MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRONICS AND ELECTRICAL ENGINEERING

Selected Topics on Electrical Machines (EE 568)
Project 1 Report

April 2022

Instructor: Dr. Ozan Keysan

Written By:
Arash Allahyari

Github link

I. Introduction

In this report the results are presented based on the project description order and subsections are named according to the projection description. Generally, report starts with analytical modelling results which was coded in Matlab to calculate the inductance, reluctance, and torque. Then, FEA modelling which was carried out in Ansys Maxwell presented considering constant relative permeability and B-H curve in section III and IV.

In section V, a control circuit suggested to create a positive torque, the control method is similar to switched reluctance motor control system by introducing a pulse shape current based on the position of the rotor to create positive torque. Section VI is related to exporting an animation of the operation of the machine which is available in this link and also have been uploaded to the my Github account. In section VII, the results of the simulation in 3D model are presented. Please consider, the winding of the machine was modeled by considering 25 rings around core with 10 turns to create 250 turns of the machine.

II. Analytical modelling

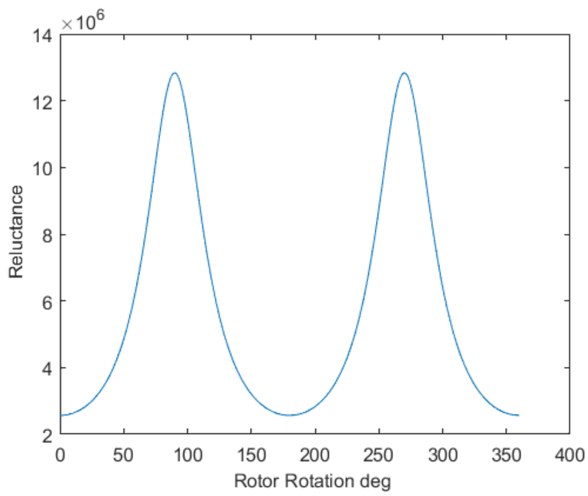
Part A) Calculate analytically the maximum and minimum reluctance (and inductance) as the rotor makes a full rotation. You can make necessary assumptions to simplify your calculations, please state them explicitly. You may assume the core is infinitely permeable for this section. Please obtain and plot the inductance variation as a function of rotation. You may assume sinusoidal variation.

Implemented code in Matlab:

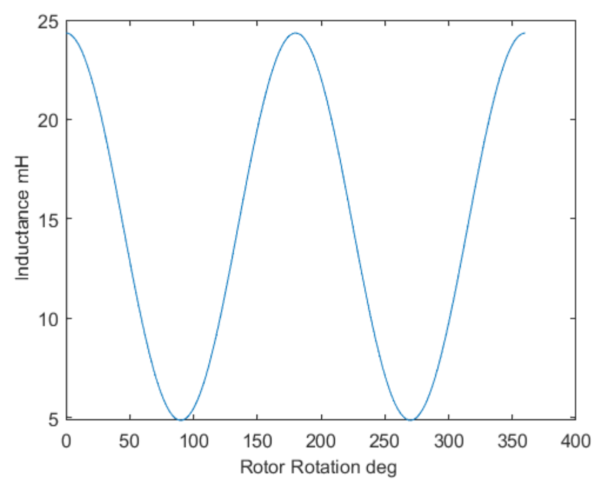
```
Lstack =20e-3;
Airgap_min = 2*0.5e-3;
Airgap_max = 2*2.5e-3;
u0 = pi*4e-7;
I_dc = 3 ;
Nseries = 250; % number of turns
Stator_Pole_arc = 74*pi/180; % 74 degree is the arc of the staor pole facing rotor
% Stator_Pole_arc = 67.5*pi/180;
Stator_radius = 12e-3;
% there are two airgaps Upper one I call Airgap1 and lower one Airgap2

% when rotor position is 90 deg minimum reluctance is achieved

Area = Stator_radius*Stator_Pole_arc*Lstack;
Rmin =  Airgap_min/(u0*Area);
% when rotor position is 0 deg maximum reluctance is achieved
Rmax = Airgap_max/(u0*Area);

theta = 0:360;

Lmax = Nseries^2/Rmin;
Lmin = Nseries^2/Rmax;
LL = (Lmax+Lmin)/2+(Lmax-Lmin)*cosd(2*theta)/2;

DL_Dtheta = -2*(Lmax-Lmin)*sind(2*theta)/2;
```

```
Torque = (I_dc^2*DL_Dtheta)/2;

figure
plot(theta,R_airgap)
xlabel('Rotor Rotation deg ');
ylabel(' Reluctance');
figure
plot(theta,L*1000)
xlabel('Rotor Rotation deg ');
ylabel(' Inductance mH');
figure
plot(theta,Torque)
xlabel('Rotor Rotation deg ');
ylabel(' Torque Nm');
```

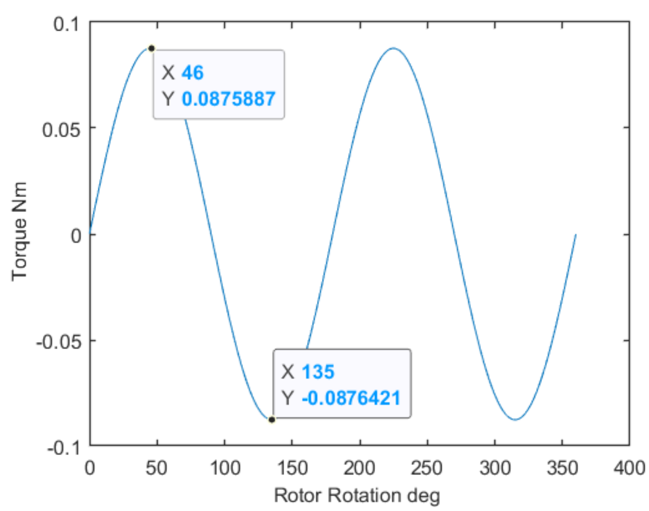
Part B) Derive and plot the torque generated in the system under constant DC excitation.
I assumed to have sinusoidal reluctance for this machine. Therefore, to mathematical equation of the reluctance, I need maximum and minimum reluctance values. Moreover, the frequency of this sinusoidal waveform will be two time the actual rotor rotation.



Plot of reluctance based on rotation



Plot of inductance based on rotation

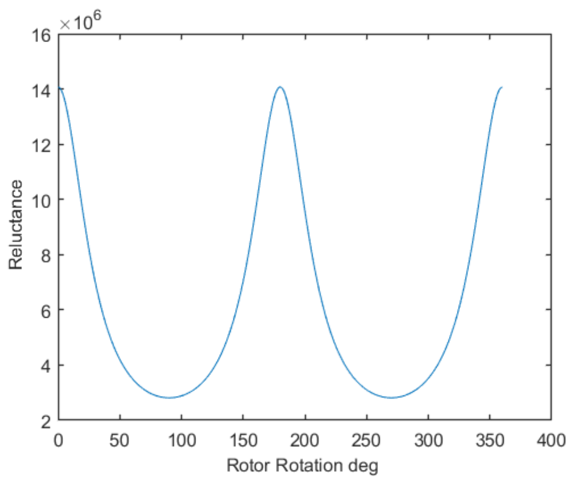


Plot of torque based on rotation

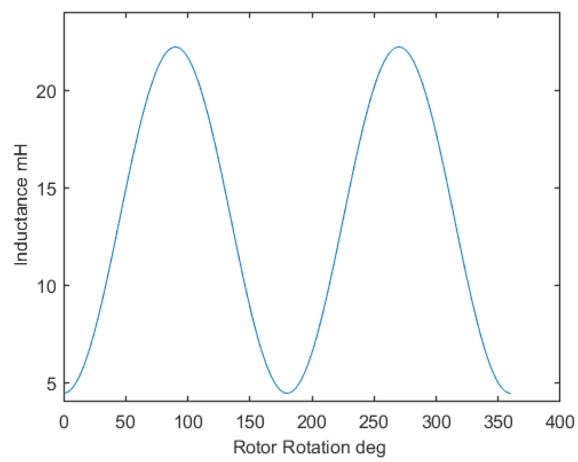
Fig. 1, plot of reluctance, inductance, and torque as a function of rotation from above code

c) Suggest a method to improve your model by including non-linear effects (fringing flux, non-homogeneous flux distribution) etc. A detailed description is enough, a full derivation is not required.

