Design of an Interior Permanent-Magnet Synchronous Motor Using a Finite-Element Analysis Software

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1 Introduction

The purpose of this exercise is to design a 3-phase permanent-magnet synchronous motor with 8 poles and 48 slots using the software Simcenter MagNet 2-D of Infolytica/Siemens. On the end of this lab exerise, the student should be capable of:

- Understanding the mechanism of the the Finite-Element Method
- Designing the basic geometry of a radial-flux motor
- Assigning material in each component of the motor
- Defining a concentrated non-overlapping winding
- Obtaining the operating parameters e.g. Electromagnetic torque, Back-EMF, Phase current

The finite element method (FEM) is a standard tool for solving differential equations in many disciplines, e.g., electromagnetics, solid and structural mechanics, fluid dynamics, acoustics, and thermal conduction. In the FEM, the domain with the sought electromagnetic field is subdivided into small subdomains of simple shape and, as an initial example, we may consider a circular domain in two dimensions that is subdivided into triangular subdomains. The collection of triangular subdomains cover the original circular domain and the triangular subdomains do not overlap each other. (Thus, the circular boundary is approximated by a polygon that consists of the outermost edges of the triangular subdomains.) The field solution is expressed in terms of a low-order polynomial on each of these subdomains and, consequently,we have a piecewise low-order polynomial representation of the field on the circular domain. In general, such a representation of the field is not flexible enough to be able to exactly fulfill the differential equation and its boundary conditions in a pointwisemanner. The FEM relaxes this requirement slightly and, instead, it attempts to find a field solution that fulfills the differential equation and its boundary conditions in an averaged sense. There are different approaches to how to construct this relaxed fulfillment of the differential equation and its boundary condition and two important methods are (i) to set the weighted average of the residual to zero and (ii) to exploit a variational method to find a stationary point of a quadratic form.

For a FEM that works correctly, the approximate solution tends to the exact solution as the size of the subdomains tends to zero and, consequently, the number of subdomains tend to infinity. Clearly, the smaller subdomains allows for a better approximation of both the circular domain and the exact field solution. The two-dimensional magnetostatic problem is described by the differential equation

$$\frac{1}{\mu_r}\frac{\partial^2 A_z}{\partial x^2}+\frac{1}{\mu_r}\frac{\partial^2 A_z}{\partial y^2}=-\mu_0 J_z-\frac{1}{\mu_r}\left(\frac{\partial B_{res,y}}{\partial x}\right)+\frac{1}{\mu_r}\left(\frac{\partial B_{res,x}}{\partial y}\right) \tag{1}$$

where:

- A_z is magnetic vector potential on the z-direction
- μ_r is the relative permeability of the Permanent-Magnet
- J_z is the current density on the z-direction
- μ_0 is the vacuum permeability
- $B_{res,x}$ and $B_{res,y}$ is the residual flux density of the permanent-magnets in x and y - direction

2 Design of geometry and assign materials definition

The geometry is the initial step of the design process. Radial flux motors can be modeled on a 2-D plane (xy plane) and have a stack length. This means that construction lines are used to create the sketch of the machine and later on, in each shaped region-plane a volume is created with along the z direction. Initially, the geometry of the rotor along with the assign of materials following by the design of the stator and coils.

- Open Simcenter MagNet as one can see on Figure 1
- Click to Files → Save as, with the IPMSM, following your student number
- Click to Tools → Set Units and set everything according to Figure 2

- Click to Tools → Keyboard Input Bar and a bar for entering coordinates will appear, see Figure 3

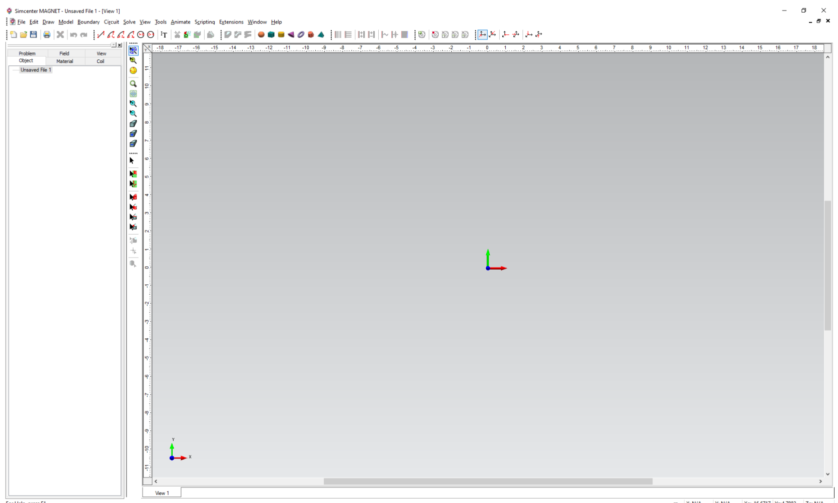

Figure 1: A blank working page of Simcenter MagNet

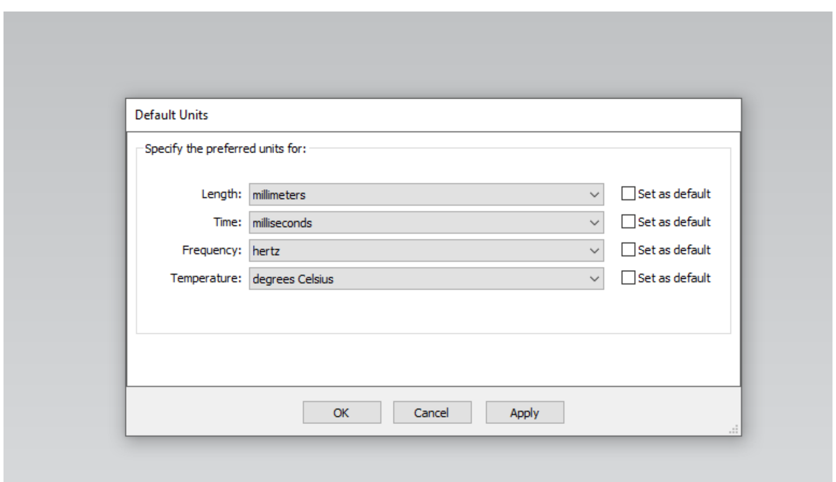

Figure 2: Units used for the design process

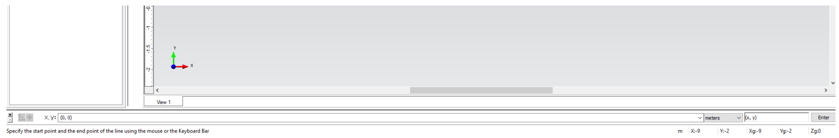

Figure 3: Demonstration of the location of Keyboard Input Bar

2.1 Design of rotor

Choose the Add line command and using the Key Input Bar (turned on cartesian coordinates) start drawing the following lines respectively:

- Line 1: Start = (0,0) End = (-15,0)
- Line 2: Start = (-15,0) End = (-15,60)
- Line 3: Start = (-15,60) End = (0,60)
- Line 4: Start = (0,60) End = (-7,80.5)
- Line 5: Start = (-7,8.5) End = (-12.5,84)
- Line 6: Start = (-12.5,84) End = (-15,60)

The created schematic should look like the one illustrated in Figure 4.

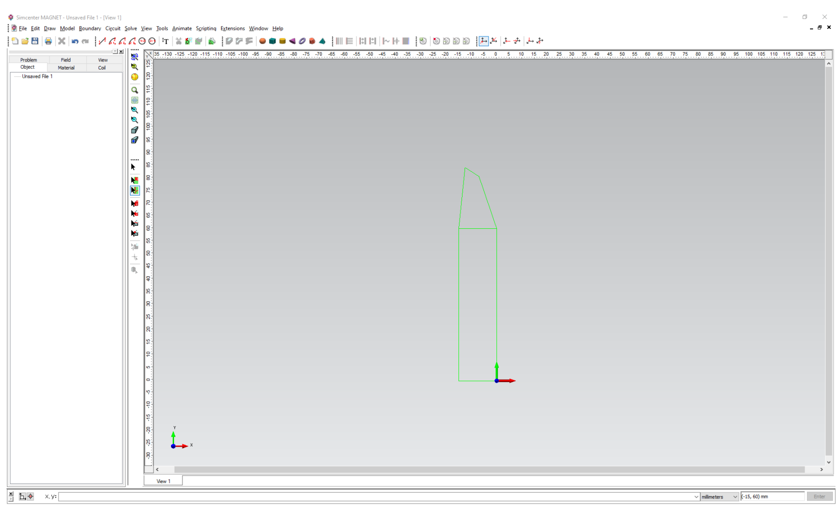

Figure 4: Constructions lines for the design of the permanent-magnet interfaced with the flux barrier

Using the command Select Construction Slice Lines/Arcs as shown in Figure 5.

