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# Effect of Changing Magnet Material on Cogging Torque and Torque Ripple of Brushless DC Motor

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## Abstract

Brushless DC motors (BLDC)are extensively used for high-control applications because of their small size, high efficiency, and high-performance qualities. It gained popularity since the permanent magnetic materials were improved, so the drive system must have precise positioning and smooth electromagnetic torque for high performance and precision. Numerous elements contribute to torque ripples in this motor; one of them is the type of permanent magnet material. In this paper, a 3-phase, four-pole, 1500 W BLDC motor was modeled based on RMxprt and Maxwell 2D software. Four magnet materials: alnico 5, ceramic 5, SmCo 28, and NdFe 35, were studied to show the effect of each magnet on motor performance. The finite element analysis (FEA) results showed that the motor's average torque and cogging torque are directly proportional to the magnet strength. Also, the torque ripple exists with using a lower magnet strength magnet. Ndfe35 and SmCo28 have strong mechanical properties, are relatively expensive, and have higher cogging torque and torque ripple. The other materials, Alnico 5 and ceramic 5, are less costly and have less cogging torque and torque ripple. The full load simulations demonstrate that weaker magnets can also provide lower torque. Due to the results presented, while choosing the magnet materials, the trade-off between nominal torque, torque ripple, and price should be taken into account. The methodology adopted in this research will allow motor designers to select the best magnet material,and leading to excellent motor performance without the requirement to construct and test several prototype motors.

.***Keywords***- PMBLDC motor, cogging torque analysis, Maxwell 2D, permanent magnet material.

## I. INTRODUCTION

Brushless DC (BLDC) motors were improved due to the development of more complex computer technology for control systems. Develops in intelligent electronics and power semiconductors are essential factors that will enhance machine uses in many applications with a wide range of services[1]. Permanent magnet (PM) machines have seen increased interest over the past ten years because of their high efficiency, high torque density, minimal torque ripple, and strong flux-weakening capacity[2].Different electric machines, including DC machines, synchronous machines, and innovative PMBL machines such as PM stepper motors, hybrid stepper motors, and PMBLDC motors, have employed permanent magnet (PM) excitation. Three general groups of PM materials include Alnico (Al-Ni-Co-Fe), Ceramics, and rare-earth materials, including samarium-cobalt (Sm-Co) and neodymium-iron-boron(Nd-Fe-B) are used in rotor of BLDC motor. SmCo is employed because of its high energy density, coercive force, and low-temperature coefficient.In contrast, Alnico and ferrites are used because of their inexpensive cost and availability. Aside from its temperature restriction, NdFeB is regarded as one of the best PM materials due to its greater residual flux density and coercive force[3]. These desirable qualities are primarily related to the PM materials. Neodymium-iron-born (NdFeB) and samarium-cobalt (SmCo) are now two popular varieties of rare-earth PMs. At the same time, ferrite and aluminum-nickel-cobalt (Alnico) are two popular nonrare-earth PMs; due to their unpredictable availability and expensive cost. Rare-earth PMs are only used in a limited number of applications. However, non-rare-earth PMs are gaining popularity because of their plentiful resources and affordable pricing [4]. The Back-EMF of PMBLDC motors takes the form of a trapezoidal wave, as opposed to the permanent magnet synchronous motors (PMSM), the sinusoidal waves [5]. Compared to typical DC motors, BLDC motors have significantly lower core and copper losses due to using permanent magnets inside the rotor to generate field flux. Moreover, that will increase the overall efficiency of the motor drive system.[6]. The BLDC motor has two significant drawbacks: torque ripple and controlling the drives at high speeds. Stator currents are trapezoidal, unlike the quasi-square wave that causes the torque ripple. Torque ripple causes changes in speed, vibration, and acoustic noise[7]. The cogging torque is present even when the machine is not powered up. It is caused by interactions between the rotor's permanent magnets and the iron teeth of the stator [8]. Cogging torque, non-trapezoidal back-emf, and phase-to-phase current commutation contribute to torque ripple. Many researchers were interested in analyzing the torque of BLDC motors. Dai used the finite element method (FEM) to examine the effects of various variables on the torque waveform. It was found that both the under-skew and over-skew of the rotor magnet significantly affect the torque waveform of the BLDC motor[9]. Boukais studied torque ripple and cogging torque of BLDC motors with several permanent magnet rotors of BLDC motors. The simulation findings show the correlation between this construction, optimal permanent magnet, and optimal segmentation design of permanent magnet on the torque ripple[10]. Pourjafari found that both cogging torque and torque ripple can be reduced using significant elements such as magnet embrace, offset, and skew[11]. Srisiriwanna investigated the cogging torque reductions of a BLDC motor with varying air gap length, rotor, and stator parts. FEM is primarily utilized to study torque reduction among these various reduction approaches[12]. Yildirim examined how a brushless DC motor's cogging torque is affected by the material and geometry of surface-mounted permanent magnets by using Maxwell 2D. By using the software program Ansys Maxwell a 2D results indicate that whereas cogging torque, back EMF, and magnetic flux density in the air gap are at their maximum for the most robust magnet material, they are at their lowest for the weakest magnet. In this investigation, three distinct magnet embrace values are taken into account, and the maximum back EMF values are roughly the same for each magnet embrace[13]. Karthick investegated the cogging torque of BLDC motor with using different magnet materials such as; neodymium magnets (NdFeB) and samarium cobalt (SmCo) magnets. The chosen magnetic material will be determined mainly by the application's temperature, device weight, size, and cost[14]. Toren investigated on the impact of magnets material of the NdFeB type in BLDC motor design and their use in electric vehicle motors. The most powerful N52 magnet material had higher motor performance values than other types of magnets, although it cost more[15]. Most of the above research studies examined either the cogging torque or torque ripple of BLDC motors. They also use software tools to accomplish their goals, such as Matlab/Simulink, Maxwell 2D, and Magnet software. This research aims to simulate and analyze a BLDC motor by using finite element analysis based on Maxwell 2D software and investigate the effect of changing magnet material on cogging torque and torque ripples, like Alnico5, Ceramic5, NdFe35, and SmCo28. . The methodology adopted in this paper conducted finite element analysis to get an accurate results of motor cogging torque, torque ripple, magnet strength, as well as the distribution of the flux density distribution in different motor parts , and that will give a good helping to the BLDC motor designers and other reserachers in selecting the suitable magnet material in rotor to get a good motor performance without the need to build and test many prototype motors.

