**METU – EEE**

Middle East Technical University – Electrical Electronics Engineering Department

**PROJECT REPORT**

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within the scope of the course

**EE568**

**SELECTED TOPICS ON ELECTRICAL MACHINES**

*by* Dr. Ozan KEYSAN

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**PROJECT REPORT NO** : 02

**PROJECT NAME** : Motor Winding Design & Analysis

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Introduction

In this report, we assume have a 20-pole, 120 slot, 3-phase machine for integral slot winding and for 20 or 22 pole number, we choose a slot number between 20 and 30 for fractional slot winding. Integral and fractional slot windings are investigated and designed. Also 2D FEA model of the fractional winding is simulated and analyzed. Winding diagrams are drawn. Distribution factor and pitch factor of the each winding are calculated. Also, 3rd and 5th harmonics winding factors are calculated.

1. Integral Slot Winding Design

We assume we have a 20-pole, 120 slot, 3-phase machine.

is the slot number per pole per phase:

is the electrical angle between two consecutive slot:

Assume each coil has 1 turns and full pitched. So, winding will be single layer.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| slot | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| winding | A | A | -C | -C | B | B | -A | -A | C | C | -B | -B |

Fig. 1: Winding diagram of the given integral slot machine for one pole pair (12 slot)

**Winding Factor**

Winding factor () of a winding includes two main parts as known distribution factor () and pitch factor ().

Distribution factor: 🡪 for 1st fundamental component

Pitch factor: 🡪 for 1st fundamental component

Where is harmonic order, is pitch angle (for full pitch, ).

Winding factor for 1st fundamental component:

3rd and 5th harmonics winding factors

Distribution factor: 🡪 for 3rd harmonic component

Pitch factor: 🡪 for 3rd harmonic component

Winding factor:

Distribution factor: 🡪 for 5th harmonic component

Pitch factor: 🡪 for 5th harmonic component

Winding factor:

As a result of this part, for selected full pitch winding the fundamental component winding factor is obtained as 0.96, 3rd harmonic component is -0.7 and 5th one is 0.25. When we plot the magnetic loading distribution (B):

plot (0.96\*sin(x)-0.7\*sin(3\*x)+0.25\*sin(5\*x))

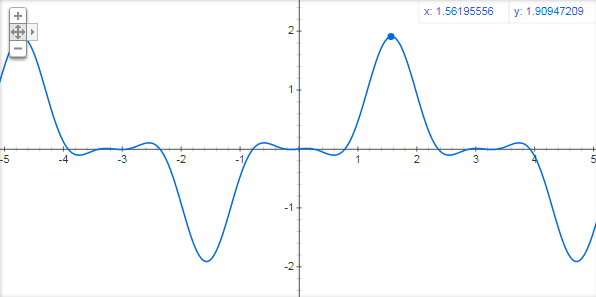


Fig. 2: Magnetic loading B of the selected integral slot winding

As seen from the figure 3rd harmonic negative winding factor causes sharpen the peaks of the total B. This effect creates long width zero crossing and smaller area under the curve that means smaller flux (φ) and energy. This type winding design creates nearly 70% 3rd harmonic component so it is inefficient design. Overcome this situation we can use fractional slot that is analyzed in next section.

2. Fractional-Slot Winding Design

In this part, we are going to analyze a 3-phase permanent-magnet synchronous machine with a fractional-slot winding.

Using the Emetor Winding Design,

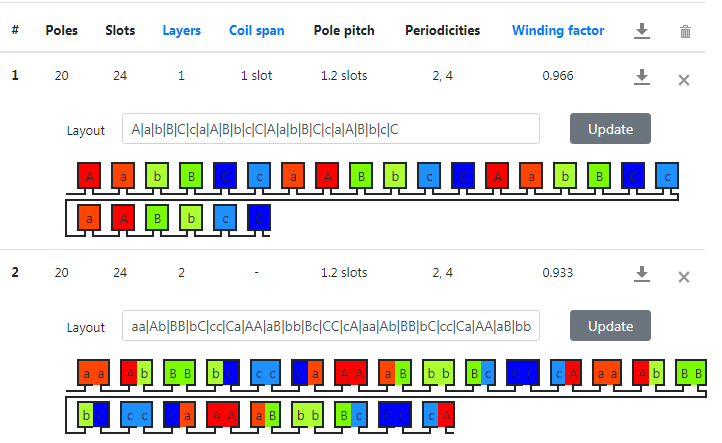
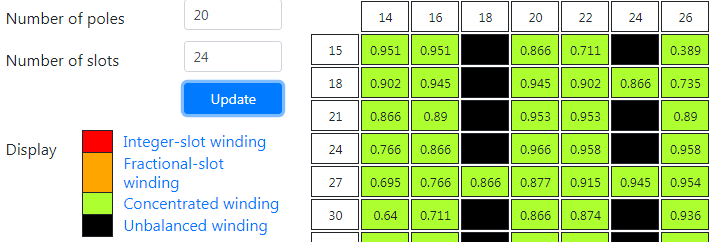


Fig. 3: Emetor Winding Design page, selected pole 20, slot 24 returns 1.2 slots pole pitch (5/6), 0.966 winding factor for 1 layer and 0.933 winding factor for 2 layer concentrated winding

is the slot number per pole per phase:

is the electrical angle between two consecutive slot:

Table 1: phase angle of the induced voltage in each slot

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1st slot | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 0o | 150o | 300o | 90o | 240o | 30o | 180o | 330o | 120o | 270o | 60o | 210o |