Figure 5: Select Construction Slice Lines/Arcs button

By clicking with the left click of the mouse and choosing it all (it should become red), click on Draw → Rotate Edges and rotate it according to Figure 6.

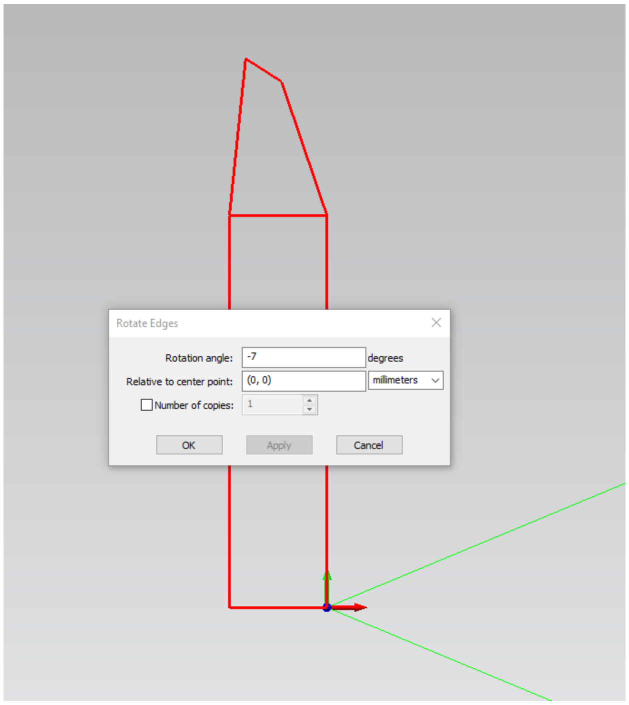

Figure 6: Rotation of 7 degrees counter-clock-wisely with respect to (0,0) of the construction lines

By using the Select Construction Slice Surfaces, select the rectangular region as shown in Figure 7.

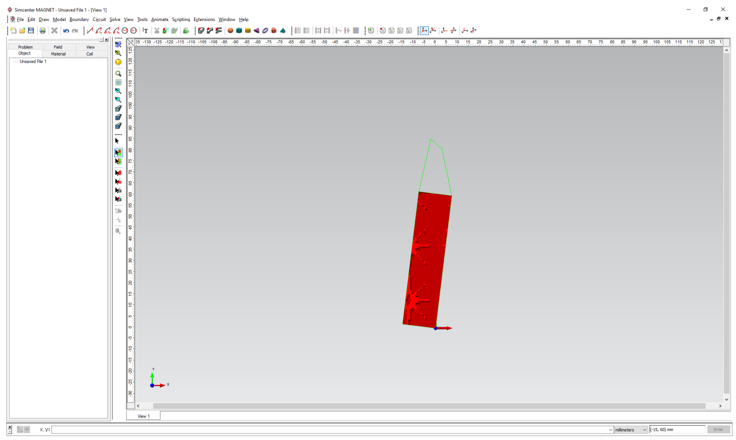

Figure 7: Construction of a permanent-magnet component using the Make Component in a Line command

Click to Model → Make Component in a Line (Ctrl+Shift+L) and fill the blank bars according to Figure 8. Fill the magnet magnetization type as: uniform and the direction with the coordinates: (0.992546190927693, 0.12186902344291, 0).

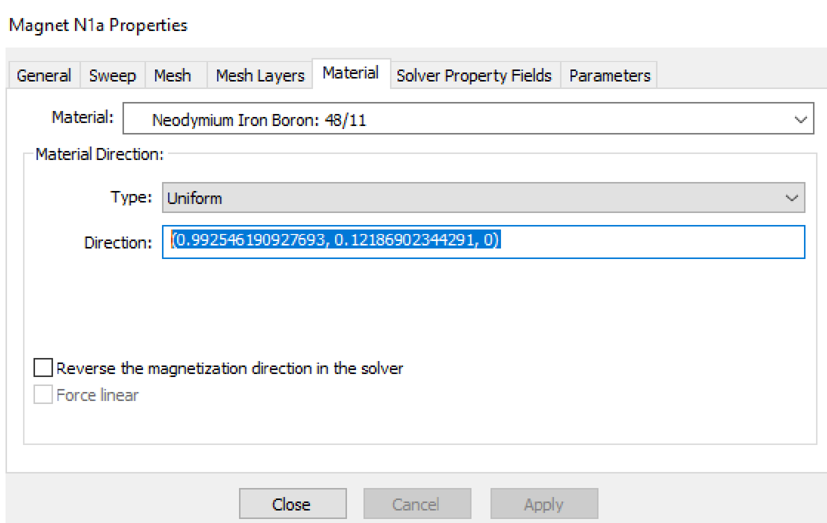

Figure 8: Assigning material properties for the magnet

Later on, fill the maximum number to elements (Figure 9), the initial temperature, the color of the material and its name (Figure 10). You can also use a higher maximum number of elements (around 1-3), with purpose to obtain more accurate results.

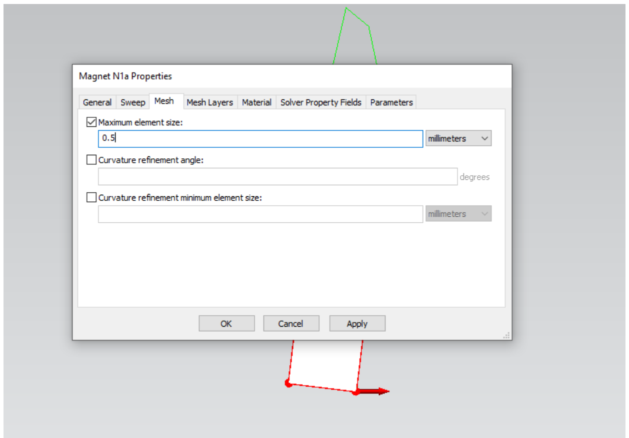

Figure 9: Setting the maximum element size for the magnet component

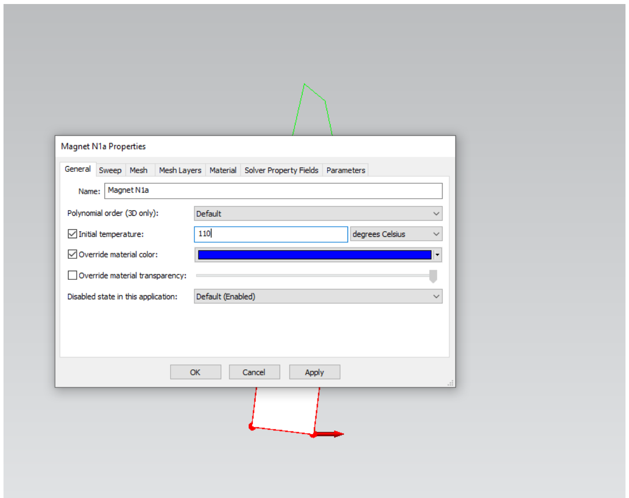

Figure 10: Setting Name, Initial temperature and Material color for the magnet

Repeat the process for the barrier of the magnet which is aparted by air (see Figure 11 and 12). Also use a maximum element size of 1mm -4mm.

The barrier is a multipurpose design feature which reduces the leakage field of the permanent magnet field, eases the saturation and offers significantly improved heat abduction. An important thing to clarify is that the bar is not just a design feature, but a feature of the real machine.

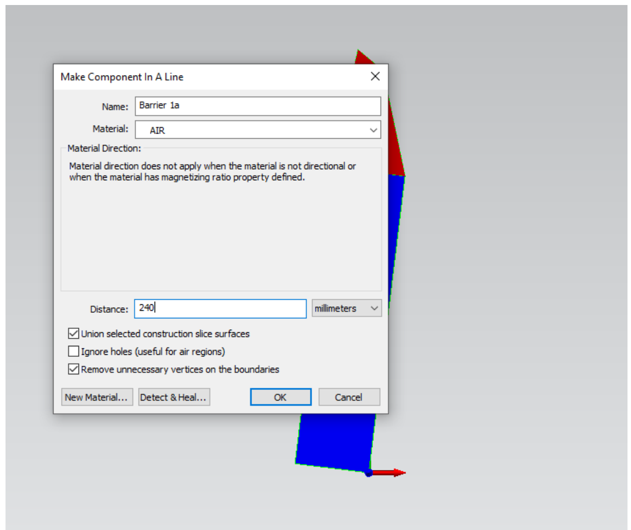

Figure 11: Creating the barrier component

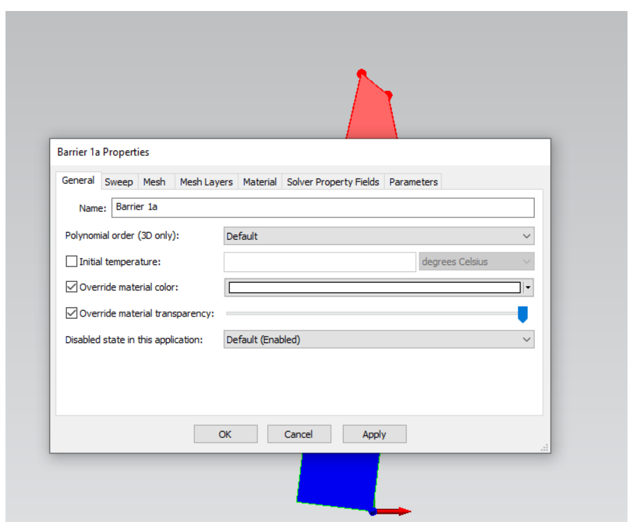

Figure 12: Setting a name and a colour for the barrier component

Choose both the permanent magnet and the barrier using the Select Components command and go to Model → Mirror Components and mirror everything with respect to x-axis according to Figure 13.