## II. MATHEMATICAL BACKGROUND

The FEM has excelled in all other electrical motor tools for calculating magnetic fields. Engineers can use it to address problems that are difficult to solve with typical analytical procedures. The approach also allows researchers to conduct an in-depth analysis of the motor. FEM is a mathematical approximation technique that uses computers to calculate machine parameters such as torque, EMF, flux density, and flux linkage. Maxwell 2D software adopted in this paper is based on FEM analysis which is based on Maxwell's electromagnetic field equations listed below[6]:

$$\nabla \cdot D = \rho \tag{1}$$

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

$$\nabla \cdot E = -\frac{\partial B}{\partial t} \tag{3}$$

$$\nabla \times E = \frac{\partial D}{\partial t} + J \tag{4}$$

Where:
(D) is the electric flux density in ( $C.m^{-2}$)
(ρ)is the volume charge density in ($C.m^{-3}$)
(B) is the magnetic flux density vector term in (Tesla)
(E) is the electric field intensity in( $V.m^{-1}$)
(H)is the magnetic field intensity in( $A.m^{-2}$)

The electromagnetic $(T_e)$ for a 3-phase BLDC motor can be expressed as[16]:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{w_m} \tag{5}$$

Where:
$(e_a\ e_b\ e_c)$ Is the induced voltage in the stator/phase
$(i_a\ \ i_b\ \ i_c)$ Is the induced current in the stator/phase
$(\omega_m)$ is the rotor's mechanical speed in ( rad/s)
or

$$T_e = K_t[f(\theta_e)i_a + f\left(\theta_e - \frac{2\pi}{3}\right)i_b + f\left(\theta_e + \frac{2\pi}{3}\right)i_c] \tag{6}$$

Where:
$\theta_e$ : is the rotor's electrical position in (°)
$K_t$: is the torque constant in (N.m/ A)
The torque ripple can be calculated in equation (7) [17].