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24th slot |
| 0o | 150o | 300o | 90o | 240o | 30o | 180o | 330o | 120o | 270o | 60o | 210o |

Then the phasor diagram for one phase is drawn by using Dolomites software:

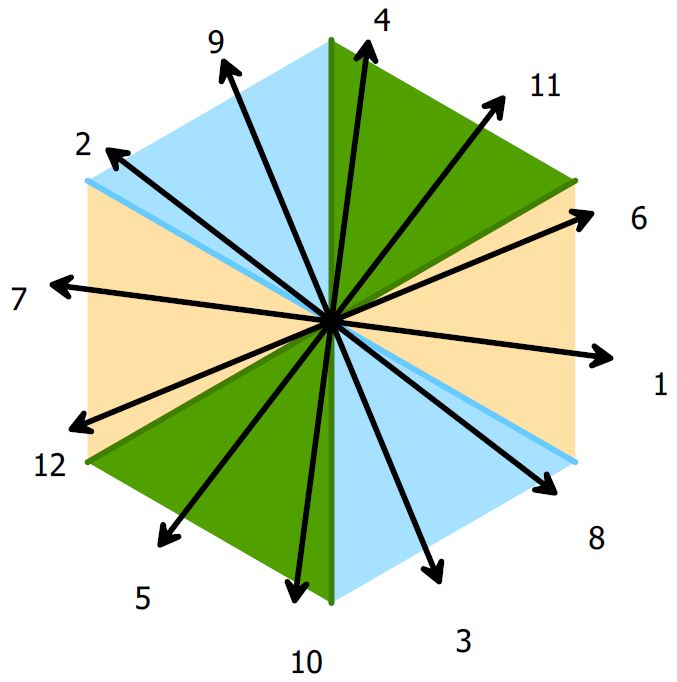


Fig. 4: Phasor diagram of 20 pole, 24 slot, 5/6 pitched winding

**2a) Flux Density Vectors for Linear Materials (0, 45, 90 degree rotor)**

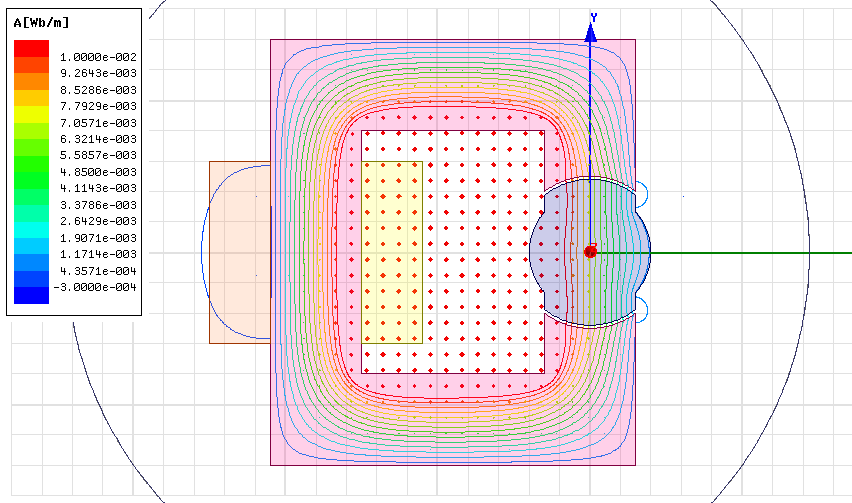
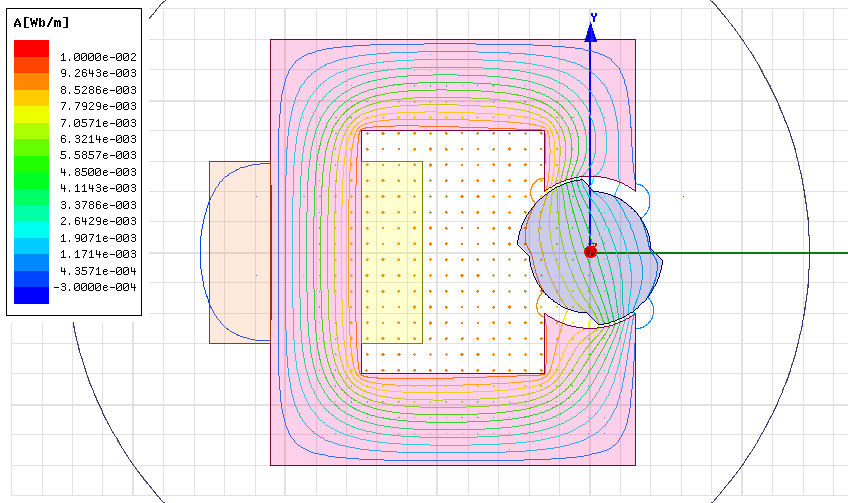
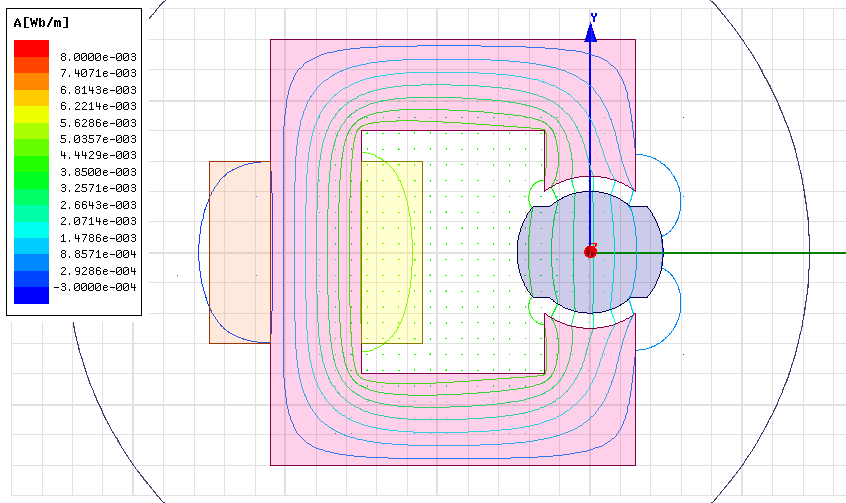
(a) 0o position(b) 45o position(c) 90o position