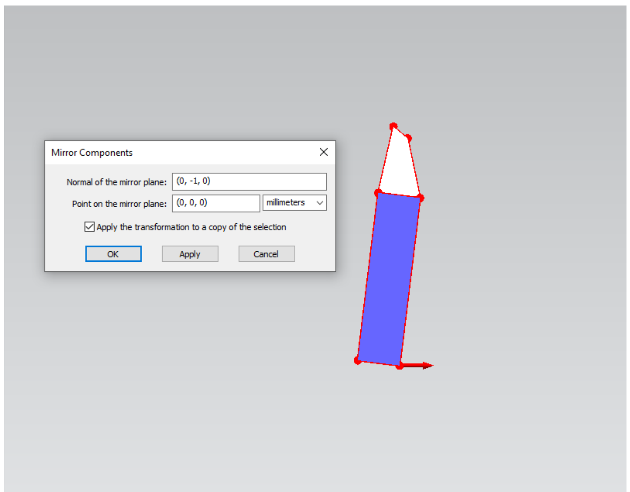

Figure 13: Mirroring the magnet and barrier component with respect to x-axis to create the full magnet pole

If the resultant bodies are the same as the ones presented on Figure 14, the mirroring was successful. Validate that the direction of the magnetization on the freshly created magnet of the pole is (0.992546190927693, -0.12186902344291, 0).

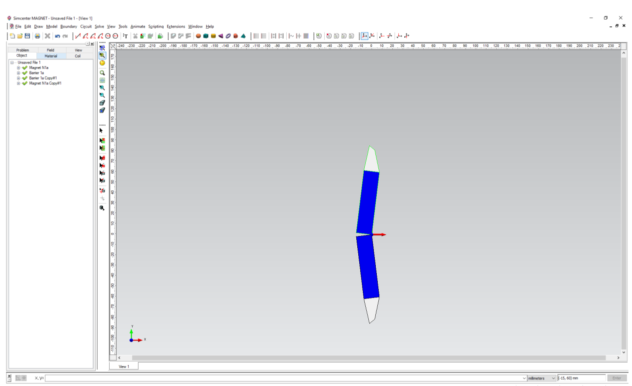

Figure 14: A full pole after the Mirror Components command

Subsequently, using the Select Components command and by going to Model → Shift Components, shift the component according to Figure 15.

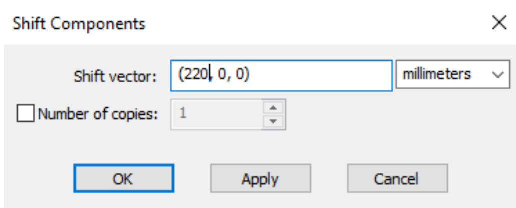

Figure 15: Shift of the whole pole

Choose all the poles (including magnets and barriers) and Rotate Edges using a 30 degree angle by setting tick to Number of copies: 1. On the created it is mandatory to change the direction of the magnetization and make look inwards on the air-gap. By pressing the magnet which is met firstly counter-clock-wisely change the direction of demagnetization to (-0.615661060629688, -0.788011077602547, 0) and (-0.788011077602524, -0.615661060629718, 0). Change also the color of both magnets to red in order to tone that these two magnets create a south pole. Later on, pick both poles, including the barrier and copy them using a rotational angle of 90 degrees for four times to create all 8 poles of the motor according to Figure 16.

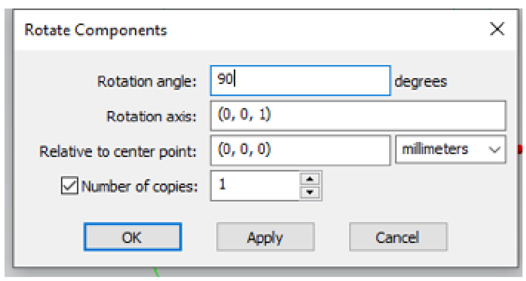

Figure 16: Rotating Components command in a pole pair with Number of copies set to 1, to create all the pole components of the machine

The final result should look as the one in Figure 17. Great care should be given on the fact that the number of permanent-magnets which a motor carries is not always equal with the number of poles. This motors proves this by having 16 magnets but half the number of poles.

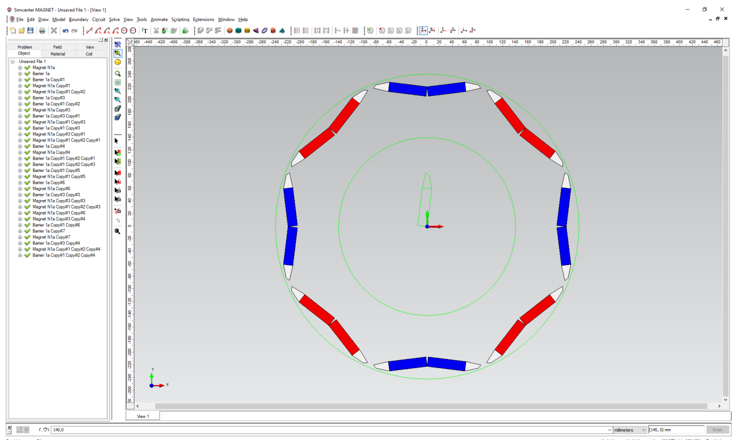

Figure 17: View of the all the poles across the circumference of a construction tube

To create the rest of the rotor, toggle between Cartesian and polar coordinate systems. The button is located on the left side of the Keyboard Input Bar. Now by clicking on the Add Circle(Center,Radius) create a circle with center (0,0) and radius 140mm and another with the same center but a radius of 240mm. Now two lines are going to be created to create the contour of circular sector which encloses the first pole. Press on the Add Line command create two lines using polar coordinates:

- Line 1: Start = (0,0) End = (242,-15)
- Line 2: Start = (0,0) End = (242,15)

Using the Select Construction Slice Edges command choose the construction lines of the first magnet and barrier and do Mirror Edges with Direction of the mirror line (1,0) and Point of the mirror line (0,0). Shift Edges to (220,0) and then start copying with rotating angles 45, 90 , 135, 180, 225, 270 and 315. By using the Select Construction Slice Surfaces command and using the left click of the mouse, start clicking in order to create the Rotor Iron Tube. Now using the Select Construction Slice Surfaces command select the circular sector shaped area and create press on Model → Make Component in a Line, filling everything according to Figure 18.

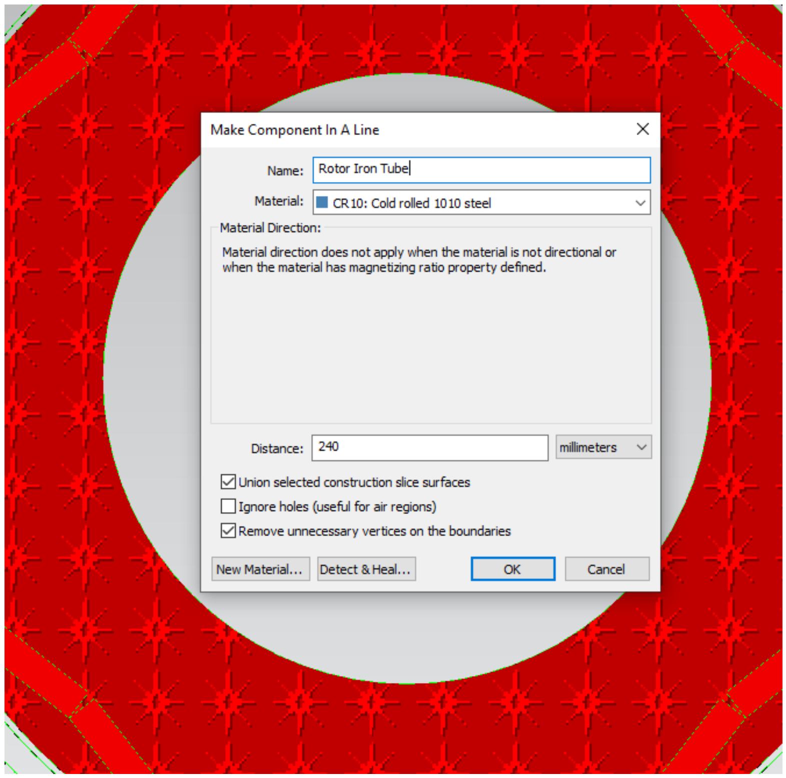

Figure 18: Creating the component of a circular sector of a tube

Choose the iron component of the rotor using the Select Components command and then by having pressed the Ctrl button click on the 2 magnets and the 2 barriers of the first pole which intersect with the component. Go to Model → Subtract Components and remove the tick choice from the magnets and barriers, since the solid rotor sector needs to be deleted. By clicking on the rotor iron part using the Select Components command, use the Rotate Edges command and copy it 7 times more by using the angles (degrees) 45, 90, 135, 180, 225, 270, and 315, since $360^o/8 = 45^o$. By choosing all the 8 created iron sectors using the Select Components command, go to Model → Union Components and leave the tick in all remaining components as it is, since we want them deleted. By choosing the resulting components press right click and go to Properties → Mesh and set the mesh at 15mm. The resulting rotor should look exactly as in Figure 19. It is also recommended to change the color at grey but this is just a personal preference.