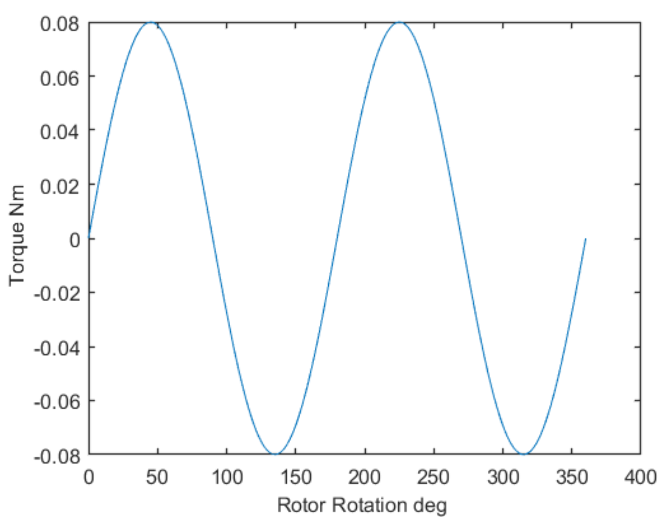
A simple method can be to decrease the arc of the stator that is facing the rotor pole to consider for the flux leakages. If we decrease the stator arc facing the rotor pole from the 74 degrees to 67.5 degrees (10% decrease) the plots of reluctance, inductance and torque would be as figure 2



Plot of reluctance based on rotation



Plot of inductance based on rotation



Plot of torque based on rotation

Fig. 2, plot of reluctance, inductance, and torque as a function of rotation for stator pole arc of 67.5 degrees

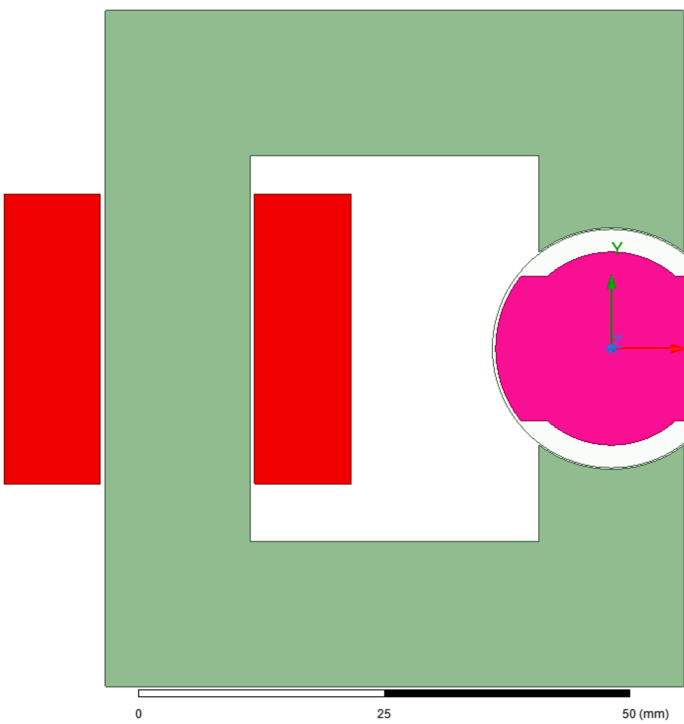
By comparison of torque at Fig. 1 and Fig. 2 it is obvious that maximum torque has been decreased from 0.087 to 0.08 due to decrease of stator pole arc facing rotor pole to compensate for the flux leakages.

Additionally, increase of airgap length is a common and effective method to consider for flux leakages. However, calculation of effective airgap is not a simple task and rather complicated due to this fact that flux does not travel from stator to rotor in a homogeneous way in which we assumed to be homogeneous in analytical calculations.

III. FEA Modelling (2D - Linear Materials)

Model the system in a 2D FEA software (you can use any software you want, please have a look at the options at the course page).

Figure 3 displays the model created in in Ansys Maxwell, model was developed with parameters to facilitate the simulation and parameters are displayed in figure 3. Red rectangles in the model are coils in which modeled as solid copper.



(a) Model in Ansys Maxwell

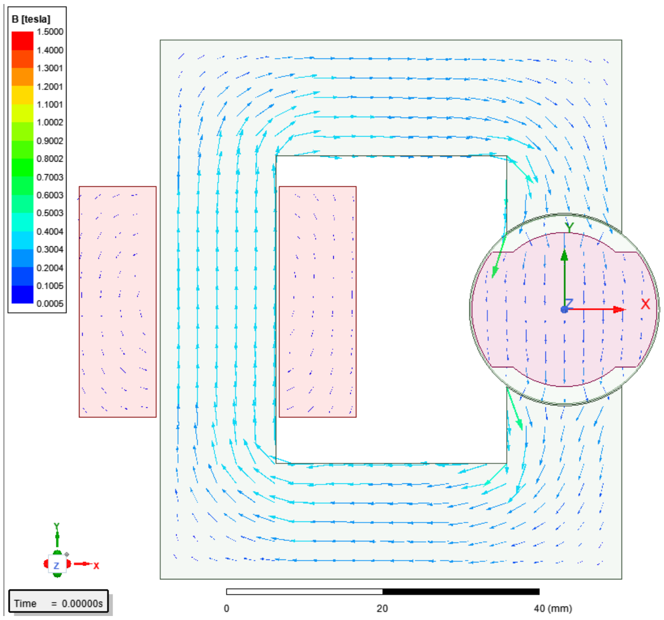
Name	Value	Unit	Evaluated Value
CoreW	60	mm	60mm
CoreH	70	mm	70mm
RotorOffset	22.5	mm	22.5mm
StatorBore	12.5	mm	12.5mm
Airgap	0.5	mm	0.5mm
StackLength	20	mm	20mm
num_turns	250		250
InitialPosition	0	deg	0deg
MachineRPM	500	rpm	500rpm
NumPoles	2		2
NumTorquePointsPerCycle	100		100
NumTorqueCycles	0.995		0.995
TimeStep	120/(MachineRPM/1rpm*NumPoles)/NumTorquePointsPerCycle		0.0012
TimeStop	NumTorqueCycles*120/(MachineRPM/1rpm*NumPoles)		0.1194

(b) Parameters of the developed model

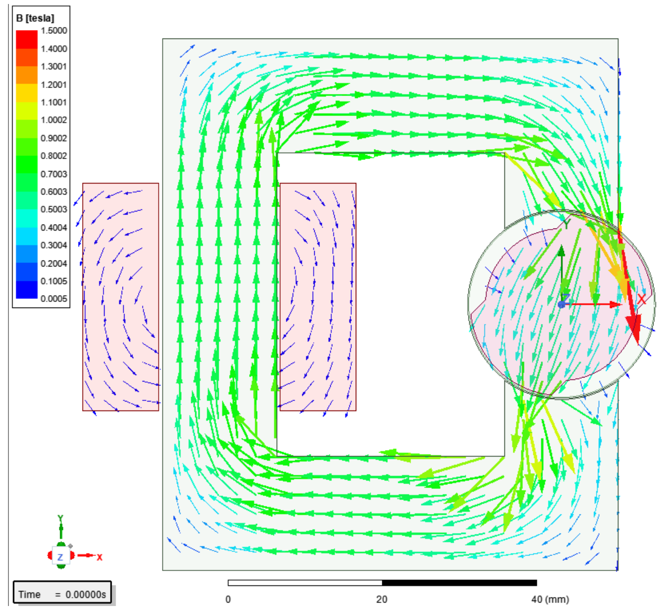
Fig. 3

Part A) Draw the flux density vectors for three positions (0, 45, 90 degrees), adjust the scales so the figures are readable.

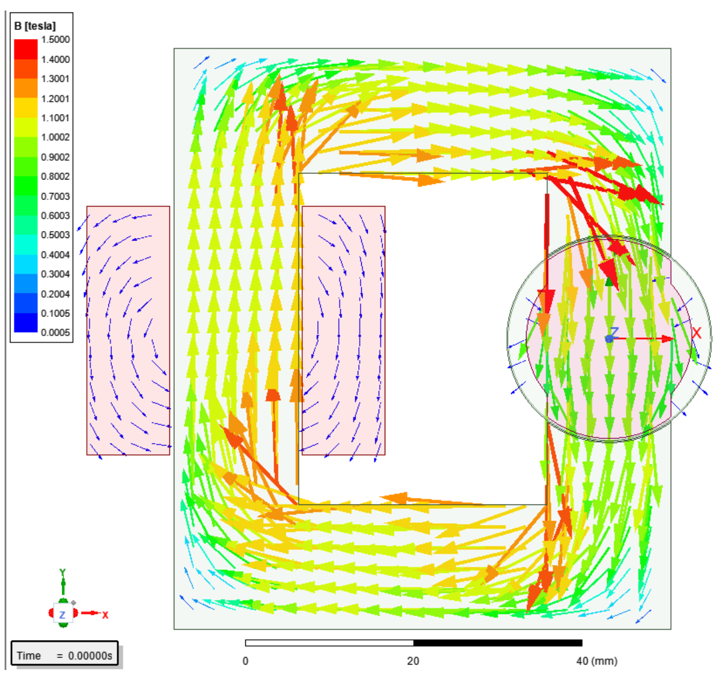
Relative permeability is assumed to be constant and equal to **4000** for this part.