Fig. 10: Flux lines and vectors for linear (µ=902.6) stator and rotor material

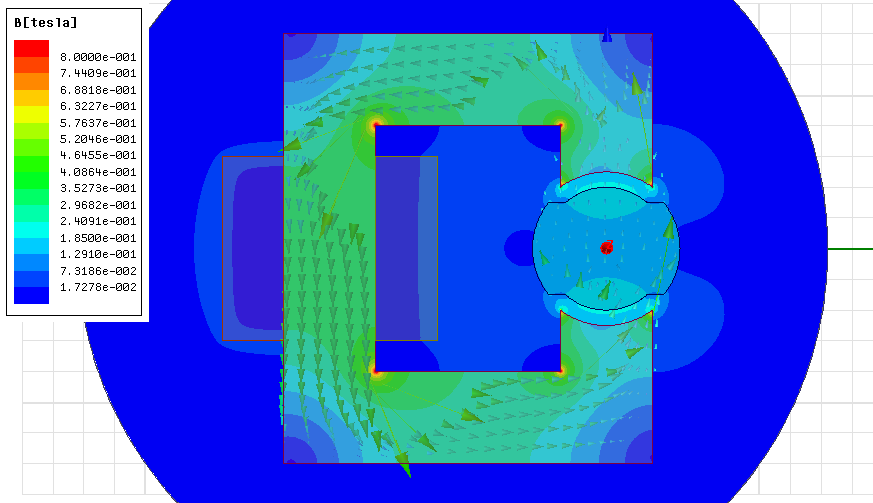
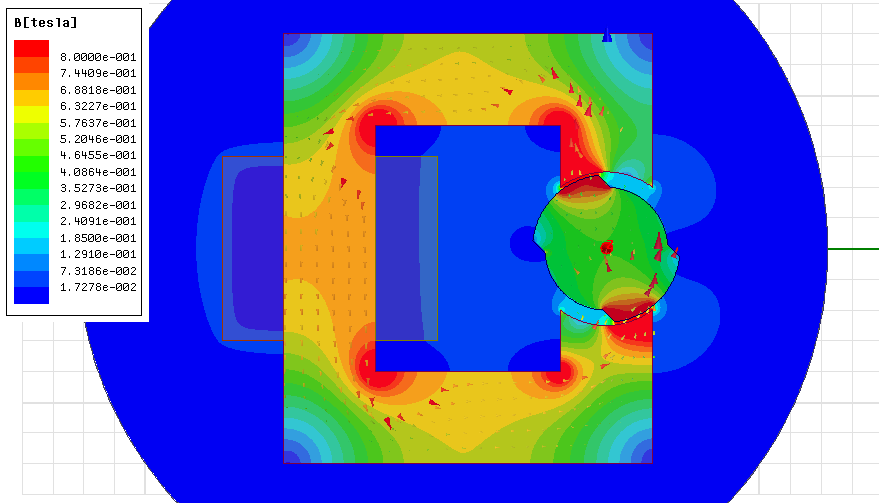
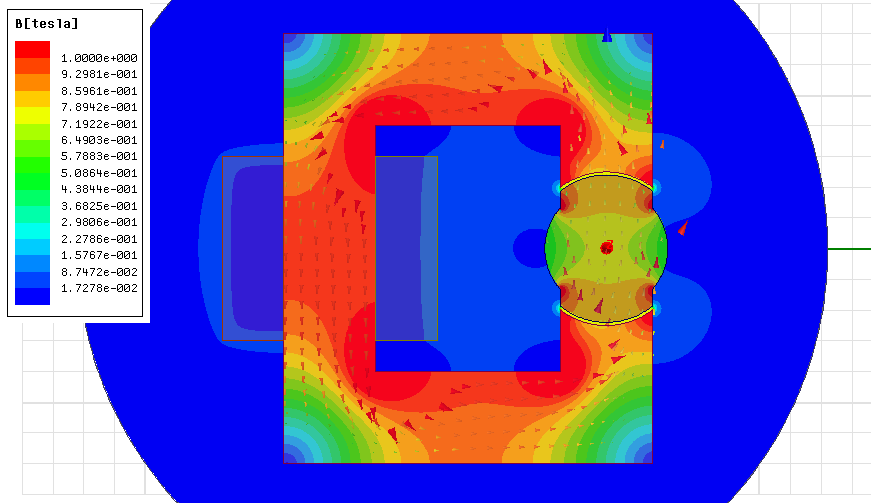
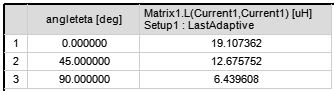


Fig. 11: Magnetic loading (B) distribution of the system with linear (µ=902.6) stator and rotor material

**2b) Inductances and Stored Energy in the System**

Inductances in the system is obtained as shown below. These values are too low with respect to analytical calculations maybe because of material depth is assumed as too low in 2D analysis.