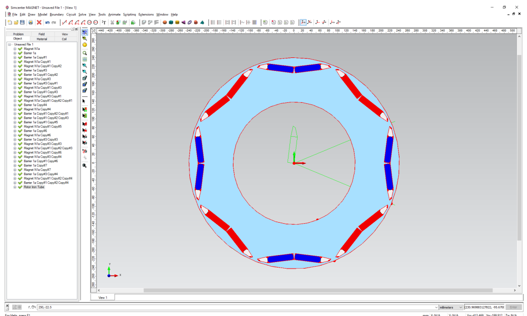

Figure 19: The final rotor iron tube with holes in the positions where the magnets and barriers are located

Lastly, it is crucial to validate that the direction of the magnetization correct because this will lead in wrong results. Choose Extensions → Modeling Toolbox and then at Materials tab click on the Display Direction Vectors. The length factor of the direction arrows can also be adjusted along with the color which is red at default. The direction vectors for the magnetization is presented in Figure 20. From the alternating direction of the arrow pair per pole and the slope of the arrows it is obvious that the magnetization pattern is correct.

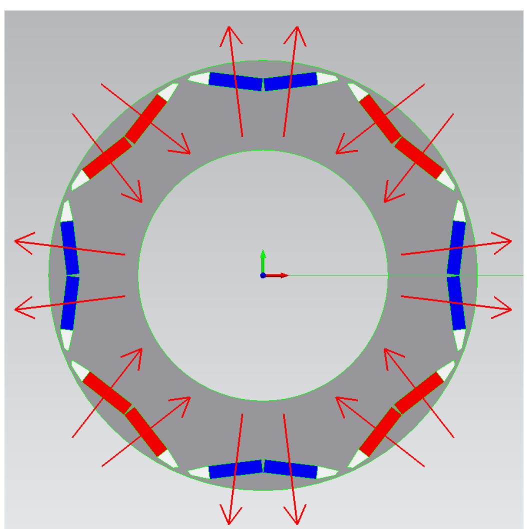

Figure 20: The final rotor component with the display of the magnetization vectors in both permanent-magnets of each pole

A technical demand of the software is that the moving components need to be enclosed in a component made by Virtual Air. This material behaves like air but it still has all the properties of a solid. Create a circle with center (0,0) and radius 240.75mm. Using the Select Construction Slices Surfaces command choose all the internal are which this circle encloses. The construction of this component is displayed in Figure 21. Use also a maximum element size of 9mm.

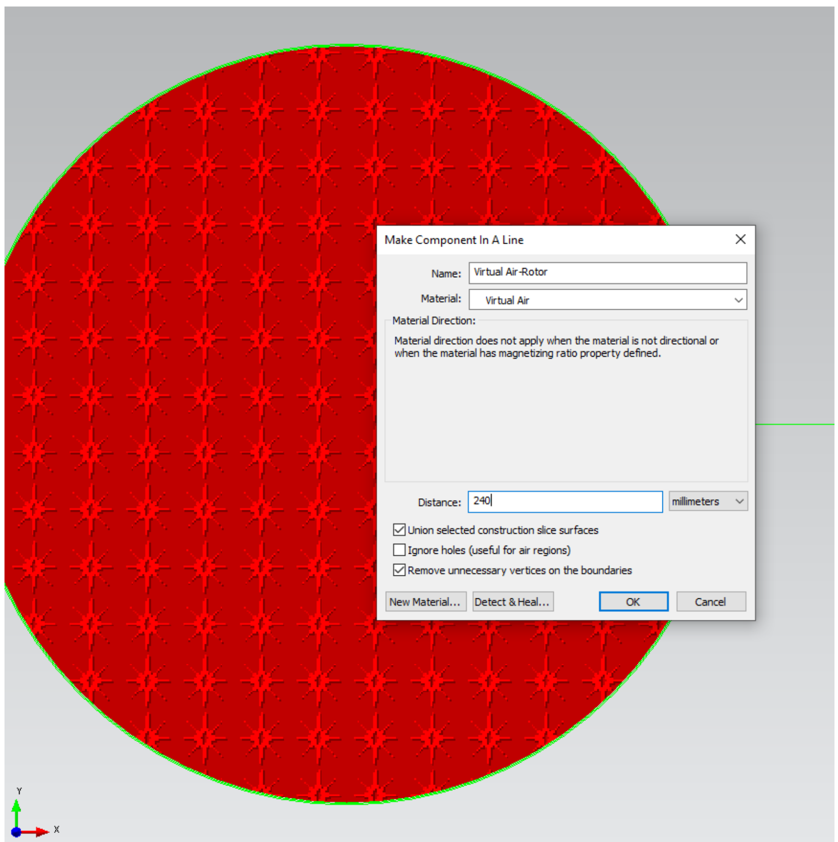

Figure 21: Creation of the Virtual Air Rotor component

2.2 Design of the air-gap component

The air-gap is the fundamental manufacturing parameter in electric machines and it is a goal to keep it always on a minimum length in order to achieve the strongest air-gap magnetic flux density possible and eventually performance.

Create two circles; one with center (0,0) and radius 241.5mm and another with same center and radius of 242.25mm. Using the Make Component in a Line command create the two tubes. Name the internal tube as Rotor Air-gap and the external Stator air-gap and use material air. Both must have material AIR. The creation of the Rotor air-gap is displayed in Figure 22. Use a mesh around 0.25-1mm for each of the tubes. Since the air-gap is a high priority region, a high number of elements is required for accurate prediction of machines' physical quantities.

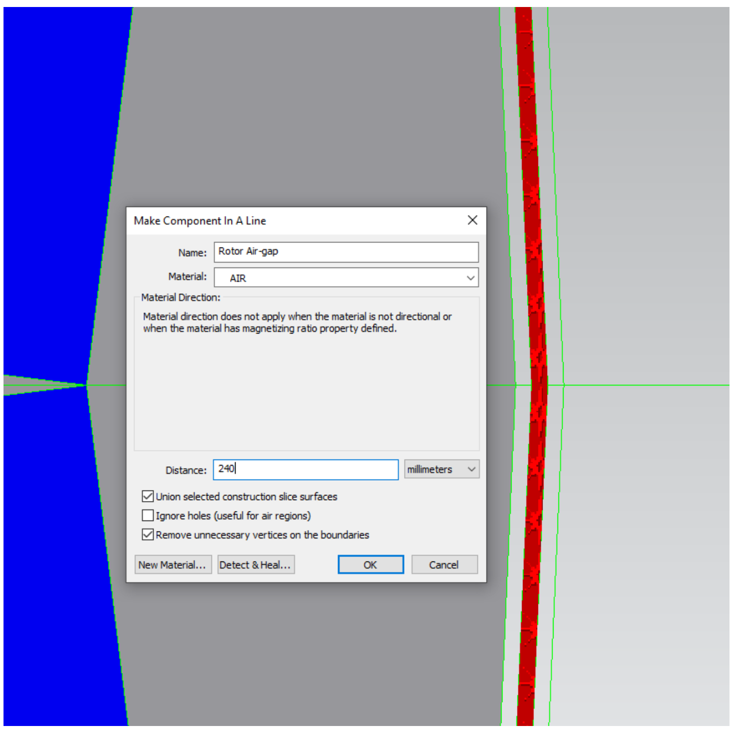

Figure 22: Creation of the air-gap component

2.3 Design of stator

The stator component facilitates the coils which are the building blocks of the winding which are inserted in slots shaped by the iron material. This motor has 48 slots which means that also has 48 teeth. Click on tab Files → Import..., and import the file Stator.mn which will give the full geometry of stator directly. The result should look like the one presented on Figure 23.

