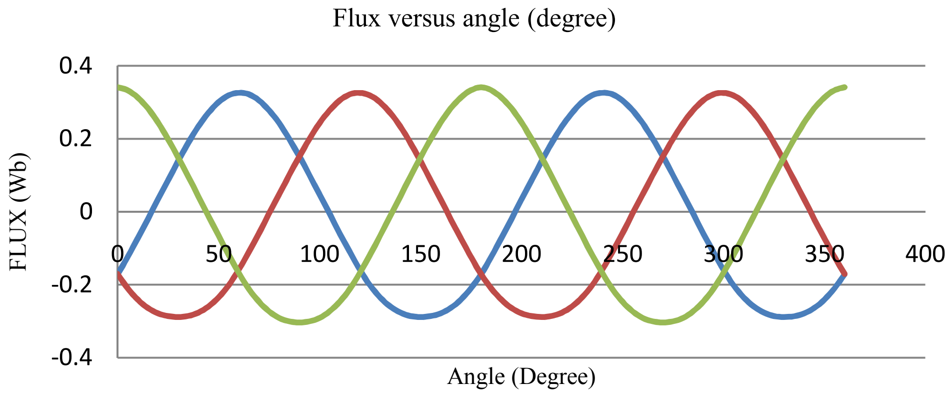


Figure 7. Flux versus angle using Alnico material

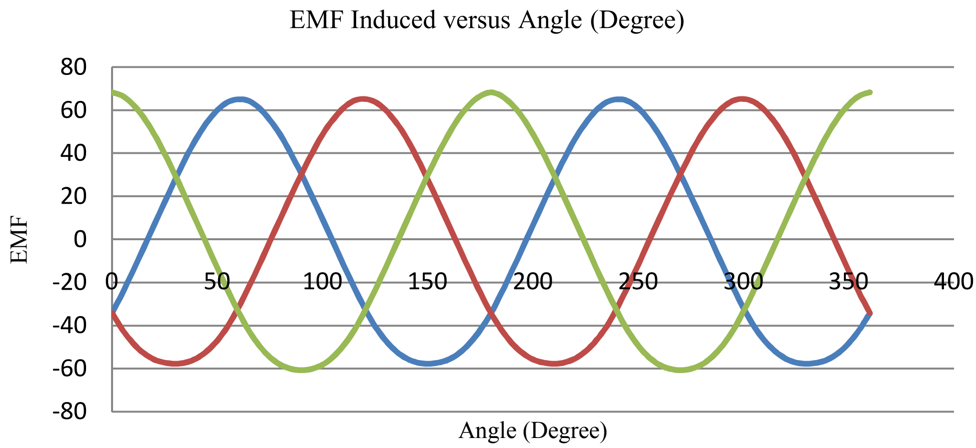


Figure 8. EMF Induced versus angle using Alnico material

Figure 9 and 10 shows the flux density with changing the rotor material to NdFeB 37 MGOe, the result is a higher flux density which related to the changing of the rotor material, better flux density reflect to better EMF and efficiency. It also shows how the magnetization distribution affects the performance of the surface permanent magnet-type motor. Table 2 shows the flux distribution at different rotor positions. Obviously, when the rotor rotates the flux distribution will change due to the change of the magnetic strength. The rotor position was taken at 0^o to 45^o because the flux distribution is repeating at each 45^o.