CoEnergies of the system for 0, 45 and 90 degree positions,

0o position 🡪

45o position 🡪

90o position 🡪

These values are meaningless for to compare with analytical solution but we can compare the linear and non-linear material difference. We expect that for linear material coenergy and energy of the system are equal each other but for non-linear material (non linear BH curve) coenergy is slightly smaller than energy.

**2c) Torque Generation in the System**

Torque data of the system is recorded for three specific angle (0, 45 and 90 degree). So the torque graph is looks like triangular but actual form must be sinussoidal. Max torque is generated at 45o angle position.

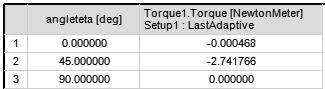
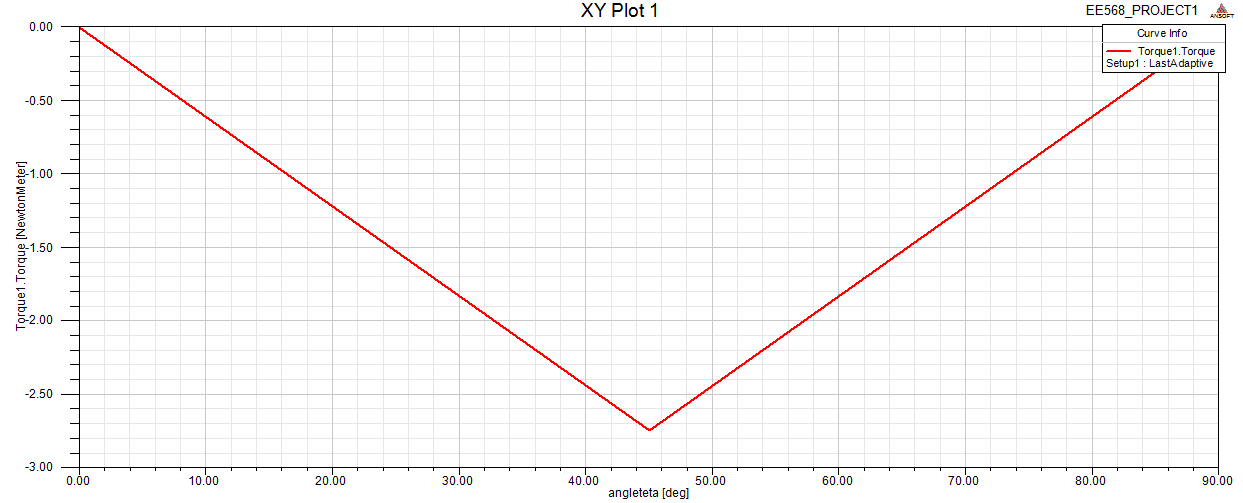


Fig. 12: Torque – position graph and actual values for linear material

3. FEA Modelling (2d Nonlinear Materials)

In this section, stator and rotor materials are selected as again steel\_1008 in Ansys/Maxwell library. But, the material property is set as nonlinear characteristic as nonlinear B-H curve that is given in Ansys/Maxwell library.