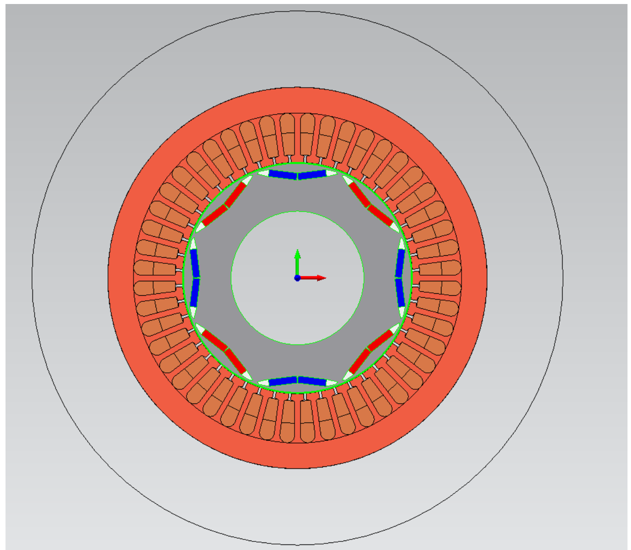

Figure 23: The geometry of stator imported

Delete the Stator Air Gap and the Stator Air Enclosure, since we already designed a stator air-gap and we will design also another stator air enclosure. Create a circle with center (0,0) and radius 400mm. Using the Select Construction Slice Surfaces and the Make Component in a Line command create the Virtual Air Stator component as shown in Figure 24. Use a maximum element size of 9mm.

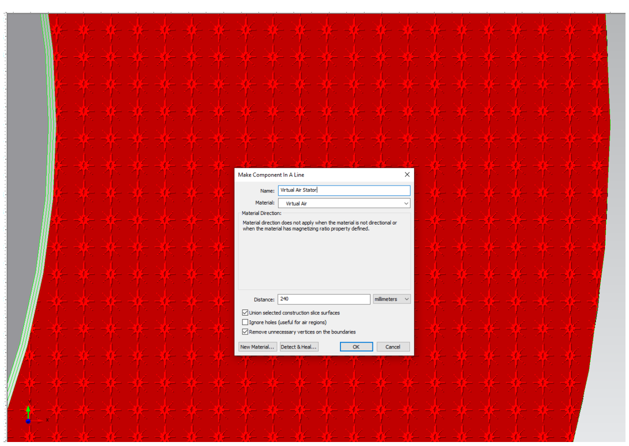

Figure 24: The Virtual Air Stator component with its features

The geometry of the stator is set. the design of the electric circuit is about to begin.

3 Creation of the motor's electric circuit

This motor carries a double layer overlapping winding. We will start left-clicking in each component with a specified sequence by having the Ctrl key pressed at all times and then using the Make a Simple Coil command (Ctrl+Shift+C), we will create a phase.

To create Phase A select the components in the following order on the Object page in the Project Bar. Hold Ctrl when clicking each component to do a multiple selection.

1. Stator Coil Side 1
2. Stator Coil Side Slotmate 7
3. Stator Coil Side 2
4. Stator Coil Side Slotmate 8
5. Stator Coil Side Slotmate 13
6. Stator Coil Side 7
7. Stator Coil Side Slotmate 14
8. Stator Coil Side 8
9. Stator Coil Side 13
10. Stator Coil Side Slotmate 19
11. Stator Coil Side 14
12. Stator Coil Side Slotmate 20
13. Stator Coil Side Slotmate 25
14. Stator Coil Side 19

15. Stator Coil Side Slotmate 26
16. Stator Coil Side 20
17. Stator Coil Side 25
18. Stator Coil Side Slotmate 31
19. Stator Coil Side 26
20. Stator Coil Side Slotmate 32
21. Stator Coil Side Slotmate 37
22. Stator Coil Side 31
23. Stator Coil Side Slotmate 38
24. Stator Coil Side 32
25. Stator Coil Side 37
26. Stator Coil Side Slotmate 43
27. Stator Coil Side 38
28. Stator Coil Side Slotmate 44
29. Stator Coil Side Slotmate 1
30. Stator Coil Side 43
31. Stator Coil Side Slotmate 2
32. Stator Coil Side 44

In the menu bar, go to Model and select Make Simple Coil (Ctrl+Shift+C). This will create a coil named Coil#1 on the Coil page of the Project bar. To rename the coil, right-click Coil1 and select Properties then change its name in the Name field.

To create Phase B select the components in the following order.

1. Stator Coil Side 5

2. Stator Coil Side Slotmate 11
3. Stator Coil Side 6
4. Stator Coil Side Slotmate 12
5. Stator Coil Side Slotmate 17
6. Stator Coil Side 11
7. Stator Coil Side Slotmate 18
8. Stator Coil Side 12
9. Stator Coil Side 17
10. Stator Coil Side Slotmate 23
11. Stator Coil Side 18
12. Stator Coil Side Slotmate 24
13. Stator Coil Side Slotmate 29
14. Stator Coil Side 23
15. Stator Coil Side Slotmate 30
16. Stator Coil Side 24
17. Stator Coil Side 29
18. Stator Coil Side Slotmate 35
19. Stator Coil Side 30
20. Stator Coil Side Slotmate 36
21. Stator Coil Side Slotmate 41
22. Stator Coil Side 35
23. Stator Coil Side Slotmate 42
24. Stator Coil Side 36

25. Stator Coil Side 41
26. Stator Coil Side Slotmate 47
27. Stator Coil Side 42
28. Stator Coil Side Slotmate 48
29. Stator Coil Side Slotmate 5
30. Stator Coil Side 47
31. Stator Coil Side Slotmate 6
32. Stator Coil Side 48

To create Phase cselect the components in the following order.

1. Stator Coil Side 9
2. Stator Coil Side Slotmate 15
3. Stator Coil Side 10
4. Stator Coil Side Slotmate 16
5. Stator Coil Side Slotmate 21
6. Stator Coil Side 15
7. Stator Coil Side Slotmate 22
8. Stator Coil Side 16
9. Stator Coil Side 21
10. Stator Coil Side Slotmate 27
11. Stator Coil Side 22
12. Stator Coil Side Slotmate 28
13. Stator Coil Side Slotmate 33

14. Stator Coil Side 27
15. Stator Coil Side Slotmate 34
16. Stator Coil Side 28
17. Stator Coil Side 33
18. Stator Coil Side Slotmate 39
19. Stator Coil Side 34
20. Stator Coil Side Slotmate 40
21. Stator Coil Side Slotmate 45
22. Stator Coil Side 39
23. Stator Coil Side Slotmate 46
24. Stator Coil Side 40
25. Stator Coil Side 45
26. Stator Coil Side Slotmate 3
27. Stator Coil Side 46
28. Stator Coil Side Slotmate 4
29. Stator Coil Side Slotmate 9
30. Stator Coil Side 3
31. Stator Coil Side Slotmate 10
32. Stator Coil Side 4

Great care must be given on the sequence which this coil sides are clicked. It should be strictly done with the order number above. After finishing the process the coils should look like the ones on Figure 25. X mark means the reference direction for positive current is going into the screen. Dot mark means the reference direction for positive current is going out of the screen.

These directions can be confirmed by looking at a coil on the Coil page. Furthermore, change the names of Coil#1. Coil#2 and Coil#3 to Phase A, Phase B and Phase C. In each Phase fill in the number of turns per half coil-side and the fill factor as it is seen in Figure 26. Press right click on each phase click on the Reverse Coil Direction command to change the direction of the coil. It should like the one displayed in Figure 33.