$$Torque\ ripple(\%) = \frac{Tmax - Tmin}{Tav} \times 100\% \tag{7}$$

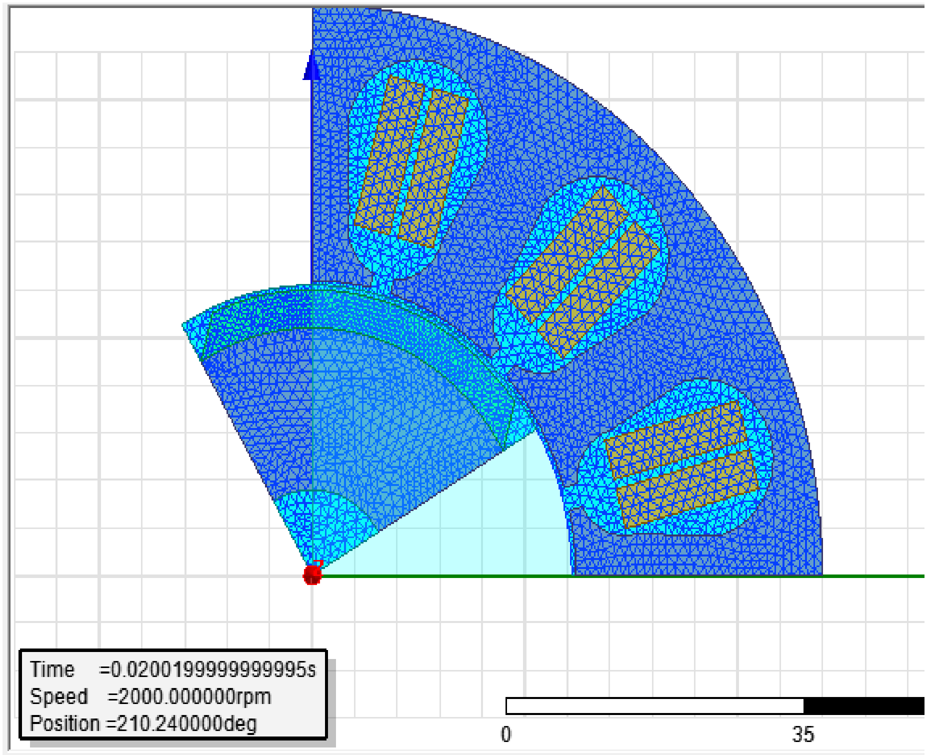
Where:
(T max): is the maximum torque in (N.m).
(T min) : is the minimum torque in (N.m).
(T av ): is the average torque in ( N. m).
The main disadvantage of BLDC motors is cogging torque and torque ripples[18]. In BLDC motors, cogging torque is the most significant feature affecting the torque ripple. Cogging torque(T cog) is caused by the interaction of the rotor-mounted permanent magnet field and the stator teeth [19].,and it can be represented in equations (8).

$$Tcog = -\frac{1}{2}\ \emptyset_g^2\ \frac{dR}{d\theta} \tag{8}$$

Where:
(R) is the reluctance of the air gap,( Øg )is the flux of the air gap, and (θ)is the rotor’s angular position [20].

## III. MODELING OF BRUSHLESS DC MOTOR

RMxprt is built-in Maxwell 2D software that uses templates to help electrical machine designers to improve their work. RMxprt can determine machine performance and make initial sizing decisions. RMxprt can automatically configure the entire Maxwell 2D project for transient electromagnetic analysis. It has design sheets that include a graphic representation of waveforms and a list of the necessary input and calculated parameters. It combines a magnetic circuit approach with conventional electric machine theory[6]. FEM is a numerical method for solving engineering issues like electromagnetics analysis[21]. FEM implies that the machine body is subdivided into smaller pieces called elements, and numerical integration is used for each element [22]. The BLDC motor under study is a three-phase, four poles, inner rotor,1500 watts. The RMxprt model can generate the 2D FEM model, and reference [23] was adopted for motor specifications.Figure.1 represents the finite element mesh of the motor model.




motor
Figure 1. The meshing of the BLDC motor model by maxwell 2D

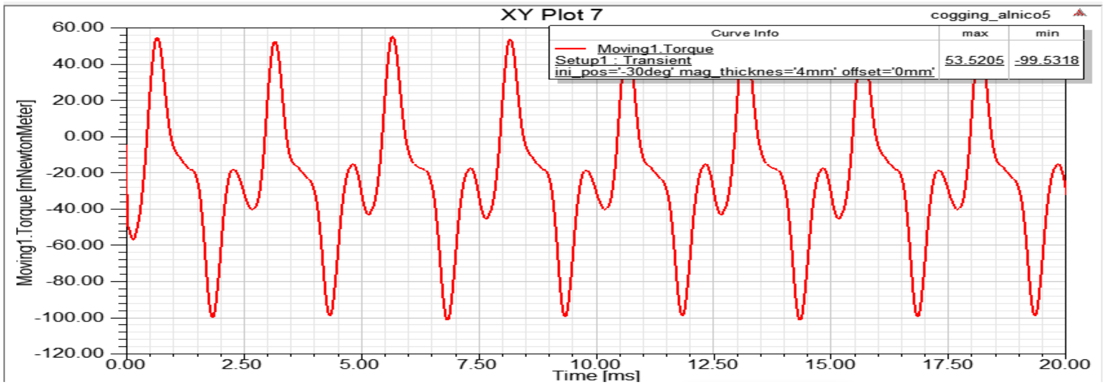
### *A. Finite Element Analysis of Cogging Torque*

The simulation is conducted on the test motor in the same setting and geometry for different magnet materials. The magnet chosen were Alnico5, Ceramic5, NdFe35, and SmCo28, with magnet strength listed in table 1.