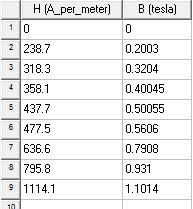


Fig. 13: Non-linear B-H curve of steel\_1008 material in Maxwell

**3a) Flux Density Vectors for NonLinear Materials (0, 45, 90 degree rotor)**

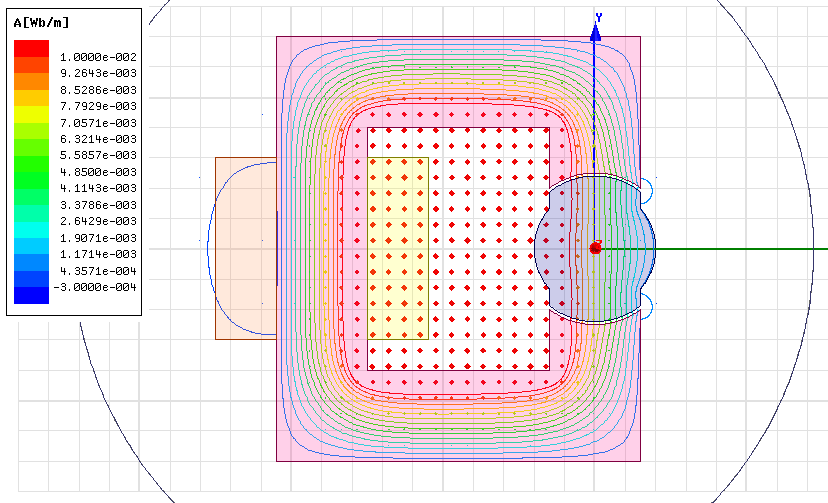
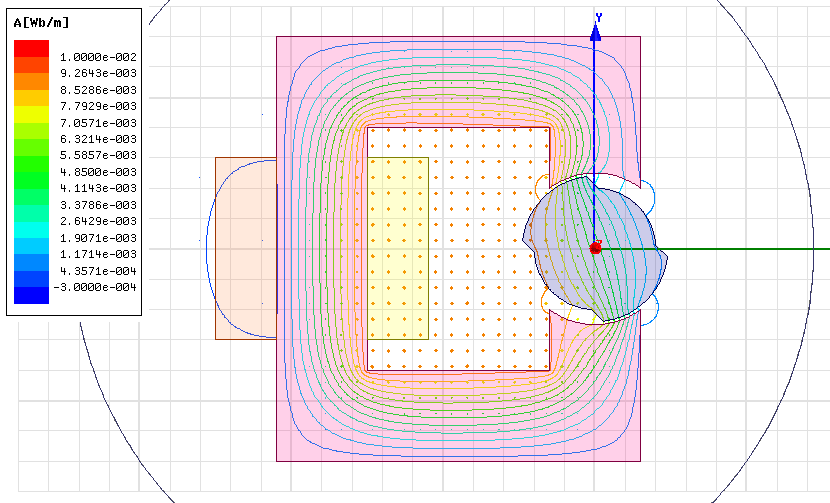
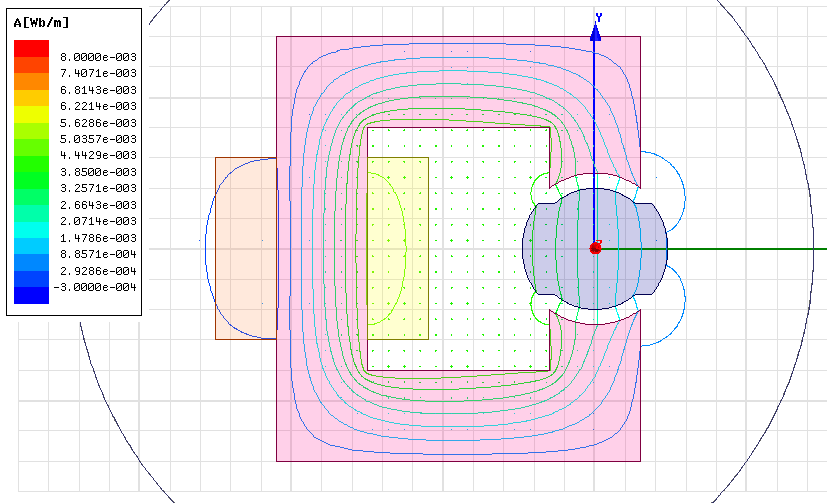
(a) 0o position(b) 45o position (c) 90o position

Fig. 14: Flux lines and vectors for no- linear (steel\_1008 nonlinear BH curve) stator and rotor material

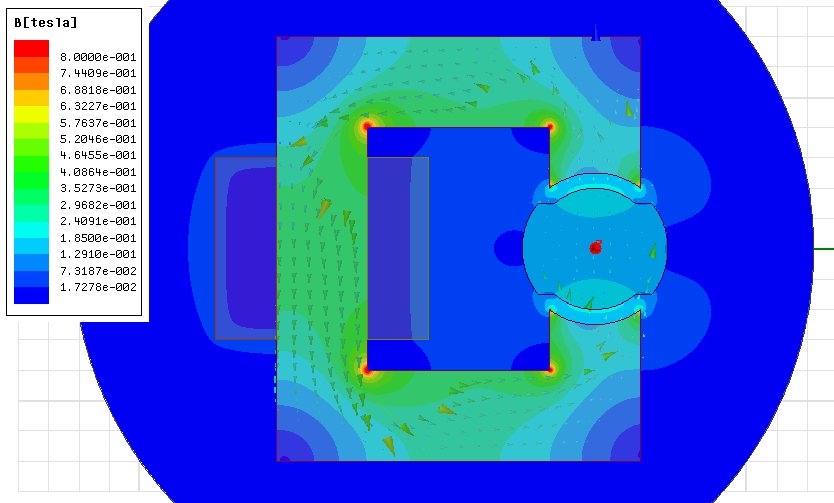
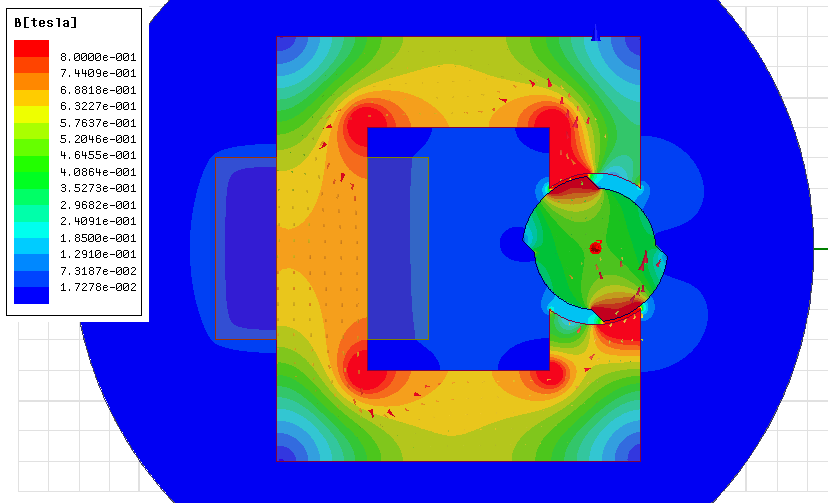
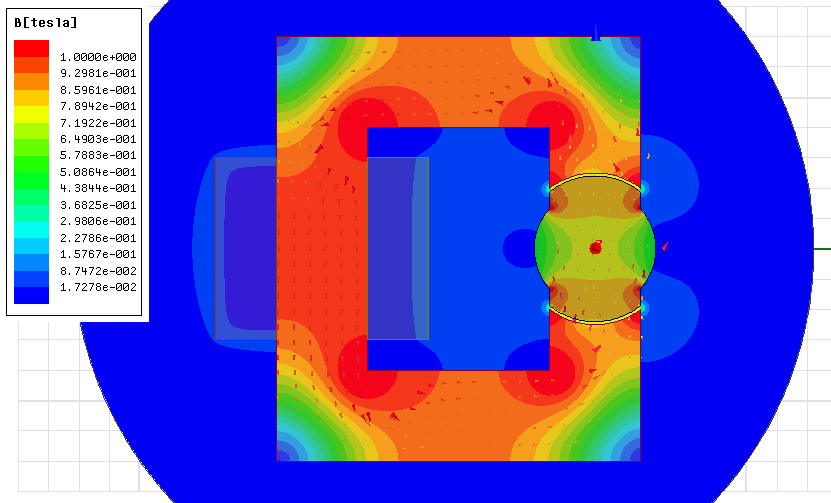
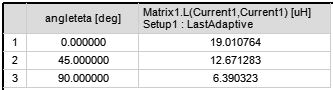