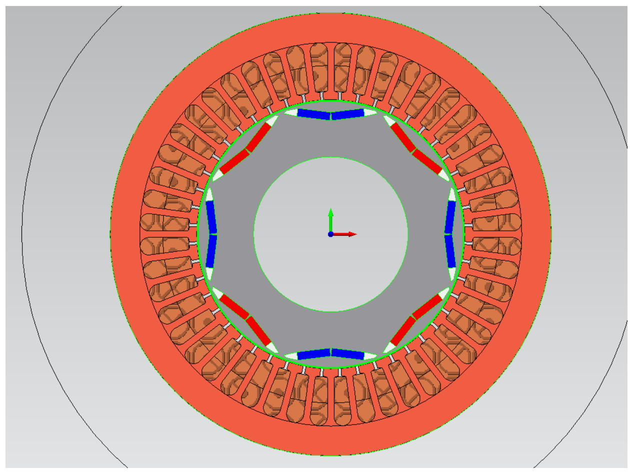

Figure 25: The final double-layer winding

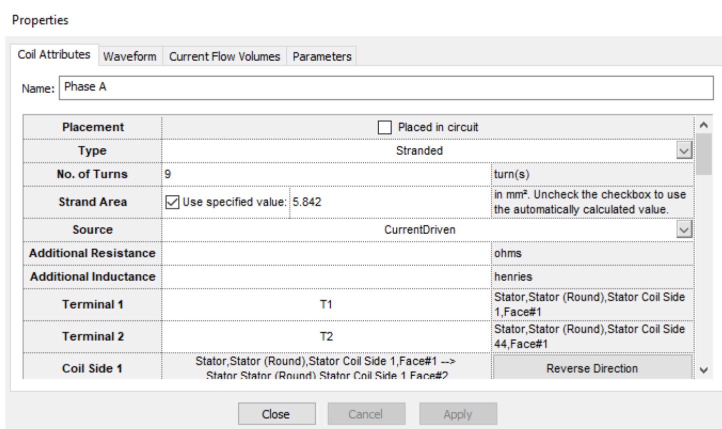

Figure 26: Number of turns and fill factor

Click on tab Circuit → Circuit View, the circuit window with the 3 created phases will appear. Drag Phase A, Phase B and Phase C into the white area with the grid. Click one more time on the Circuit tab and create 2 Current Sources, VI and I2. Fill their features according to Figures 27, 28. A third Current Source is not required since the current in the third phase is determined using KCL. *The amplitude of the current used must be equal with 10+X, where X is the last digit of your student number.* Connect them in star (Y), according to Figure 29. Since it is a 3-phase machine with a 3-phase winding the three voltages must be three sine-waves with equal amplitudes and phase differences of 120^o. The 3 phases create a rotating magnetic field which can be expressed with a rotating vector. The rotor with permanent-magnets creates also a rotating magnetic field. The two magnetic fields interact and their relative position is the one that creates the torque.

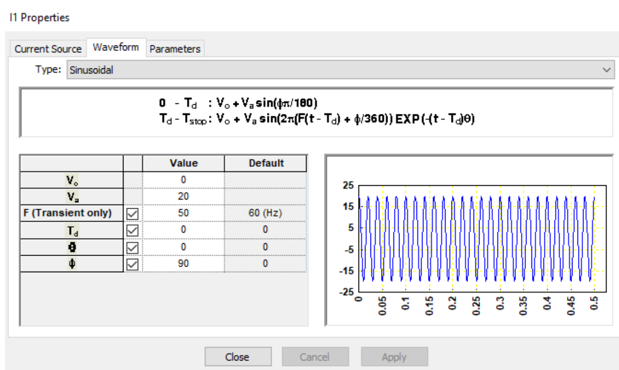

Figure 27: Current applied to Phase A

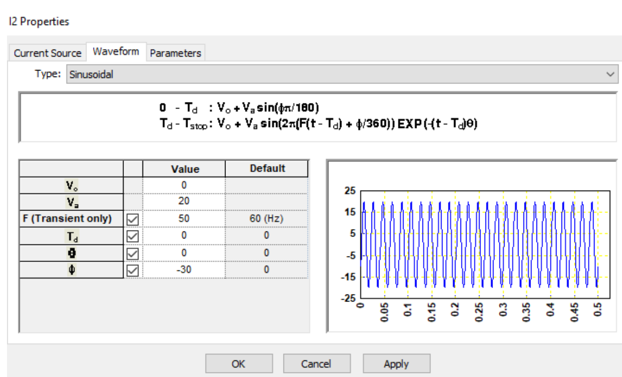

Figure 28: Current applied to phase B

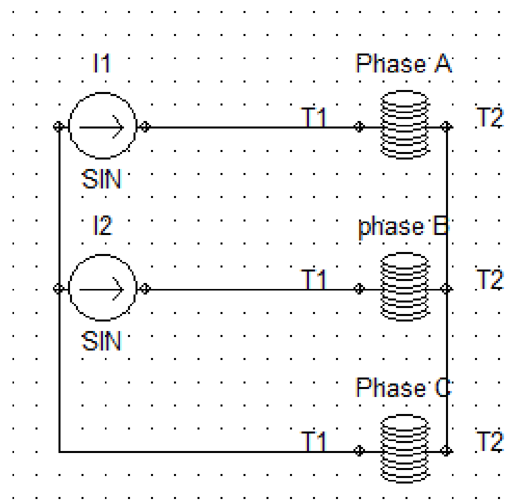

Figure 29: The electrical circuit with the star (Y) winding connection

4 Creation of the motion component

A Motion Component is created by selecting geometric components that will all move together as a single rigid body. Since we are modeling the whole 360 degree span of the motor, this model would be set up as a Type A motion model. For Type A motion, the model must have a single component that completely surrounds the components included in a Motion Component. The motion solver will choose this component to be the remesh component.

To create the Motion Component, first select the Virtual Air Rotor component, on tab Model → Make Motion Component (Ctrl+Shift+O).

- Permanent-Magnets
- Flux barriers
- Rotor iron material

To set the time-step of the simulation click on the tab Solve → Set Transient Options and fill everything according to Figure 30.

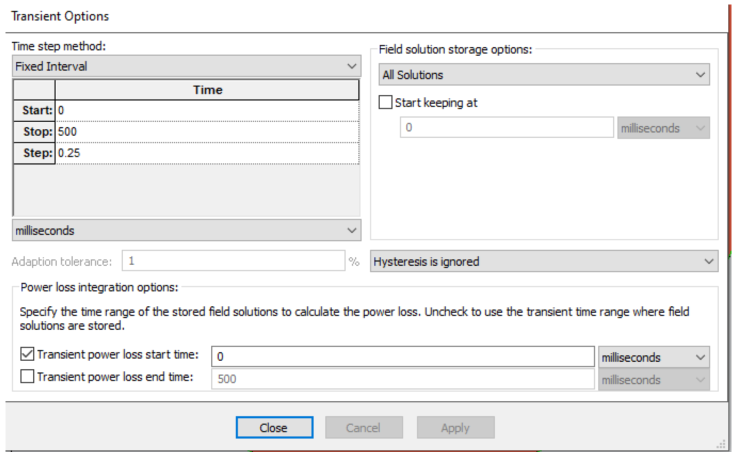

Figure 30: Setting the starting/ending and the time - step of the simulation

Going to properties of Motion#1 speed and the way of the simulation is ran (load/velocity driven can be chosen) using the two following Figures 31 32. The initial position of the rotor defines the known torque angle delta. This angle is basically the electrical angle which the stator and rotor rotating magnetic fields have.

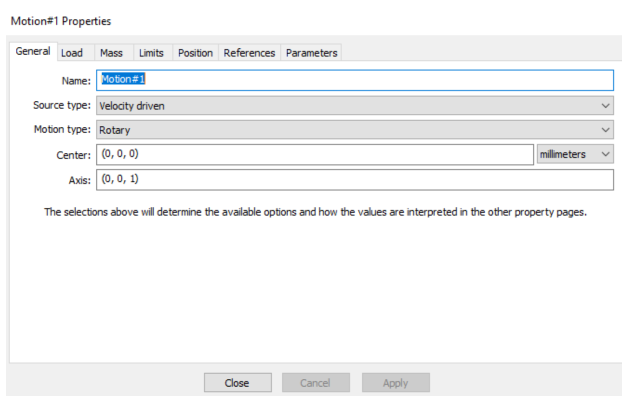

Figure 31: Setting the source type as velocity driven

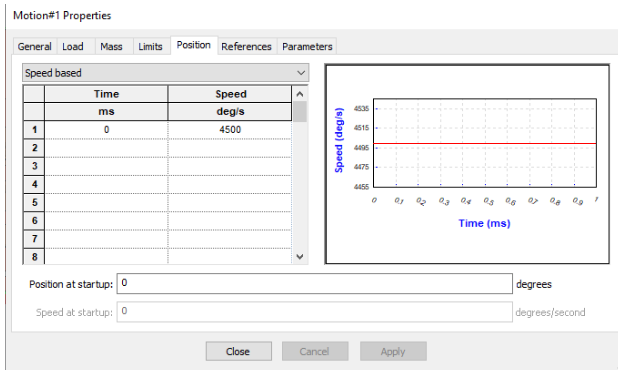

Figure 32: Setting the speed in $^o/sec$

Now the simulation is ready for solving in steady state with a constant speed of 750rpm. Click on Solve → Transient 2-D with Motion... . The solver will start if there aren't any problems.