**Table 1.The coercive force for four materials in (A/m)[13].**

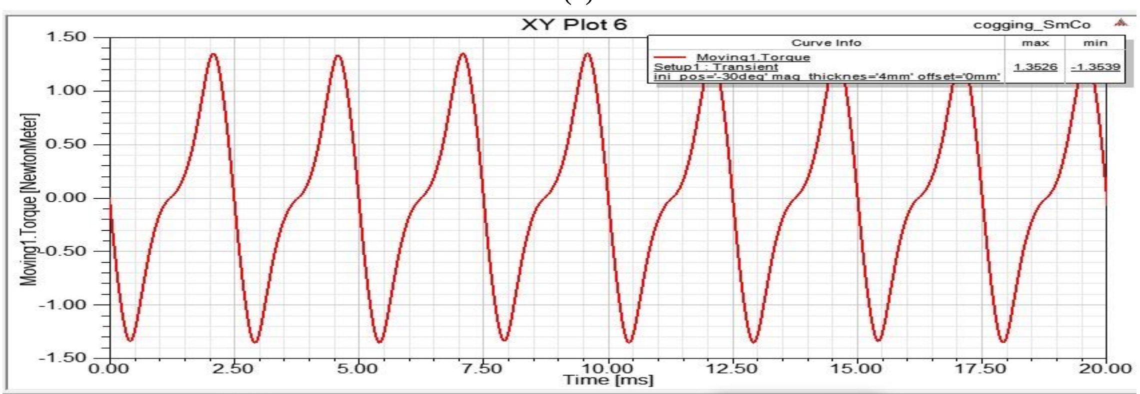
| Type of Magnet Material | Coercive Force in (A/m) |
|---|---|
| Alnico 5 | -50930 |
| Ceramic5 | -190186 |
| SmCo28 | -820000 |
| NdFe35 | -890000 |

The simulation was run, and the results were derived from Maxwell 2D for the four materials, as shown in figure(2). At no excitation, the rotor is rotated with an external force to determine cogging torque by setting the current to zero.




(a)


(b)

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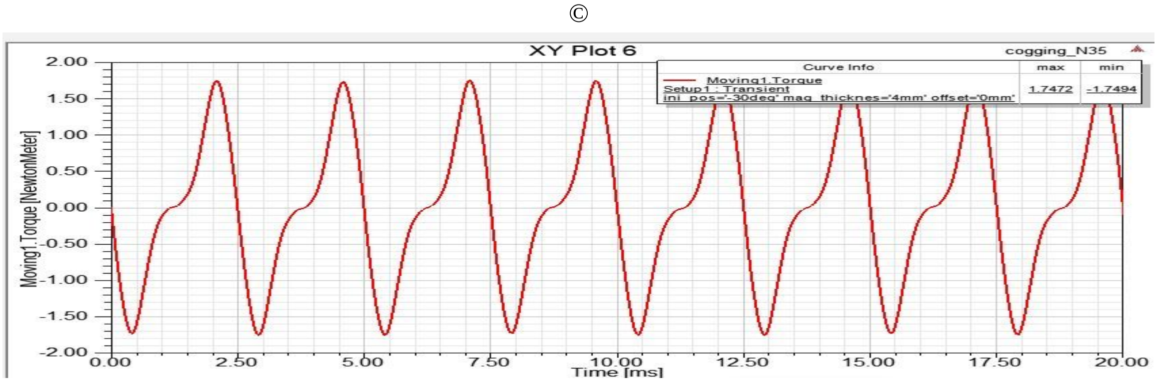



(d)

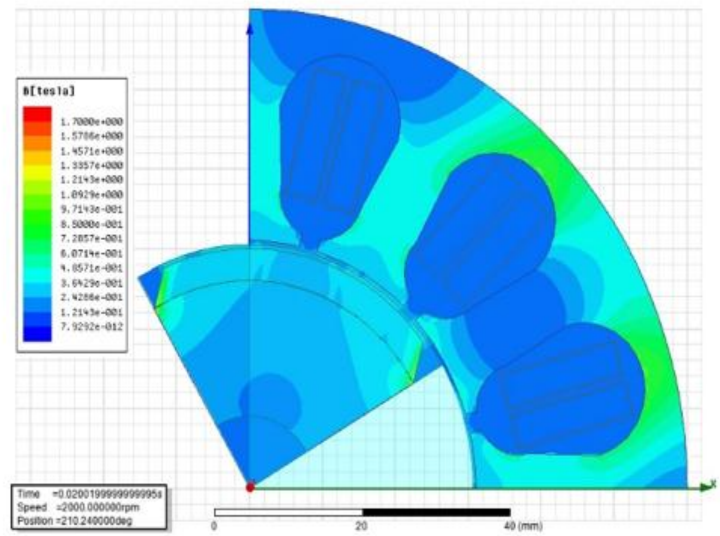
**Figure2. Cogging torque of BLDC motor for different types of four magnet materials: (a)Alinco5(b)ceramic 5(c)smso28(d) NdFe 35**

The maximum value of cogging torque for the four materials is listed in table- 2.