Fig. 15: Magnetic loading (B) distribution of the system with non-linear (steel\_1008 nonlinear BH curve) stator and rotor material

**3b) Inductances and Stored Energy in the Nonlinear System**

Inductances in the nonlinear material used system is obtained as shown below. These values are too low with respect to analytical calculations maybe because of material depth is assumed as too low in 2D analysis.



CoEnergies of the system for 0, 45 and 90 degree positions,

0o position 🡪

45o position 🡪

90o position 🡪

When we compare these result with respect to linear material used result, we can see the coenergy of the system decreases slightly because of the nonlinear characteristic of BH curve. For energy comparison, the situation is vice versa.

**3c) Torque Generation in the Nonlinear Material System**

As expected, maximum torque value at 45o position is slightly smaller than linear material based system because of the inductances. Inductances of the nonlinear based system are obtained slightly smaller than linear based system. Torque expression contains Ld-Lq statement. So, for nonlinear based system, this difference is slightly bigger than linear system.

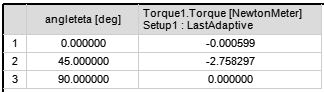
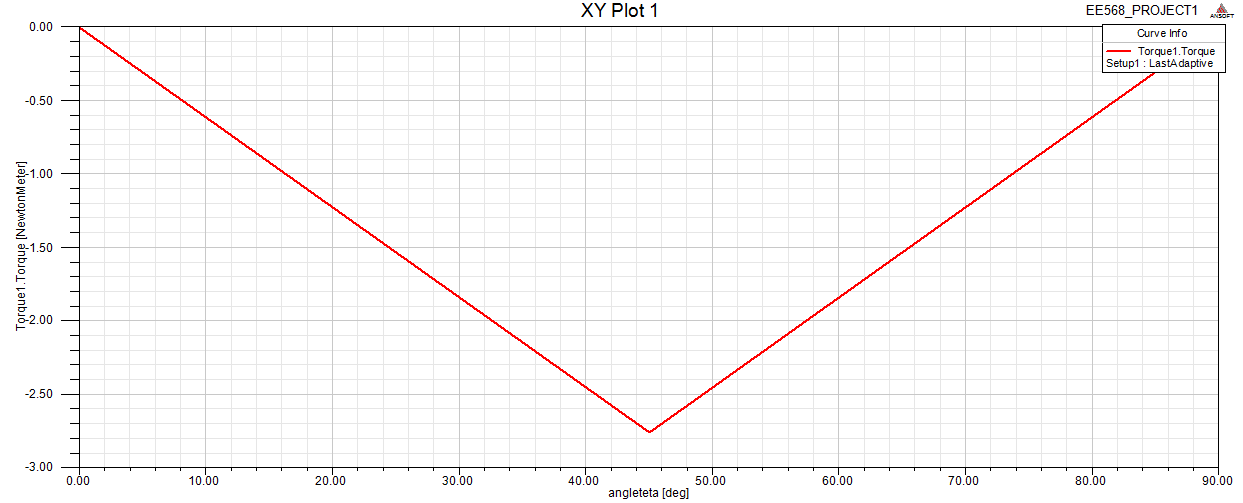
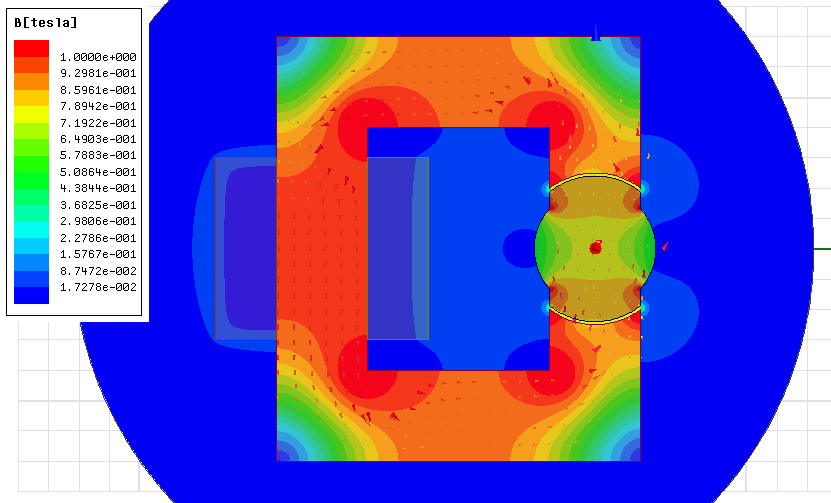
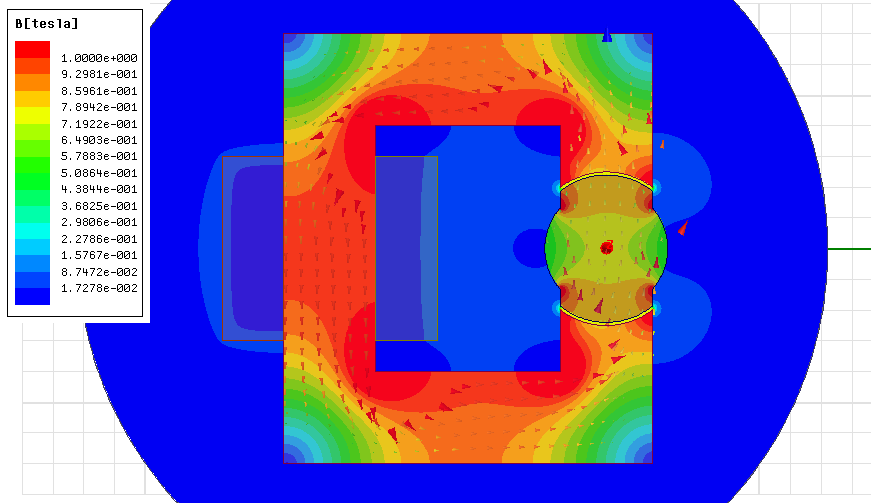