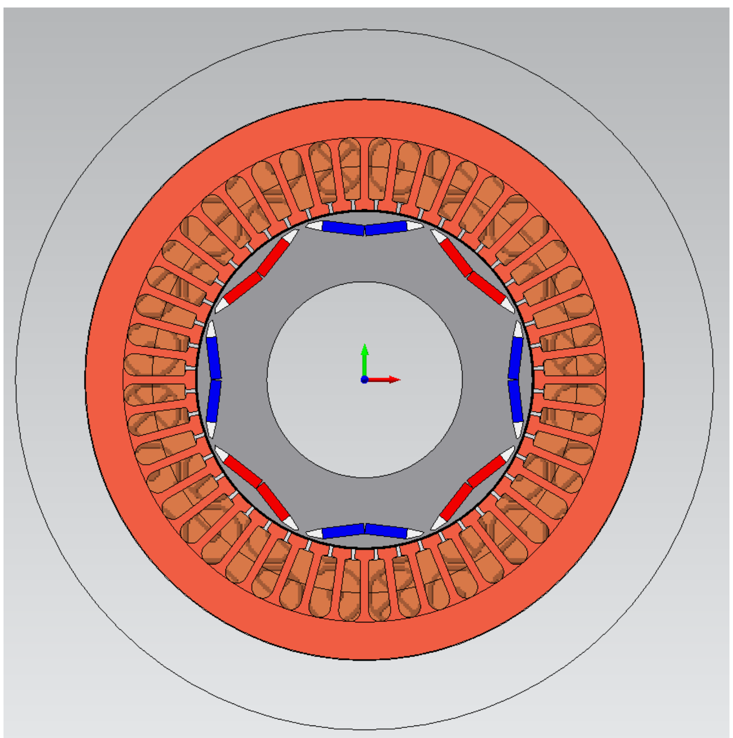

Figure 33: Final model

5 Calculation of all physical quantities - Lab report

In this section it is shown how all quantities can be calculated. For where it's needed, use a current of 10+X, (X is the final digit of your student number) and do all the calculations. All the waveforms, should be included on a report file and every waveform must have comments which explain how it's originated.

5.1 Calculation of on-load voltage, electromagnetic torque and flux-linkage

The electrical period of the current and voltage is $1/50 = 20msec$. To display the result click on the Results tab that will appear after stopping the simulation. To choose multiple quantities e.g. the Voltage tab and using the Ctrl button choose the three voltages on phase A, phase B and phase C as shown in Figure 34. To plot them on the same graph click also on the Overlap curves button. Press on Graph Selection... and the waveforms will be presented with the data columns given on the left side of the screen. After running for sufficient number of time-steps the 3 on-load voltages is shown in Figure 34. The electromagnetic force is also displayed in Figure 35. The flux-linkage for each phase is also presented in Figure 36.

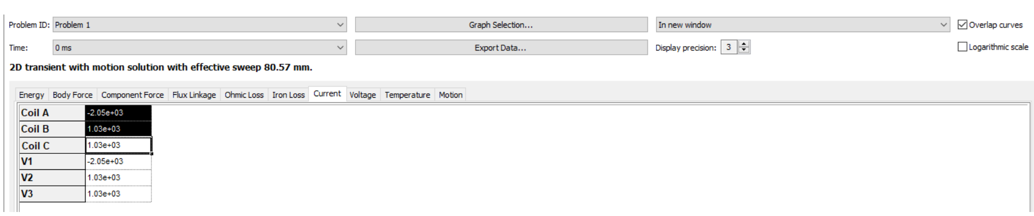

Figure 34: The tabs to extract or plot the data

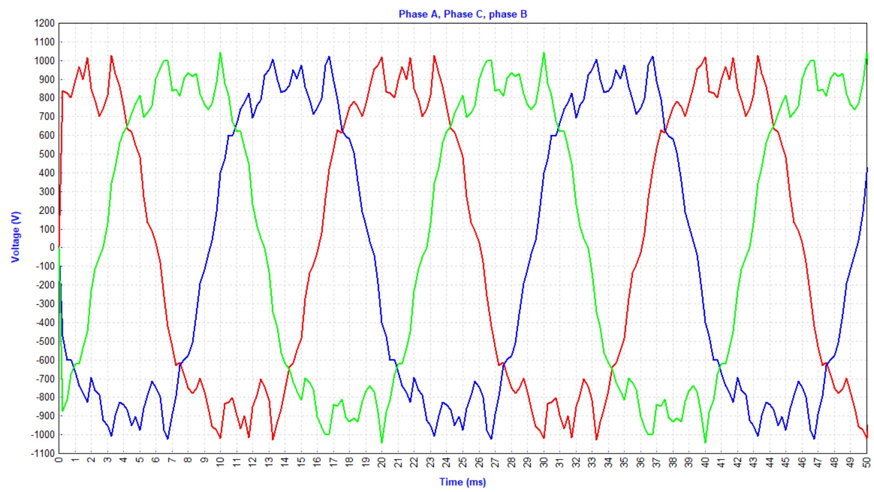

Figure 35: The voltage in each phase when the amplitude of the currents in each phase is 20A

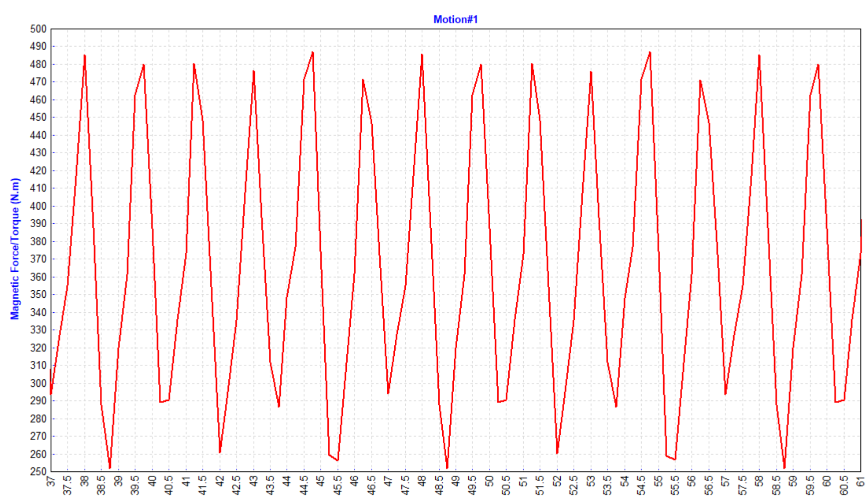

Figure 36: Electromagnetic torque when the amplitude of the currents in each phase is 20A

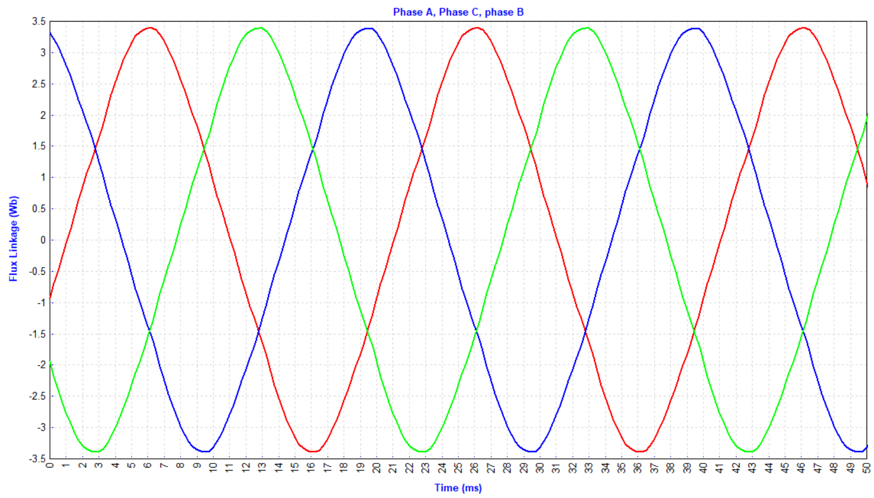

Figure 37: The flux-linkage of each phase when the amplitude of the currents in each phase is 20A

5.2 Calculation of Cogging-Torque and Back-EMF distribution in all phases

The Cogging-Torque is the tangential force created by the interaction of the stator teeth with the rotor's permanent-magnets. The mechanical period of this signal is $360^o/LCM(P,Q) = 360^o/48 = 7.5^o$. This torque is completely unwanted because it creates a torque ripple on the electromagnetic torque, which is basically noise and vibration. To calculate accurately this torque, the mass or the inertial of the rotor must become zero and the rotor must be rotated on a no-load condition, i.e. a condition which the current in the stator coils is zero. Right click on the Motion#1 component and on properties and on the mass tab they can be negated, as shown in Figure 38. By setting them to 0 the solver won't start, so a really small value must be given (1e-30). The same must be done for the current in the coils e.g. Figure 39 and 40. The Cogging-Torque waveform is given on Figure 41. The Back-EMF is the no-load voltage, i.e. the which is induced on the stator winding due to the permanent-magnet magnetic field when the stator current is zero. In reality, both Cogging-Torque and Back-EMF is two quantities that is difficult to be calculated accurately using experiment because even at a no-load condition, the rotor itself is a very small load, thus it draws a small current. On the contrary, for a generator the EMF voltage can be easily calculated using experimental procedure by measuring the voltage when the generator rotates with the phases open-circuited.