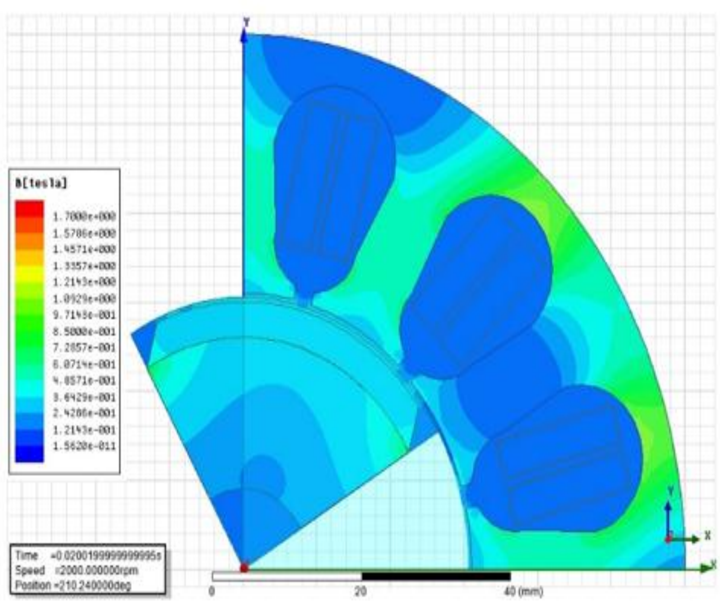
Table 2.Cogging torque for BLDC motor for each magnet material

| **Type of Magnet** | **Cogging Torque(N.m)** |
|---|---|
| Alnico5 | 0.076 |
| Ceramic5 | 0.046 |
| SmCo28 | 1.35 |
| NdFe35 | 1.74 |

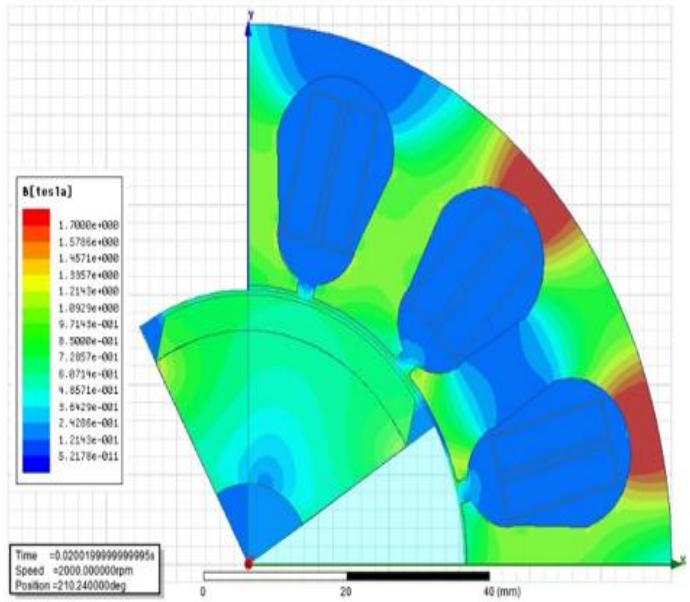
The flux density distribution of the BLDC motor from FEM analysis by Maxwell 2D is illustrated in figure 3.



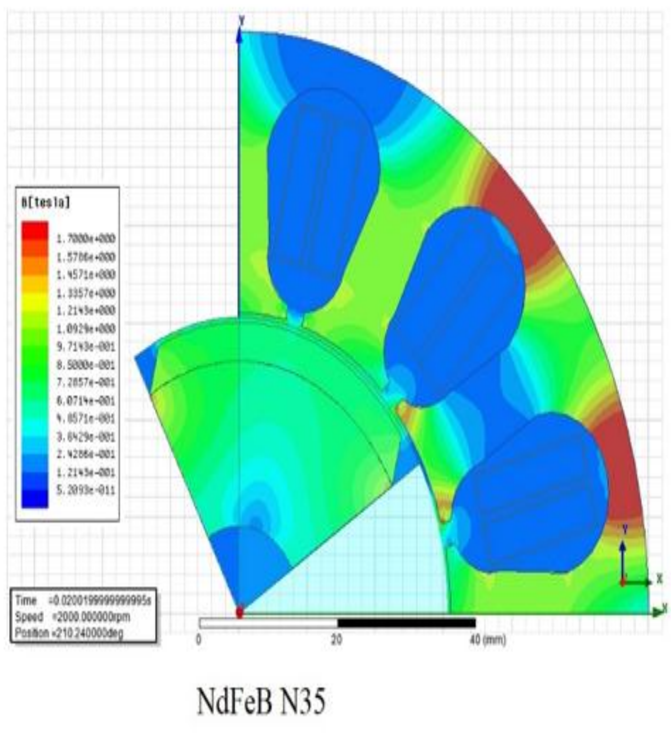

(a)