Fig. 16: Torque – position graph and actual values for non-linear material

**3d) The effects of fringing and saturating effects with the linear and non-linear materials**

The difference between linear and nonlinear materials based system can be seen from given figure below that shows the magnetic loading (B) distributions in same scale for 0o position.



(a) Linear stator and rotor material (b) Non-linear stator and rotor material

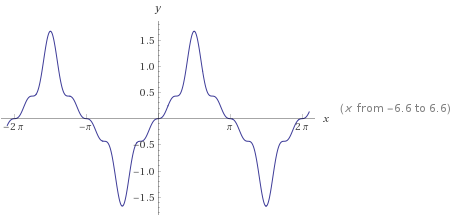
Fig. 17: Magnetic loading distributions at 0o position for linear and non-linear BH curve materials

For linear material, the magnetic permeability of the material is constant all location on the geometry. So, magnetic loading increases at the inner corners of the stator because of the small length of flux paths. But, the material tries to distribute this loading to homogeneous. In non-linear material, magnetic permeability is constant up to 1.4T, after that value nonlinear region starts and permeability decreases. So, inner corners of the stator expose this non-linear region and permeability is low in these areas and magnetic loading saturates.

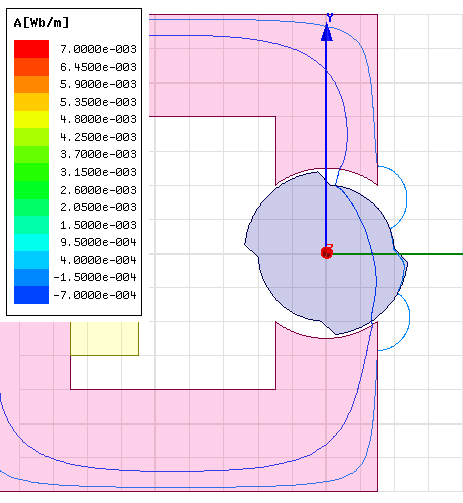
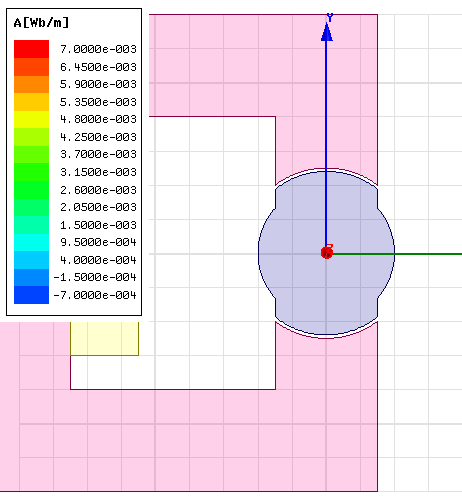
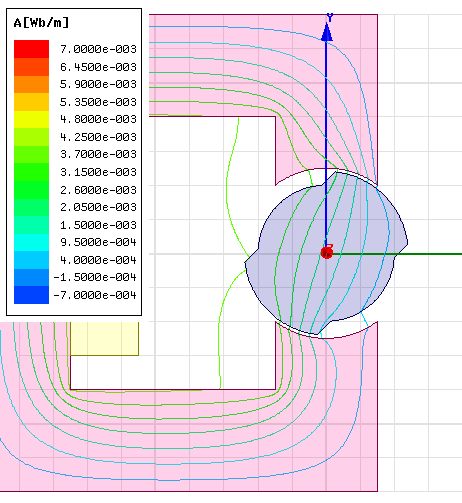
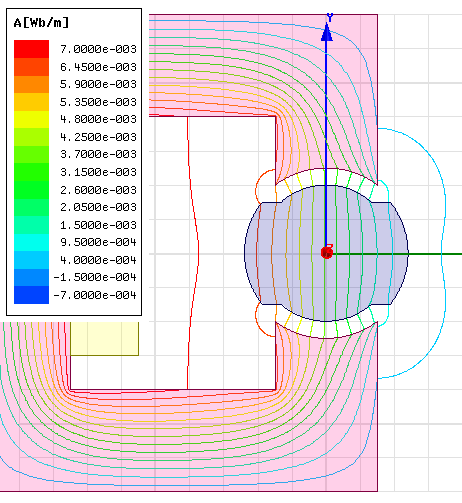
4. Control Method