Flux density vectors at rotation 0 degree (B scale 0-1.5 T)



Flux density vectors at rotation 45 degree (B scale 0-1.5 T)

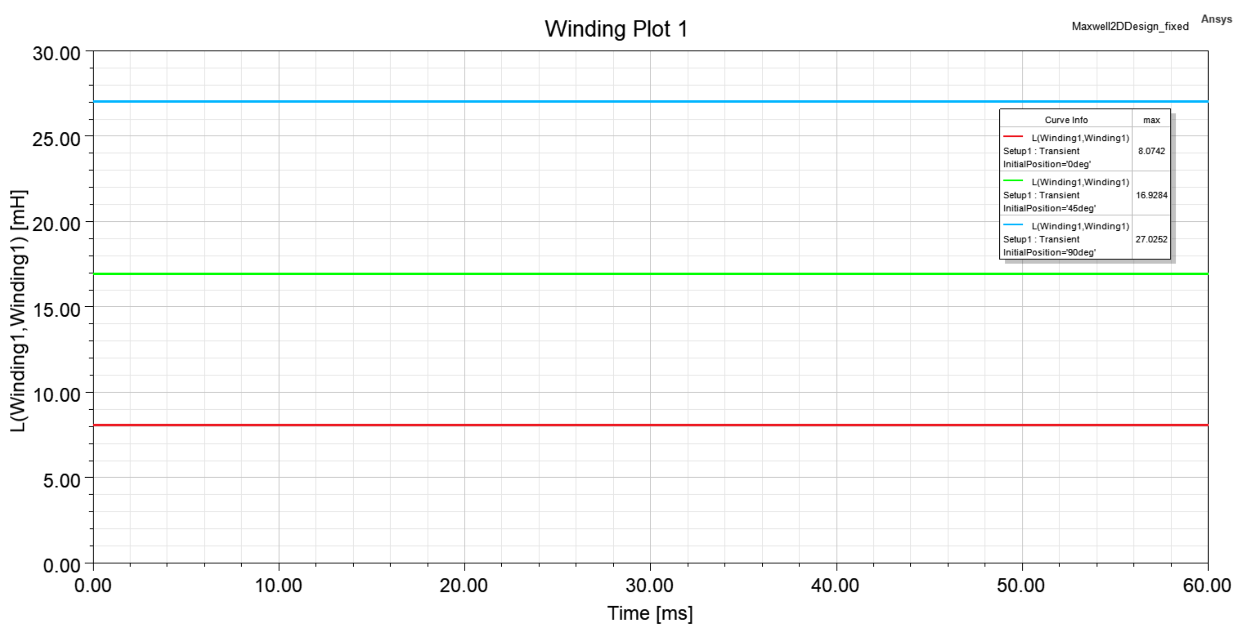


Flux density vectors at rotation 90 degree (B scale 0-1.5 T)

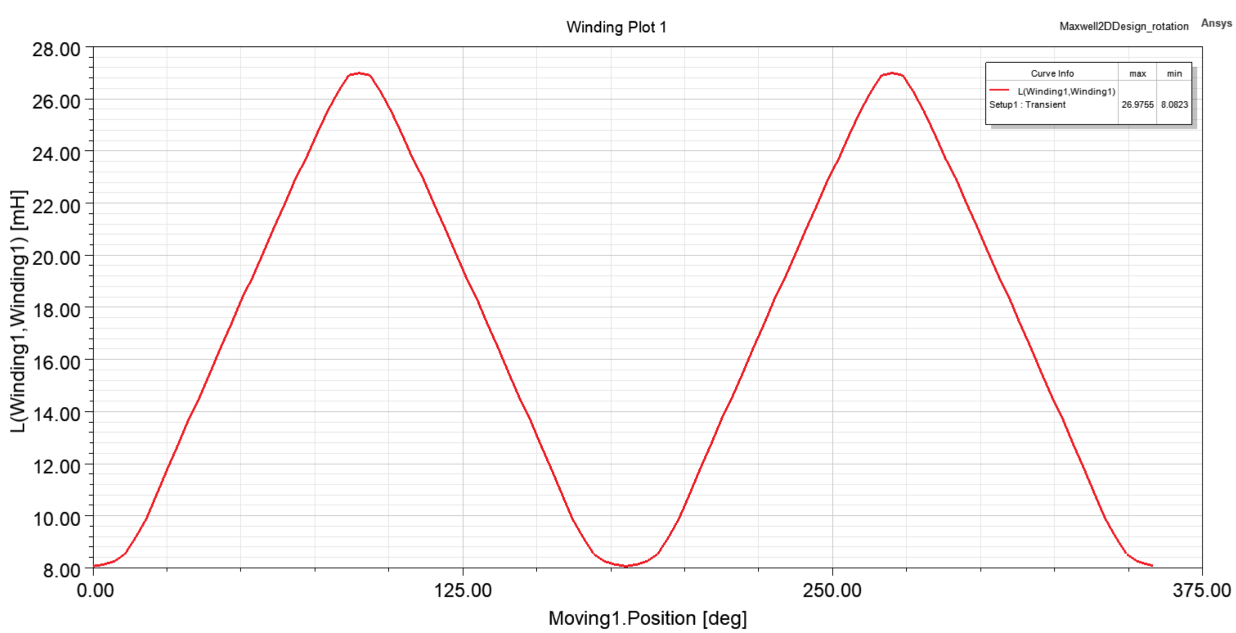
Fig. 4

Part B) Calculate the inductance, and stored energy in the system for these three positions.

Plot of inductances of the machine in Fig. 5 by transient simulation



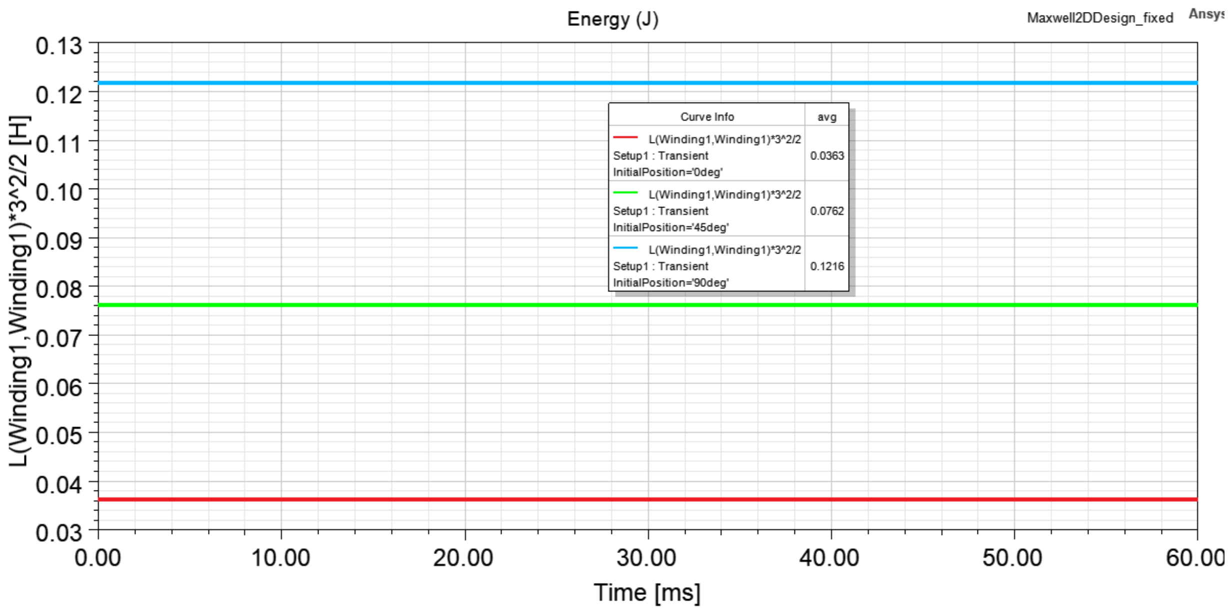
Inductance of the winding at 0, 45, 90 degree positions



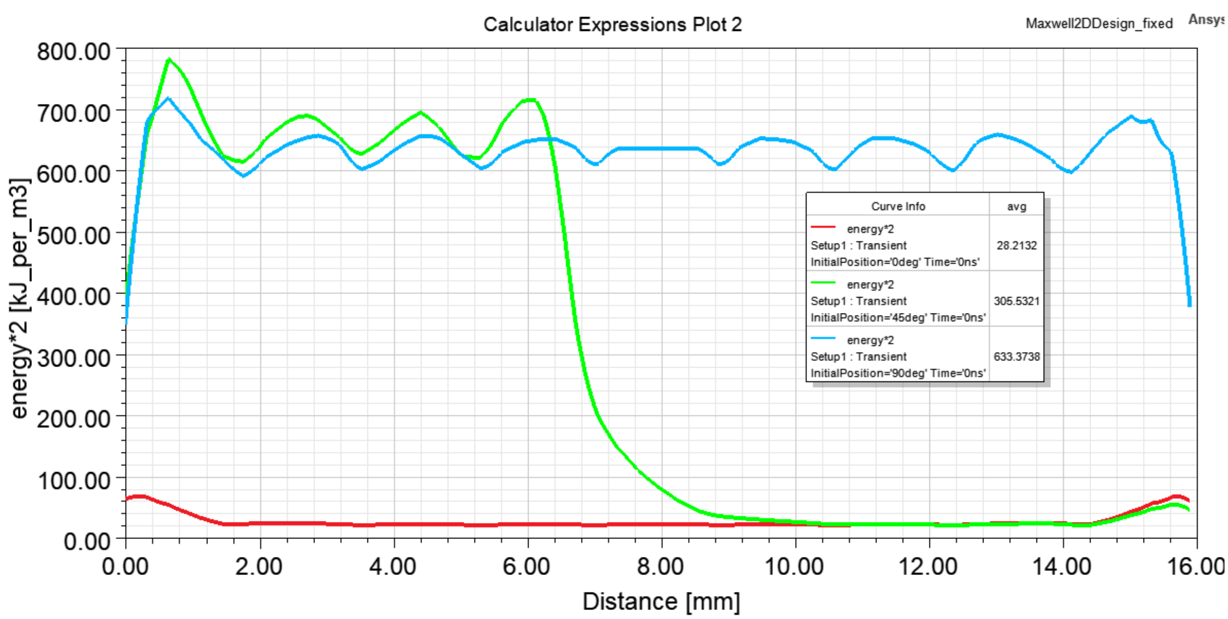
Inductance of the winding based on rotor degree position (max: 16.9, min: 8 mH)

Fig. 5

Plot of energy based on the position in Fig. 6



(a) Calculation of energy from ½ L I^2 based in the different rotor positions,



(b) Calculation of energy using FEA in the different rotor positions,

Fig. 6

The calculated energy in airgap from equation ½ L I^2 and direct calculation of energy using FEA in the airgap is shown in Fig. 6. Fig. 6b shows the energy density (J/m3) and since there two airgaps, the value has been multiplied by 2. However, I am not sure which volume (whole rotor volume or only airgap volumes) should be multiplied to calculate energy from energy density in Fig. 6b.