(b)




(c)



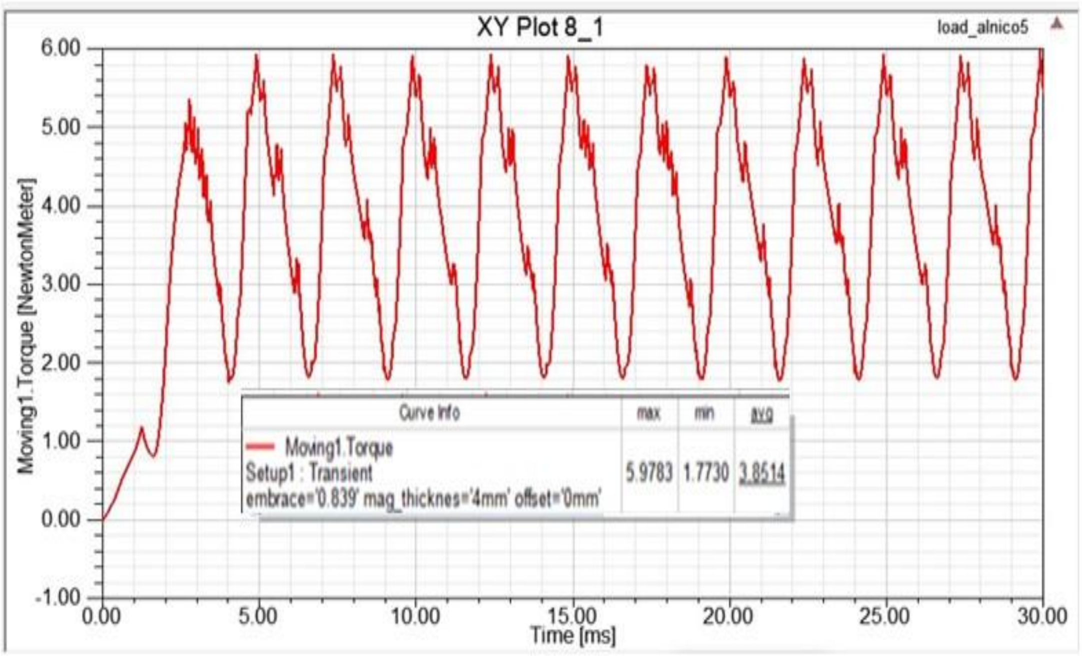

(d)

**Figure 3. Magnetic flux density distribution for magnets:(a)alnico 5(b)ceramic5(c)smso28(d)Ndfe35**

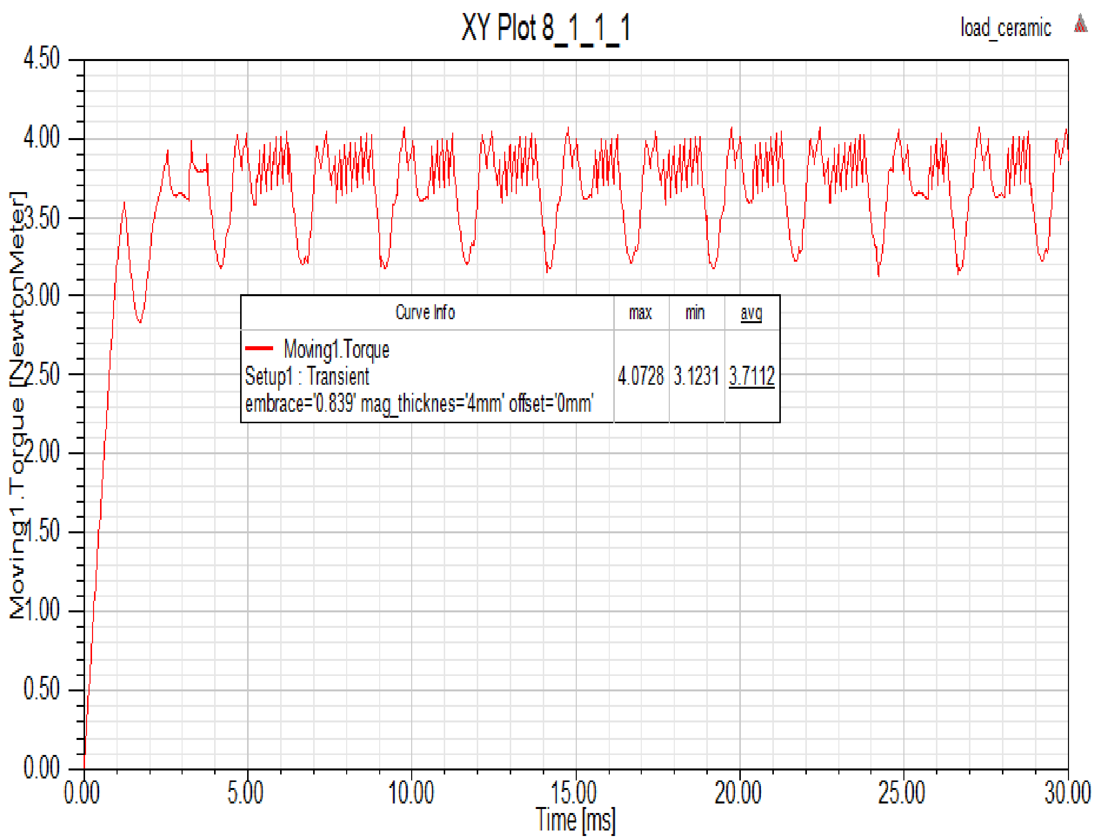
The above simulation results showed that the cogging torque is directly proportional to the magnet strength. So using more powerful magnets will increase the amount of cogging torque amplitude. However, it is necessary to consider other operating characteristics to better judge. Therefore in the next part, the different magnet materials will be simulated in their nominal load operation.