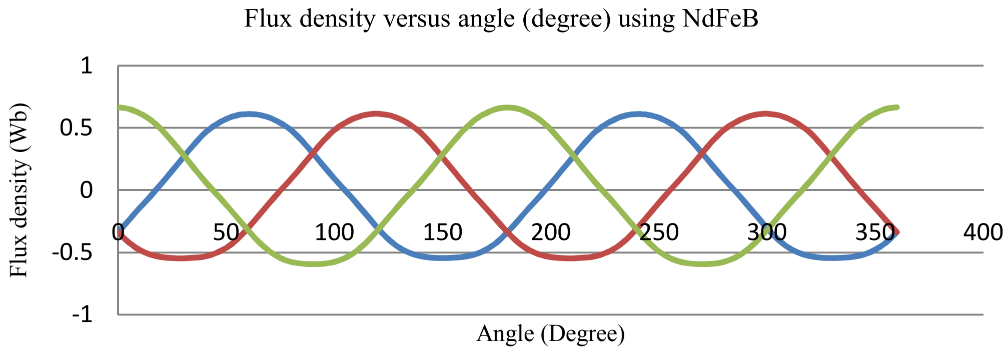


Figure 9. Flux density versus angle using NdFeB material

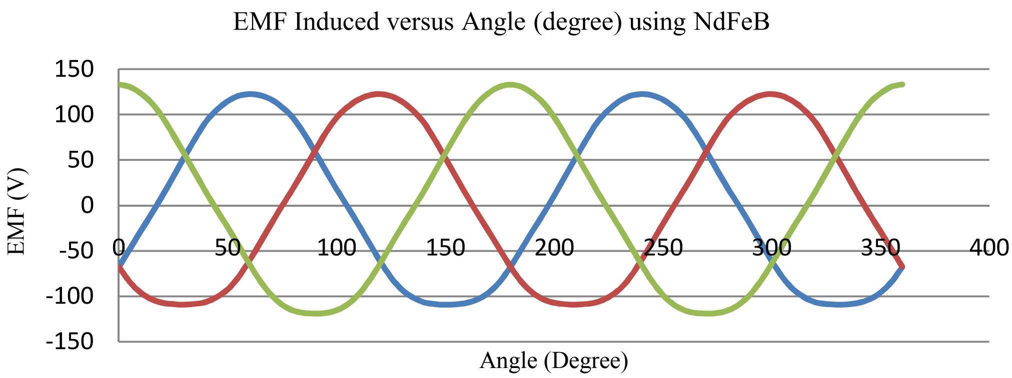
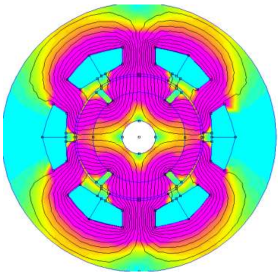
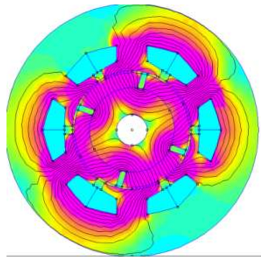
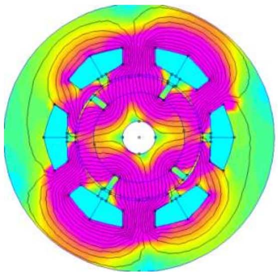
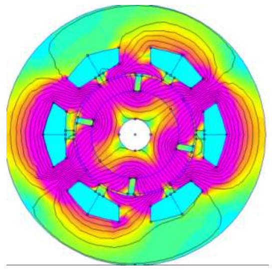
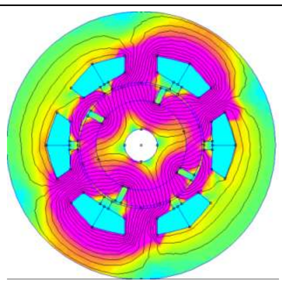
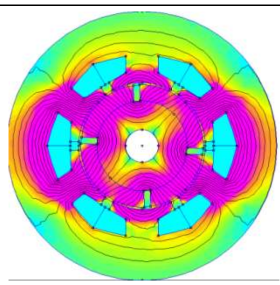


Figure 10. EMF Induced versus angle (degree) using NdFeB

Table 2. Flux distribution at different rotor positions

Rotor position	Flux distribution image	Rotor position	Flux distribution image
0^o		27^o	
9^o		36^o	
18^o		45^o	

6 BRUSHLESS DC MOTOR PERFORMANCE EVALUATION

Brushless DC motor with 4 poles and 6 slots with specified sizes were presented. The motor speed and the current were taken from [1], because the prototype has been developed and tested. The motor was running at a speed of 1600 rpm on no-load and the current value was 0.28A. Based on the current flowing and resistance of the wire values the copper losses is computed using equation (2), and mechanical losses using equation (1). From the total losses copper loss is deducted directly and the motor iron losses are obtained. The efficiency is computed using equation (3). The performance valuation for brushless DC motor using Alnico and NdFeB respectively is depicted in Table 3 and 4.

Table 3. Performance evaluation of BLDC motor with Alnico rotor material

Parameter	Value
Wire resistance Ω	7.85
Current (A)	0.28
Emf (V)	44
Copper losses (W)	1.846
Iron losses (W)	0.69
Mechanical’ losses (W)	27.57
Input power (W)	30.12
Torque (kgf.cm)	1.72
Efficiency (%)	91.576

Table 4. Performance evaluation of BLDC motor with NdFeB rotor material

Parameter	Value
Wire resistance Ω	7.85
Current (A)	0.28
Emf (V)	84.7771
Copper losses (W)	1.846
Iron losses (W)	0.69
Mechanical’ losses (W)	36.09
Input power (W)	38.63
Torque (kgf.cm)	2.24
Efficiency (%)	93.4

7 CONCLUSION

The knowledge gained from the model and analysis of the proof of concept design has indicated areas in which the brushless DC motor can be further improved, such as increasing the flux density and optimizing the motor performance. The maximum flux density is radically raised when the air gap length is small.

The permanent magnet length, material, air gap length and magnet depth designing factor has been performed in the brushless DC motor. The design improves the brushless DC motor performances over a suitable range of power. To reduce the cogging force between the core and permanent magnet, the length of the permanent magnet or the air gap length is reduced. The permanent magnet length is a critical factor to the EMF value of the brushless DC motor. It is demonstrated that to obtain the maximum output three phase voltage from the motor, there is a specific length for the permanent magnet. In the general design point of view, the brushless DC motor is preferable because it is more compact.

REFERENCES

Akinaga, T.H., Pompermaier, C., Kalluf, F.J.H., & Ferreira da Luz, M.V. (2011). *Performance evaluation of brushless DC permanent magnet motor using finite element method*. IEEE International Electric Machines & Drives Conference (IEMDC).

Baltzis, K.B. *The FEMM Package: A Simple, Fast, and Accurate Open Source Electromagnetic Tool in Science and Engineering*. Radio Communications Laboratory, Section of Applied and Environmental Physics, Dept. of Physics, Aristotle University of Thessaloniki, 54124, Thessaloniki, Hellas, November 2008.

Kostaridis, A., Soras, C., & Makios, V. (2001, January) *Magnetostatic Analysis of a brushless DC motor using a two-dimensional partial differential equation solver.* Laboratory of Electromagnetics, Department of Electrical and Computer Engineering, University of Patras, Greece.

Mekker, D. *Finite element method magnetic*. Retrieved Nov 10, 2010, from http://www.femm.info/wiki/Homepage

TeCGraf/PUC-Ria. (2000). *The programming language Lua*.