Part C) Derive the torque generated in your system as a function of rotation angle for at least ten positions. Compare your results with the analytical model results from part 1.

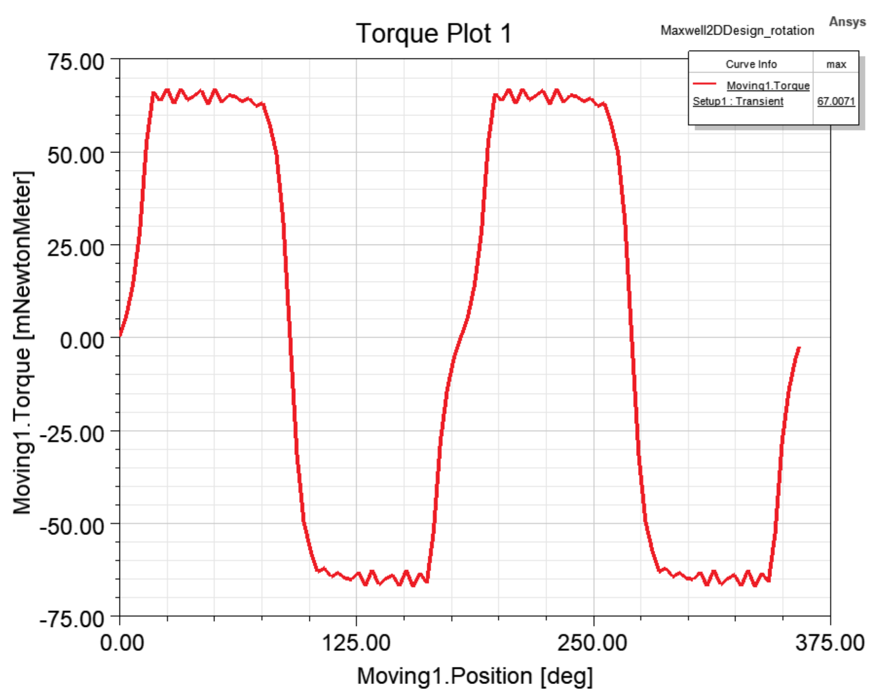
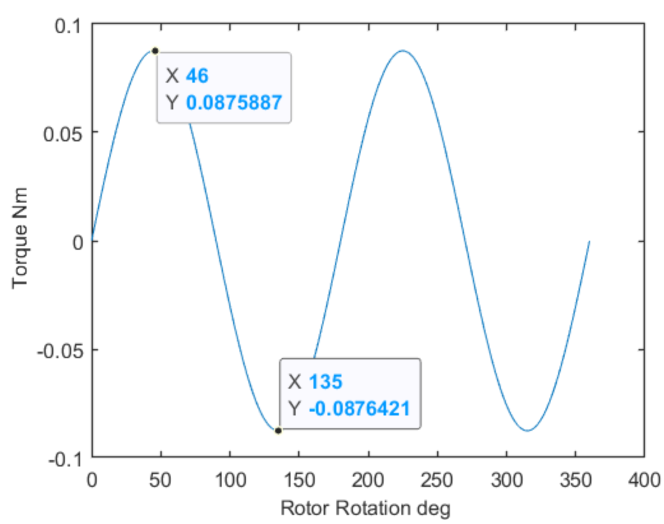


Fig. 7 Torque vs. rotor position from FEA with linear core material



Analytical torque curve From figure 1

Fig. 7 displays the torque vs. rotor moving position at constant 3 A dc current. The maximum value of torque is 67.27 mNm which is lower than what has been obtained by analytical approach which was around 87 mNm.

By comparison of torque of Fig. 7 and analytically calculated torque from figure 1 several differences are considerable. One is the difference of maximum value of torque and the other is the difference of torque waveform. Maximum value of torque difference is related to the inductance calculation which was done without considering flux leakages in analytical approach, therefore, it is reasonable to end up with a higher torque. Plus, regarding the waveform of torque which is different from each other, in analytical approach a sinusoidal variation is assumed for the inductance which is not entirely true because the inductance/reluctance variation is also matter of shape of pole of stator or rotor. Hence, it can be stated that the sinusoidal assumption is another reason to have a higher torque in analytical approach.

IV. FEA Modelling (2D - Nonlinear Materials)

In this section, use the same model, but make the material properties NON-LINEAR (i.e. permeability will change as the core saturates).

The selected non-linear material is steel 1008 with B-H curve shown in figure 8

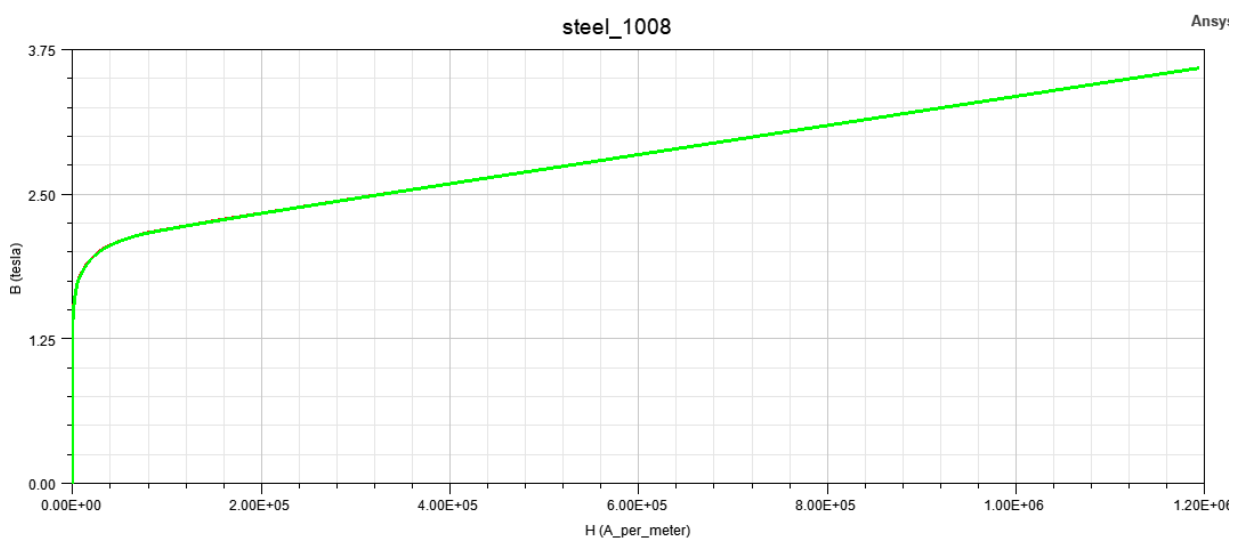
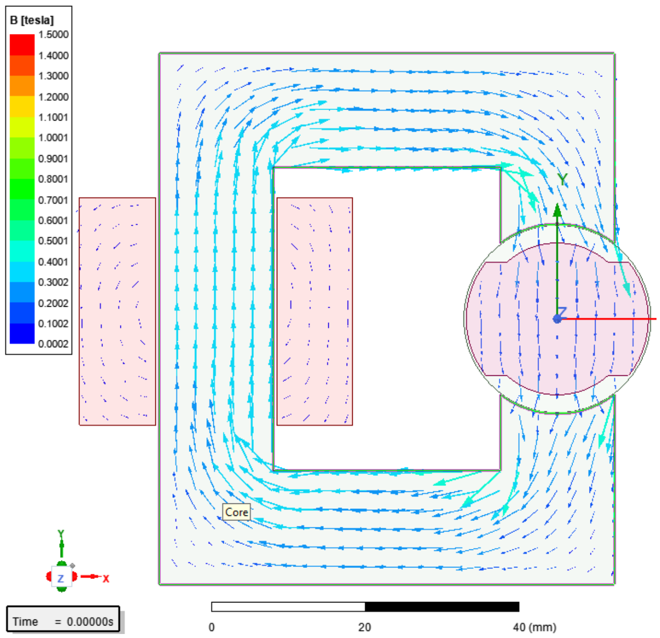
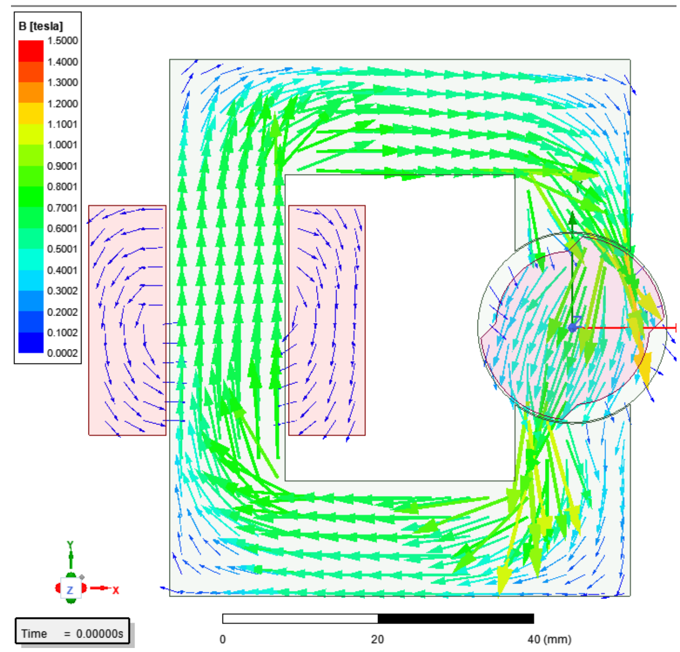