***B. Finite Element Analysis of Torque***

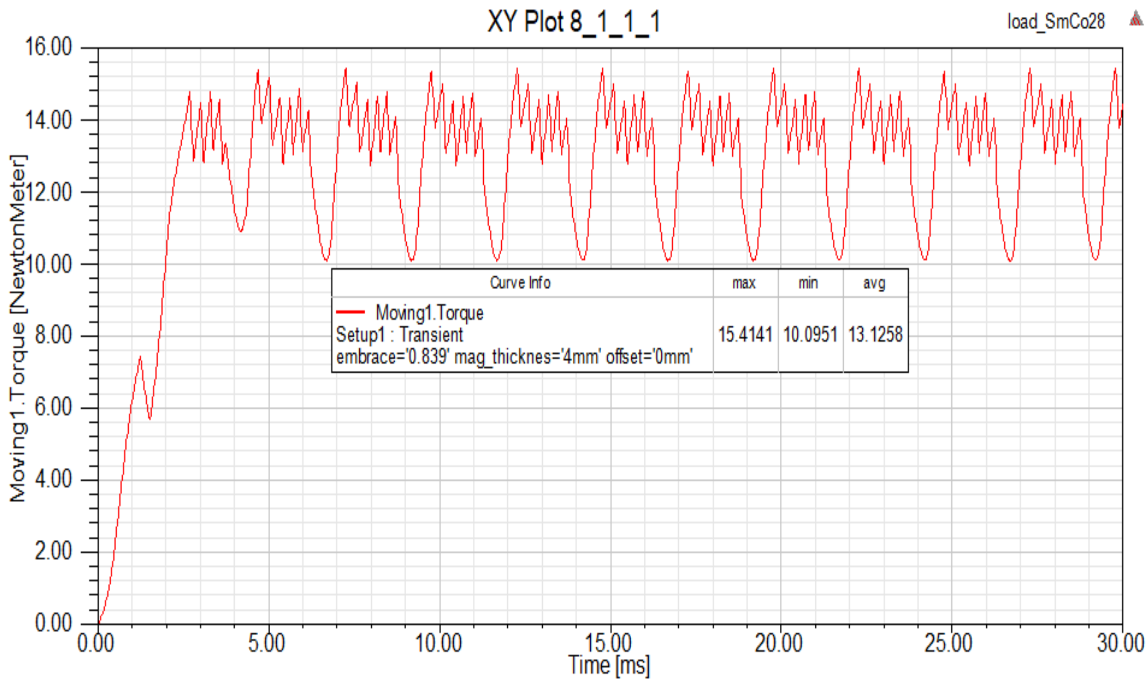
The simulations are conducted full load with the same circuit and initial positions for different magnet materials. The outcomes are shown in figure 4.