Beacuse of the saliency of the rotor, rotor tries to come to position 0o (180o) position (figxx-b3) for minimizing the reluctance. So, in that position there will not any excitation (avoiding the locking rotor). In this manner, we have to excite the system with maximum energy at near of 90o (270o) position of the rotor. After this excitation rotor gains speed and tries to keep it with its inertia up to next maximum excitation at 270o (90o) position. The excitation wave form with respect to rotor position angle θ is given in figure below.

plot | sin(x) - 0.33 sin(3 x) + 0.2 sin(5 x) - 0.14 sin(7 x)



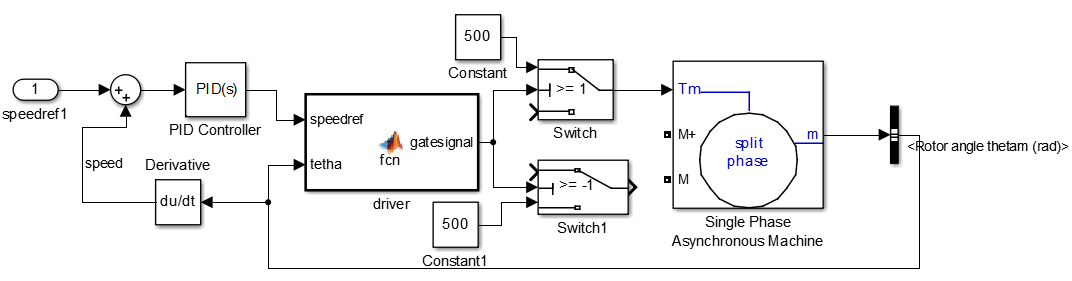
(a)



(b)

Fig. 18: (a) Stator excitation signal for control the rotor (b) Rotation motions with flux lines of the control method

With this logic, we can design a basic speed controller for this machine with PID controller as shown below. There is no ready to use motor model exactly same as our model, So, I used the this general model with torque input. Driver function controls the two seperated switch that can also connect the DC source for creating single phase signal as we designed. So the stator excited when the rotor at position every 90o and 270o position.



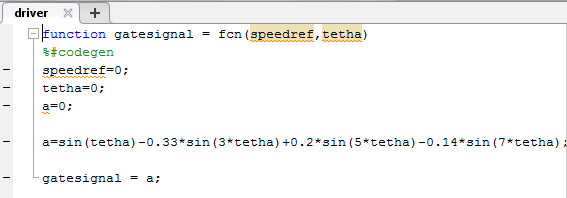


Fig. 19: Designed control system in MATLAB/Simulink

The generated torque is shown in figure below that obtained by Maxwell with designed excitation. As expected, maximum torques are obtained at 135o (also continues periodically at 45o 135o 225o 315o).

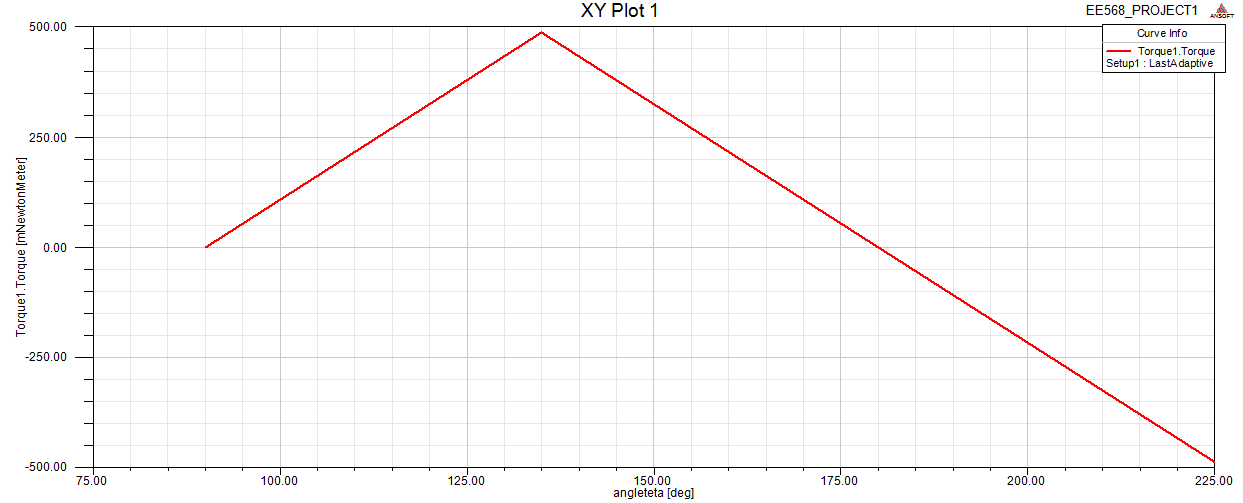


Fig. 20: Generated torque from FEA analysis when the excitation is derived from designed control system

5. Motion Animation

Animation videos are added on github.

<https://github.com/SerhatOzkucuk/EE568-Selected-Topics-on-Electrical-Machines/blob/master/ee568_ozkucuk_control_method_animated.avi>

<https://github.com/SerhatOzkucuk/EE568-Selected-Topics-on-Electrical-Machines/blob/master/ee568_ozkucuk_dcexcitation_animated.avi>

# REFERENCES

1. <https://github.com/odtu/ee568>

2. <http://keysan.me/ee568/>