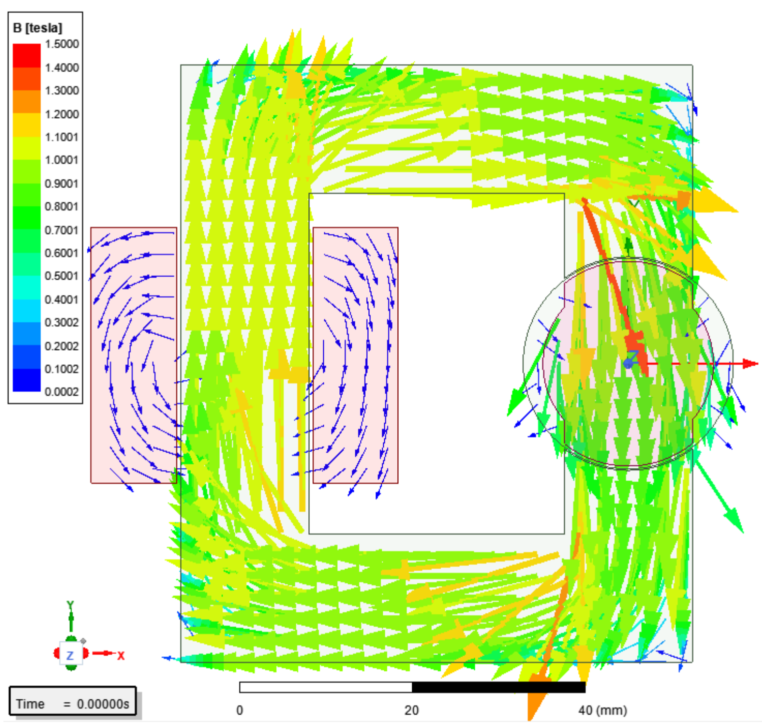
Fig. 8 B-H curve of steel 1008



Flux density vectors at rotation 0 degree (B scale 0-1.5 T)



Flux density vectors at rotation 45 degree (B scale 0-1.5 T)

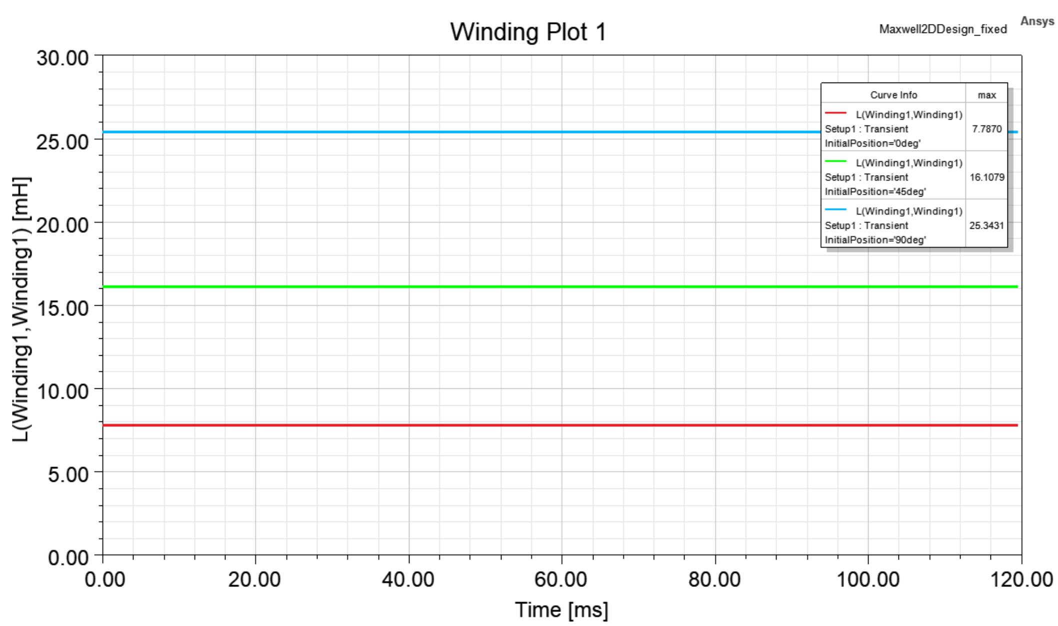


Flux density vectors at rotation 90 degree (B scale 0-1.5 T)

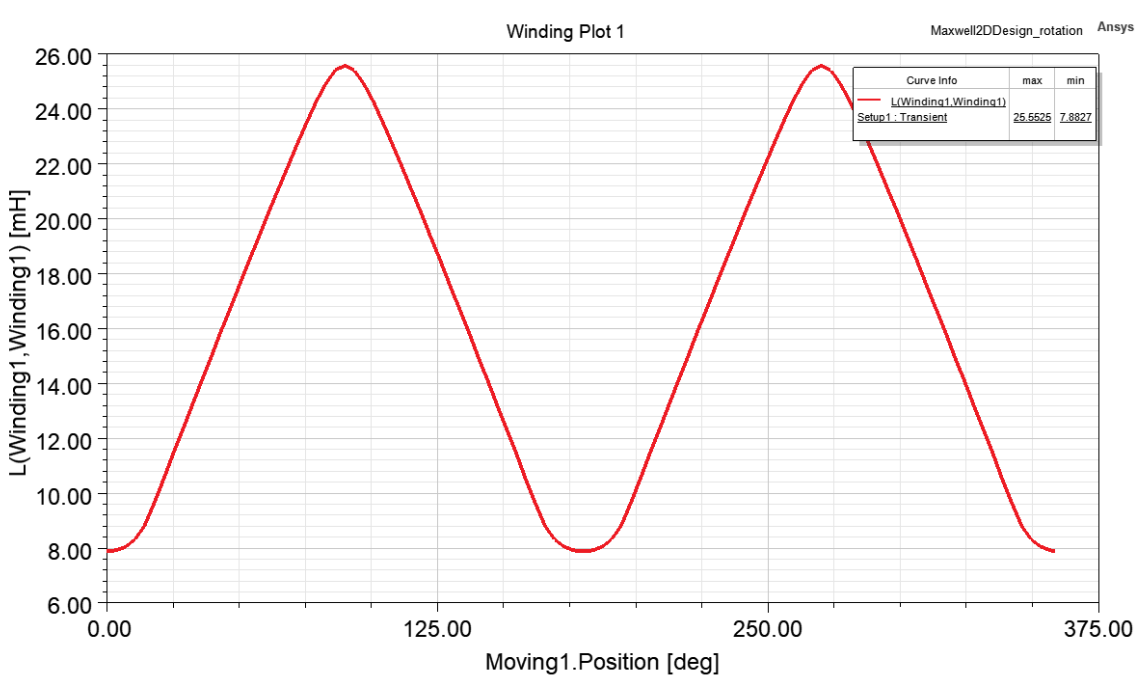
Fig. 9

Part B) Calculate the inductance, and stored energy in the system for these three positions.

Plot of inductances of the machine in Fig. 10 by transient simulation



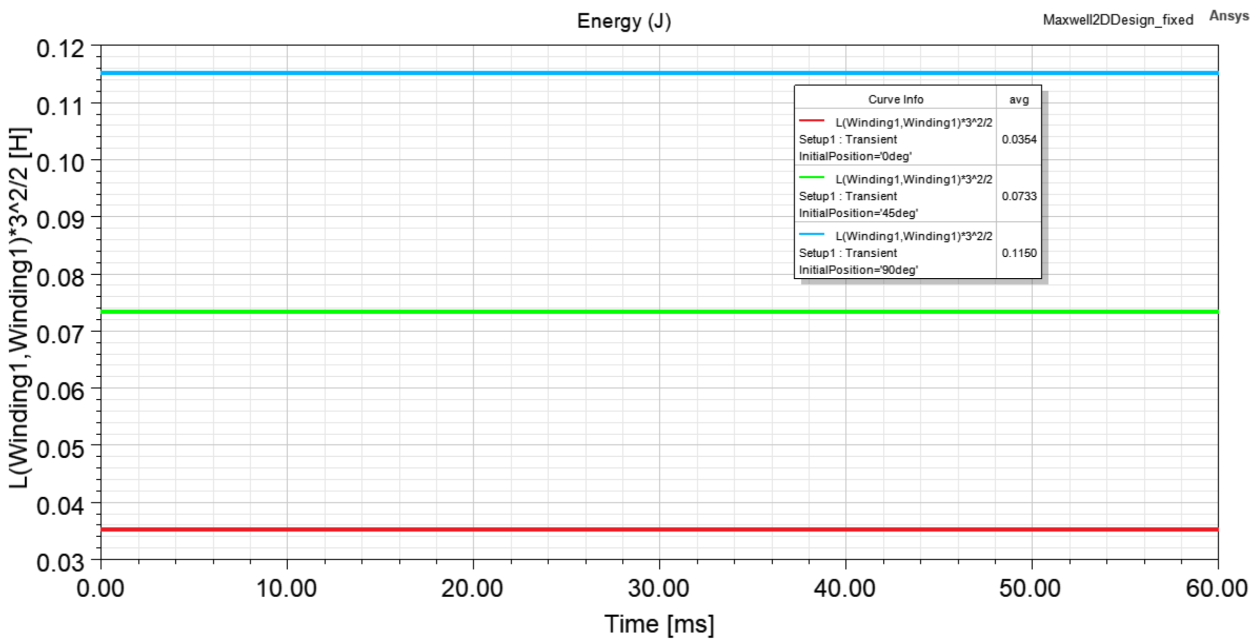
Inductance of the winding at 0, 45, 90 degree positions