XY Plot 8_1
load_alnico5
Moving1.Torque [NewtonMeter]
Time [ms]
Curve Info
max
min
avg
Moving1.Torque
Setup1 : Transient
embrace='0.839' mag_thicknes='4mm' offset='0mm'
5.9783
1.7730
3.8514

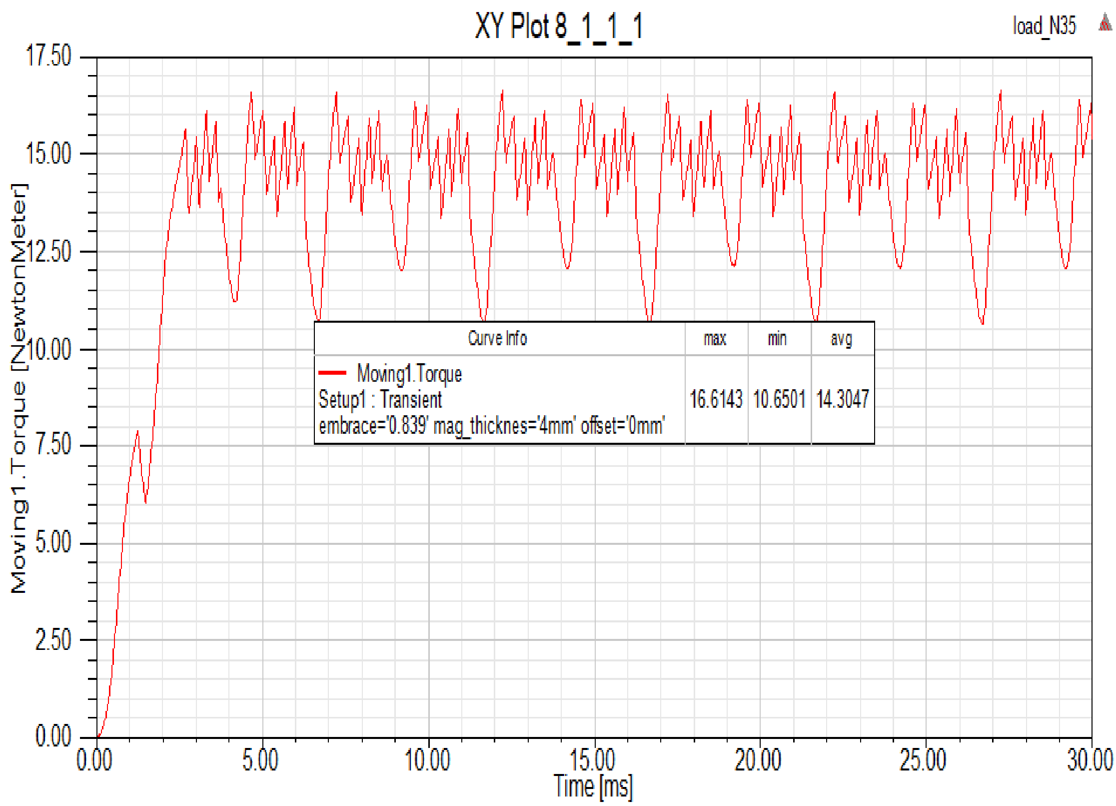
(a)


XY Plot 8_1_1_1
load_ceramic
Moving1.Torque [NewtonMeter]
Time [ms]
Curve Info
max
min
avg
Moving1.Torque
Setup1 : Transient
embrace='0.839' mag_thicknes='4mm' offset='0mm'
4.0728
3.1231
3.7112

(b)




( c )




(d)

**Figure 4. The effect of changing magnet on torque ripple of BLDC motor: (a)Alinco5(b)ceramic 5(c)smso28(d) NdFe 35**

Table 3 shows the average torque and torque ripple for the BLDC motor for each type of magnet material.

**Table3.**Torque and torque ripple vs. permanent magnet material

| Type of magnet | Average torque (N.m) | Maximum torque (N.m) | Minimum torque (N.m) | Torque ripple(%) (N.m) |
|---|---|---|---|---|
| Alnico5 | 3.85 | 4.97 | 1.77 | 109% |
| Ceramic5 | 3.71 | 4.07 | 3.12 | 25.6% |
| SmCo28 | 13.13 | 15.41 | 10.09 | 40.5% |
| NdFe35 | 14.31 | 16.61 | 10.66 | 41.6% |

The above result showed that the average torque is proportional to magnet strength ( a low average torque in Alinco5 and a high average torque in NdFe 35). Also, Alinco 5 has a high torque ripple, so it is not desirable to use in the rotor of BLDC motor for applications that need high torque and quiet operation.

## IV. CONCLUSION

A BLDC motor was modeled and analyzed successfully based on Maxwell 2D software with the assistance of RMxprt software. Four different magnets were adopted in the rotor of the test motor to study the effect of changing the motor's magnet on cogging torque and torque ripple. The FEM results showed that the cogging torque and the nominal torque are directly proportional to magnet strength, while the torque ripple is high in the lower strength of magnets. The flux density distribution inside different parts of the motor model can be obtained for many magnets. Due to the results of the BLDC motor designer should make a trade-off between motor nominal torque, torque ripple, and cost to select the proper type of magnet material used in the rotor of this motor. The research's methodology will give BLDC motor designers and other researchers a straightforward way to assess the effect of altering the rotor magnet material on BLDC motor performance without having to construct and test expensive prototype motors.

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