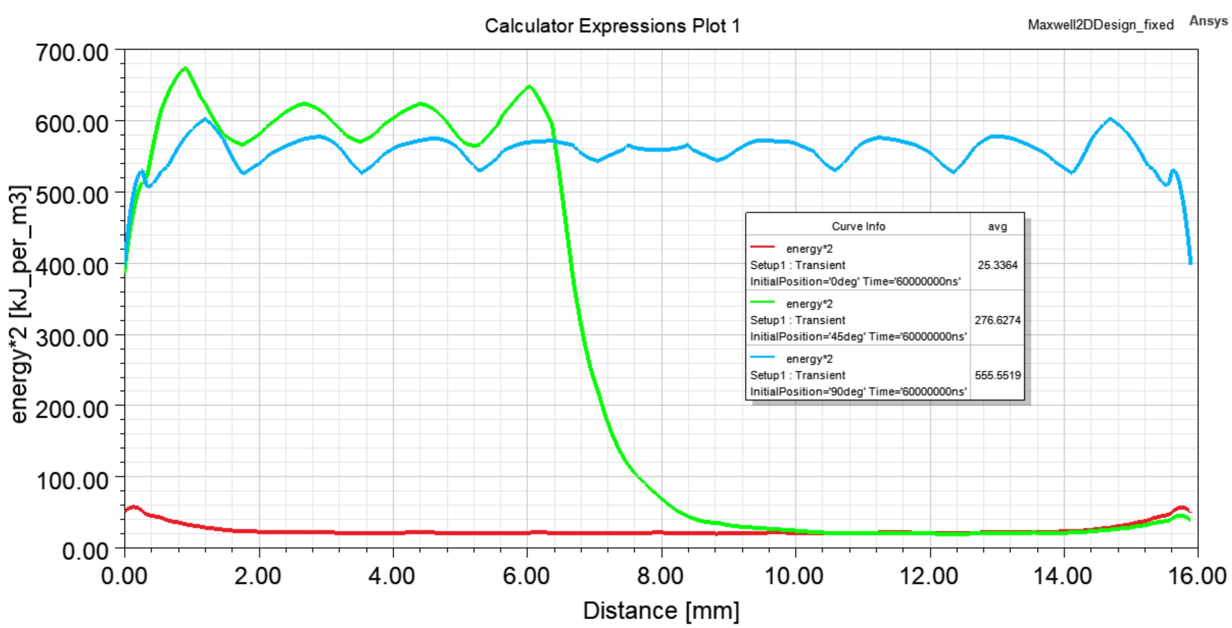
Inductance based on rotor position

Fig. 10 Inductance calculation

Plot of energy based on the position for nonlinear material FEA simulation



Calculation of energy from ½ L I^2 for different rotor positions



Calculation of energy using FEA in the airgap for different rotor positions

Fig. 11 energy calculation

The calculated energy in airgap from equation ½ L I^2 and direct calculation of energy using FEA in the airgap is shown in Fig. 11. Fig. 11b shows the energy density (J/m3) and since there two airgaps, the value has been multiplied by 2. However, I am not sure which volume (whole rotor volume or only airgap volumes) should be multiplied to calculate energy from energy density in Fig. 11b.

Part C) Derive the torque generated in your system as a function of rotation angle for at least ten positions. Compare your results with the analytical model results from part 1.

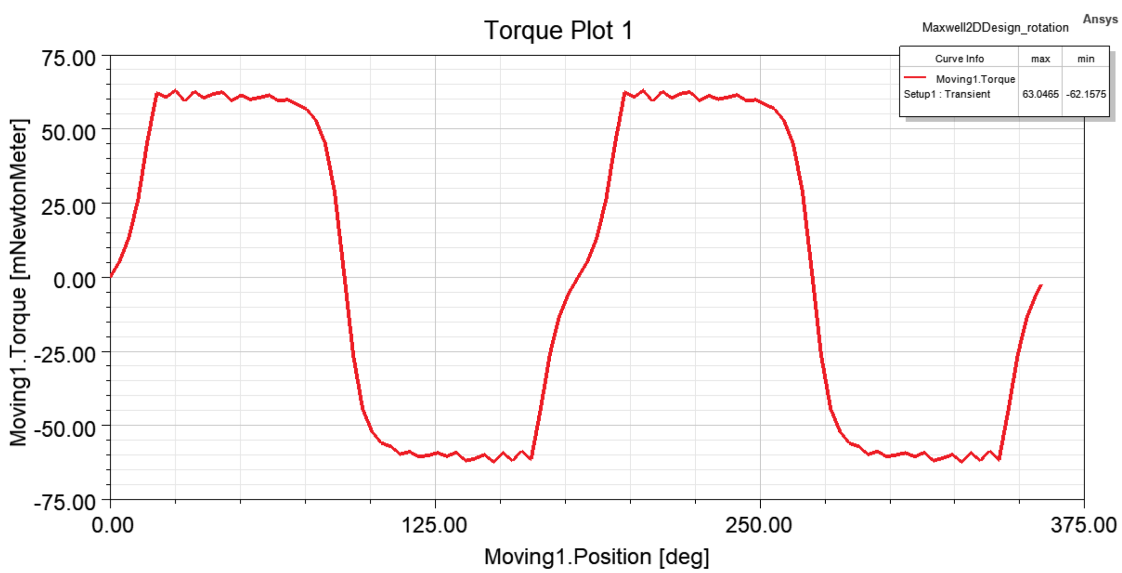


Fig. 12 Torque vs. rotor position from FEA with nonlinear core material

Comparison of results from analytical, linear material and nonlinear

Table I			
	Analytical method	2D FEA with linear material	2D FEA with nonlinear material
Inductance at 0 degree (mH)	4.89	8.03	7.78
Inductance at 45 degree (mH)	14.6	16.92	16.1
Inductance at 90 degree (mH)	24.34	27.07	25.34
Maximum torque (mNm)	87	66.74	63.04

As shown in Table I, as the simulation get more realistic the inductance and torque decreases. Hence, in a more detailed and realistic analysis the actual torque would be less than the 2D FEA with nonlinear material.

V. Control Method

Propose a control method to enable continuous rotation. You can use an on/off DC current, square wave, sinusoidal excitation as you like. Show a positive torque can be generated by using your analytical model and your 2D models. Present any graphs or FEA results to prove your point.

Considering the figure 7, it is not possible to create a continuous torque by just providing a constant DC current to the system. However, if a pulse current with a specific start angle and a specific width is provided, a positive average torque can be achieved. To do that a transient simulation is implemented in the Ansys Maxwell with the use of external circuit to provide the required current waveform. The current waveform should have periodic pulse waveform. The start point of pulse and duration of this pulse is also important. The duration or the width of pulse is directly related to the arc of the rotor and stator. It is also obvious from figure 12 that torque becomes zero at 90 degree of rotor rotation then goes to negative in which we do not want that happen. Hence, the pulse width should be smaller than 90 degrees. Furthermore, we should not let the torque to become negative. So, a smaller value than 90 degrees, 85 degrees has been selected for the pulse width. Here the series resistance won't make any difference in torque value because a current source is providing the required current.

Drive circuit is as simple as figure

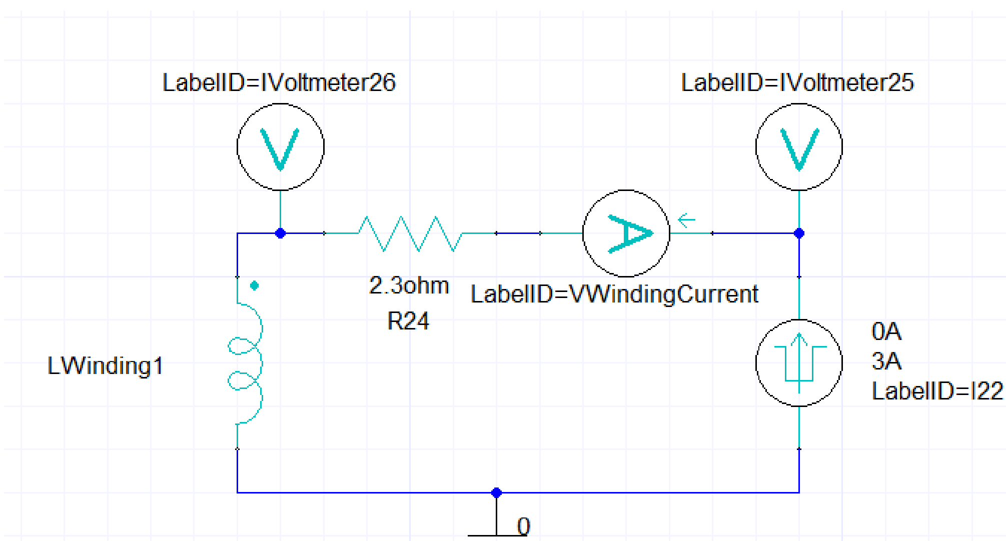


Fig. 14 control circuit to create average positive torque

The results of torque produced by this method is as follows:

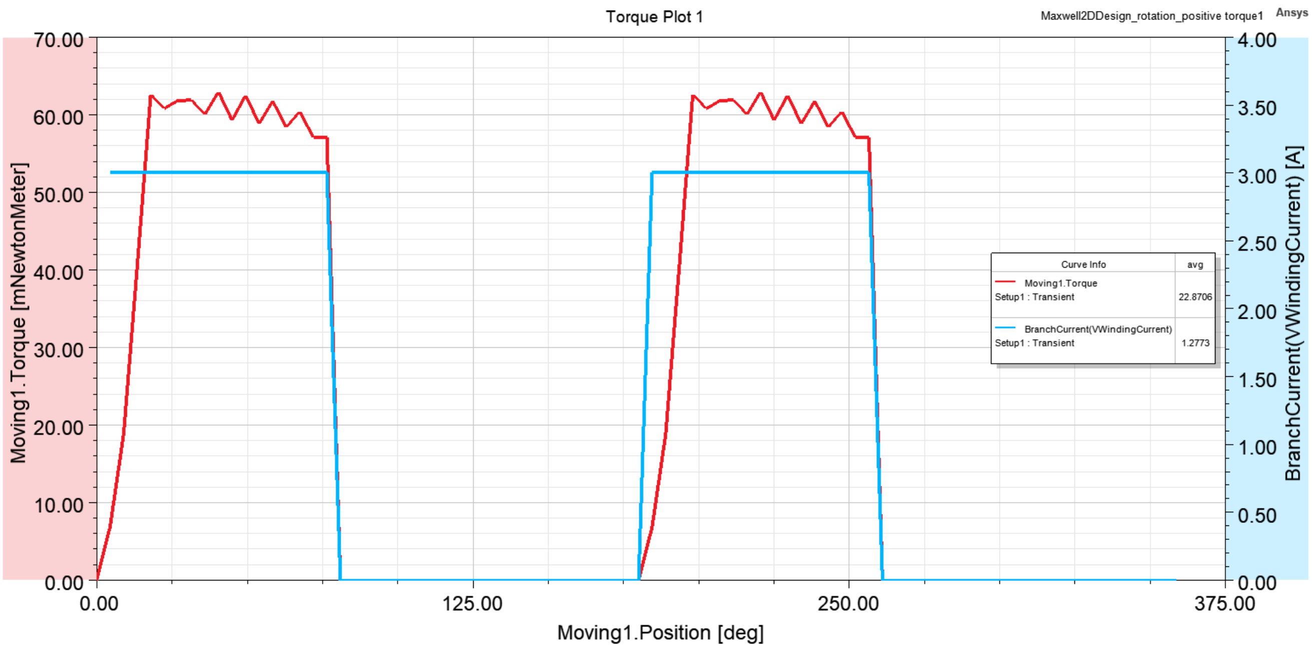
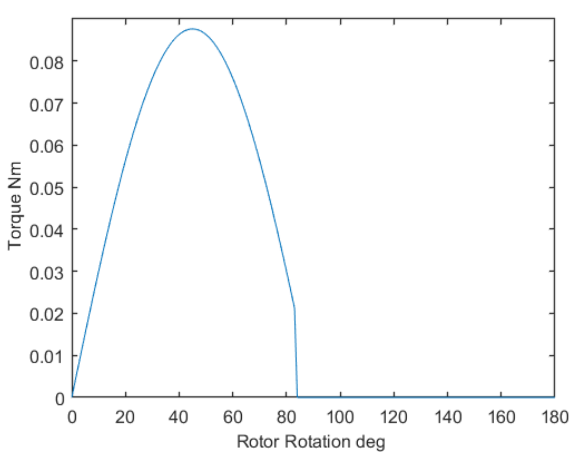


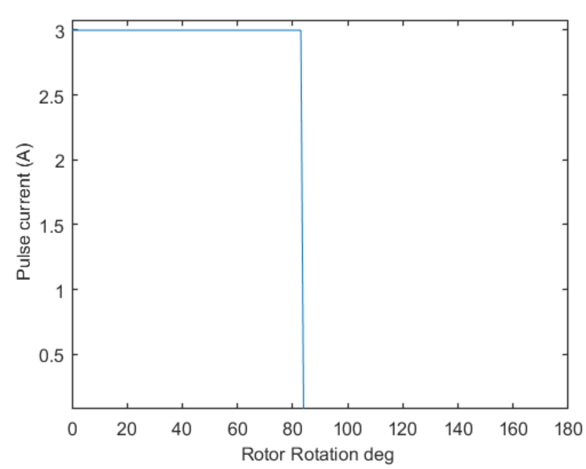
Fig. 15 the created pulse and resultant torque

The blue line is the pulse current generated by the drive circuit to keep the torque a positive value. The pulse width is 85 mechanical degrees with the initial angle of 2 mechanical degree. As a result of designed drive circuit, the average achieved torque is 22.87 mNm.

Analytical approach for this method would be simple. Since the pulse is only effective for 85 mechanical degrees (MDEG), therefore, pulse start from 0 MDEG to 85 MDEG. So, the resultant torque would be similar to Fig. 16.



Resultant torque by utilizing a pulse current



Input pulse current

Fig, 16, analytical approach for the control circuit (up 180 mechanical degree)

Since there are two poles in the machine, average value of torque must be multiplied by two get the total average torque which has been calculated to be 54.8 mNm. While using FEA the average torque calculated to be 22.87 mNm.

An alternative method would be to use a sinusoidal current and a thyristor to control the firing to keep the input current a positive value only in the positive torque region. This method is similar to providing a pulse which was presented in this section.

VI. Bonus-I (Motion Animation)

Prepare a short video, or .gif image to animate the rotation of the rotor. You can use the conditions in Q3, or Q4. In the animations show the flux density variation (either lines or vectors) in the core during rotation.

Exporting animation of the operation of the machine from Ansys Maxwell is available in this link and also have been uploaded to the my Github account.

VII. Bonus-II (3D FEA Analysis)

3D model created in Ansys Maxwell is shown in figure below. I used a Transcoil from Maxwell library to create the coil. The coil was modeled with 25 coils in which every coil has 10 turns to make 250 turns in total. The distance between coils is 0.1 mm.

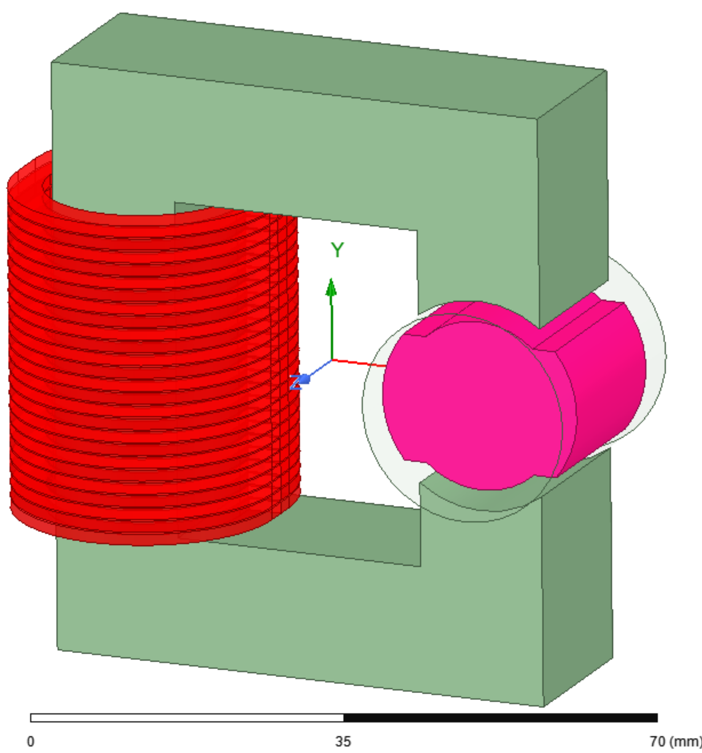
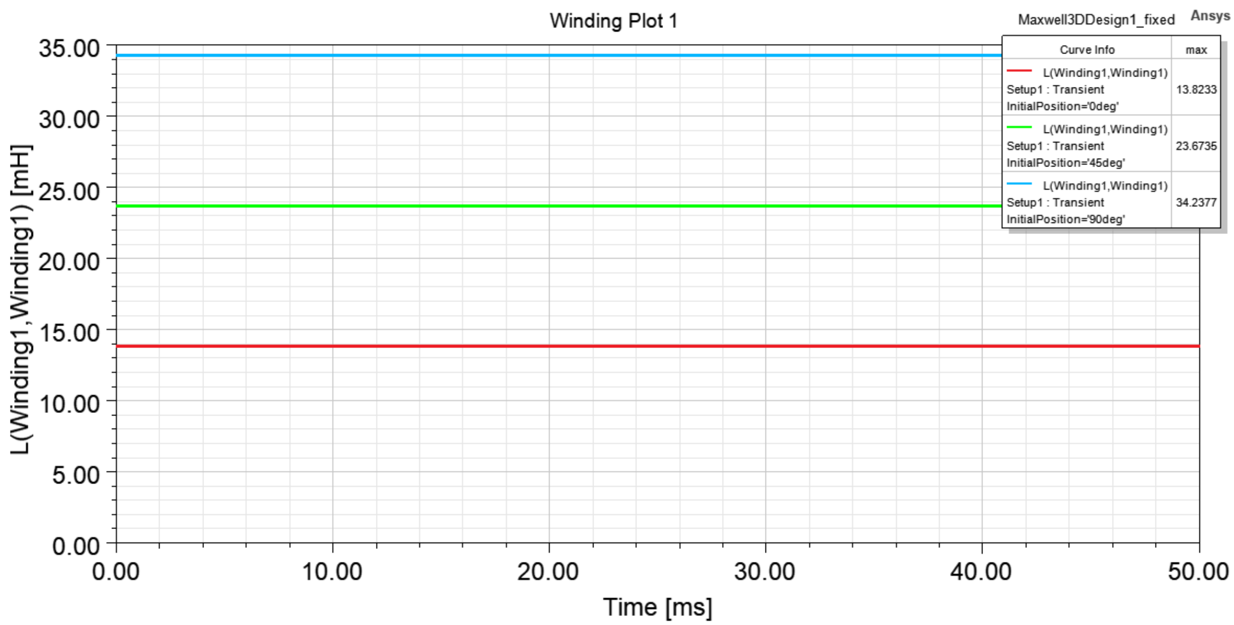
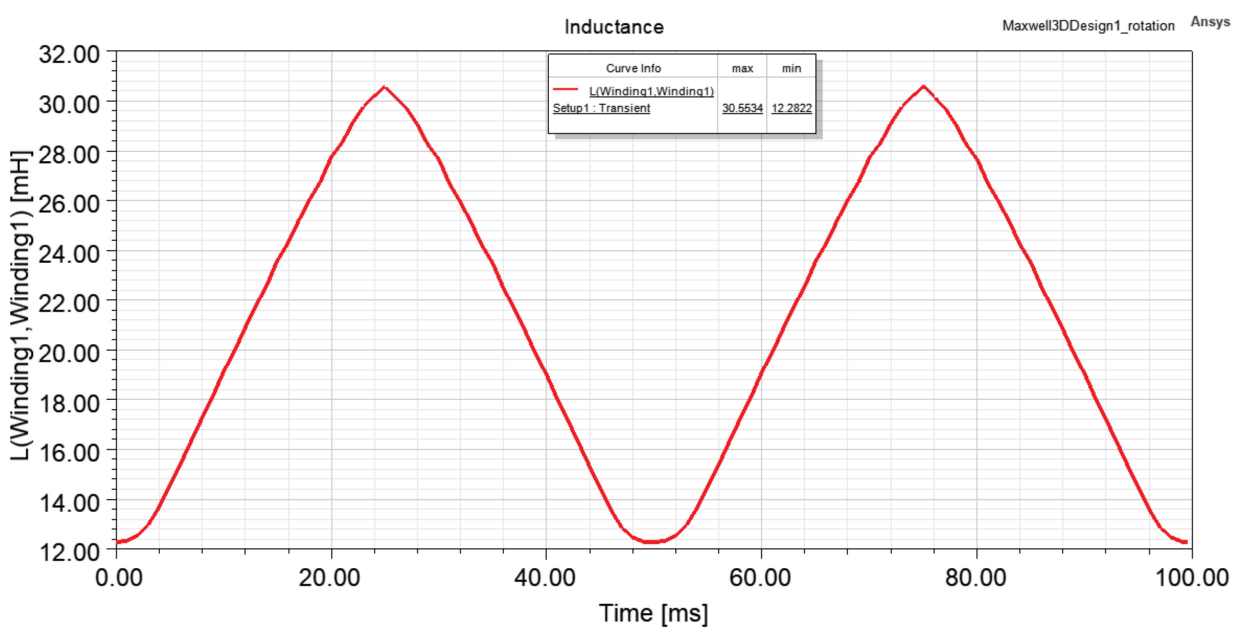


Fig. 17 the 3D designed model of the core

Inductance calculation results are shown in Fig. 18



Inductance of the winding at 0, 45, 90 degree positions



Inductance based on rotor position

Fig. 18 inductance calculation

Plot of energy based on the positions, nonlinear material FEA simulation

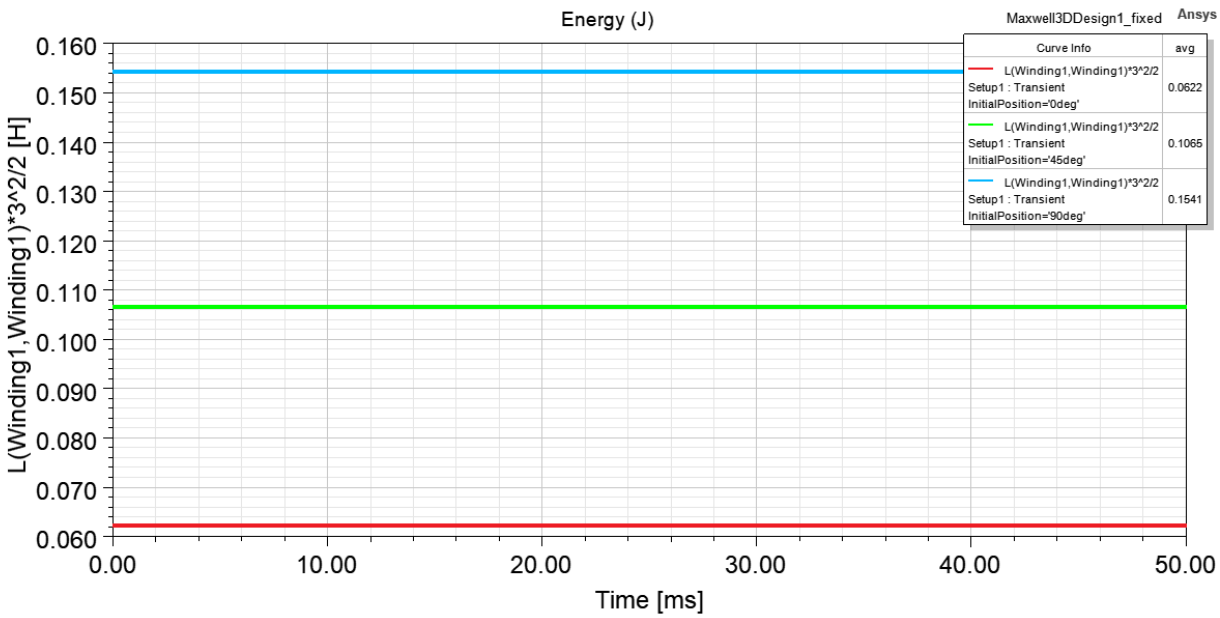


Fig. 19, Energy based equation ½ L I^2 at 0, 45, 90 rotor positions

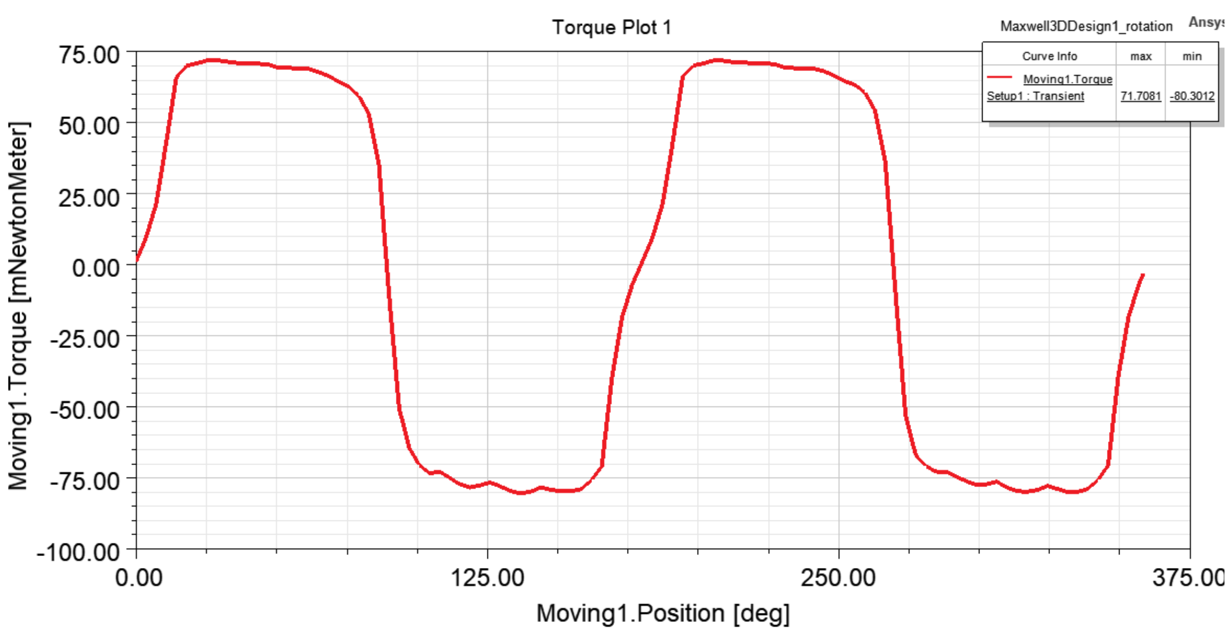


Fig. 20 Torque vs. rotor position from 3D FEA with nonlinear core material

Comparison of results from analytical, linear material and nonlinear and 3D FEA

Table I				
	Analytical method	2D FEA with linear material	2D FEA with nonlinear material	3D FEA with nonlinear material
Inductance at 0 degree (mH)	4.89	8.03	7.78	12.8
Inductance at 45 degree (mH)	14.6	16.92	16.1	23.67
Inductance at 90 degree (mH)	24.34	27.07	25.34	34.23
Maximum torque (mNm)	87	66.74	63.04	71.7

Well, results obtained in 3D FEA is interesting because the inductance values and maximum torque has been increased in comparison with 2D FEA results. I expected more decrease of torque and inductance. Maybe it is related to method I used to simulated coils.