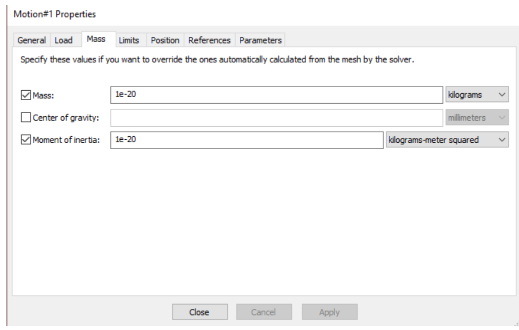

Figure 38: Negating the inertia of the rotor

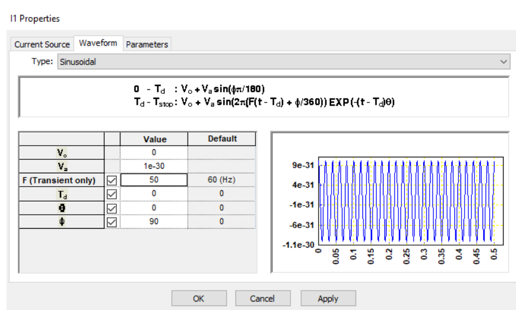

Figure 39: Negating the current of phase A

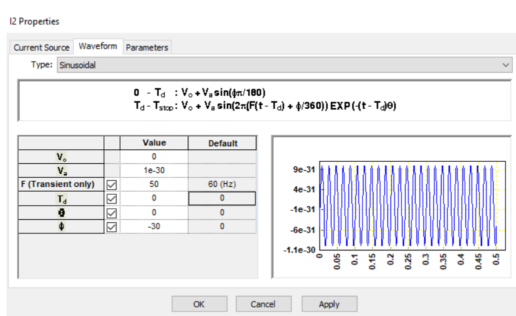

Figure 40: Negating the current of phase B

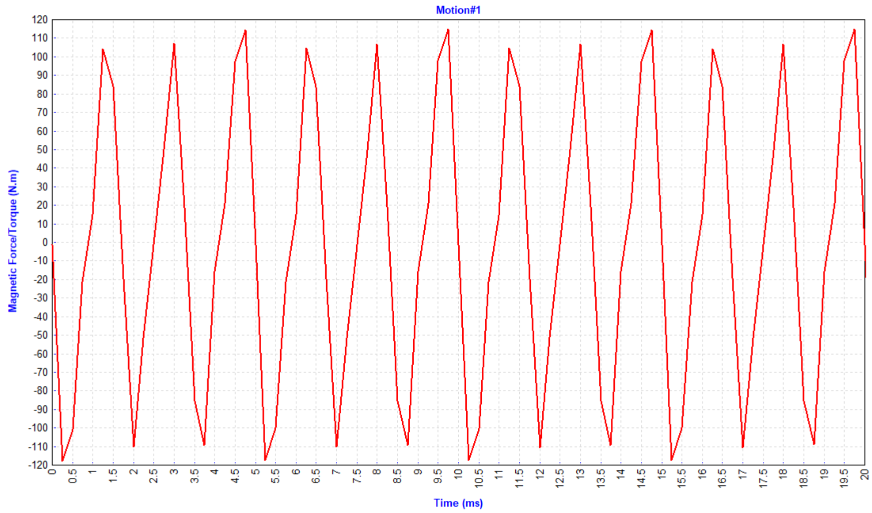

Figure 41: Cogging-Torque waveform

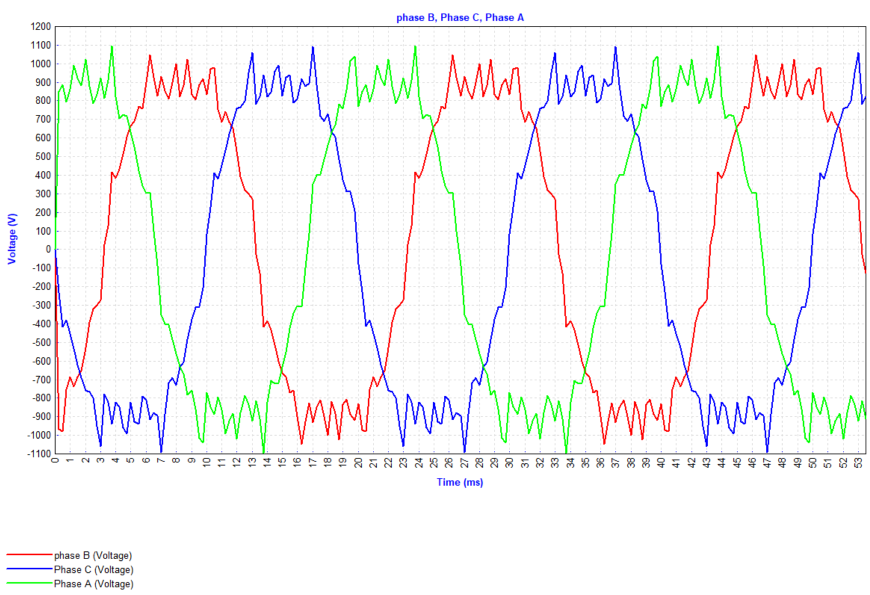

Figure 42: Back-EMF waveform

5.3 Calculation of reluctance torque distribution

The reluctance torque is another component that is added on the main torque and unlike the cogging-torque, it's useful. It may add an additional ripple but adds also a DC component which overcomes the disadvantage of the ripple. This torque is created between the rotating magnetic field of the stator and the rotor iron material. It is known also as the torque produced by the difference between the direct and quadrature inductances $X_d - X_q$. To calculate this torque the motor should be energized using the same way as in an on-load condition with the only difference that the magnets must be disabled. The reluctance torque is presented in Figure 43.

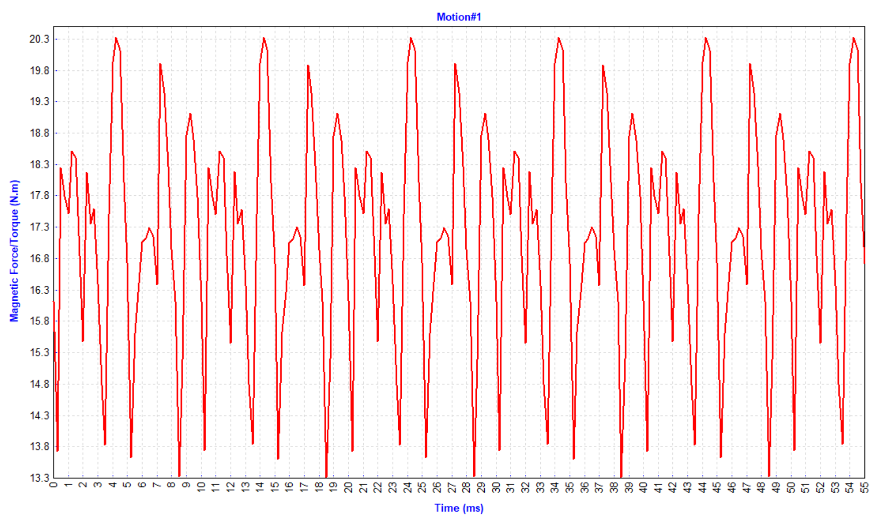

Figure 43: Reluctance torque waveform

5.4 Calculation of electromagnetic and reluctance torque versus angle delta distribtution

This is the known to all as the graph of electromagnetic torque versus the angle delta. The angle delta is the angle between the two rotating magnetics which are rotating with the same speed. The more we load the shaft of the motor, the more the torque angle increases and the current increase. We supply the motor with DC current $I_a = 10 + X$ $I_b = -(10 + X)/2$ $I_c = -(10 + X)/2$, the vector of the stator magnetic field becomes stationary and we only vary the position of the rotor. This characteristic is really important since it can show many things, such as the position of the maximum torque before de-synchronisation happens. The characteristic is presented in Figure 44. Furthermore, the reluctance torque versus angle delta is displayed in Figure 45. We can see the reluctance torque has twice the spatial frequency of the main electromagnetic torque. By substituting the iron materials with others that have the same mass and inertia but their relative permeability is zero, and running the same simulation we will obtain the electromagnetic torque versus delta which originates only

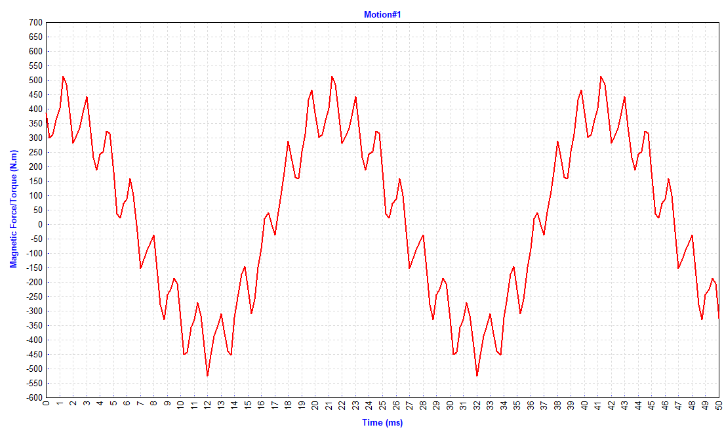

Figure 44: Electromagnetic torque versus angle delta

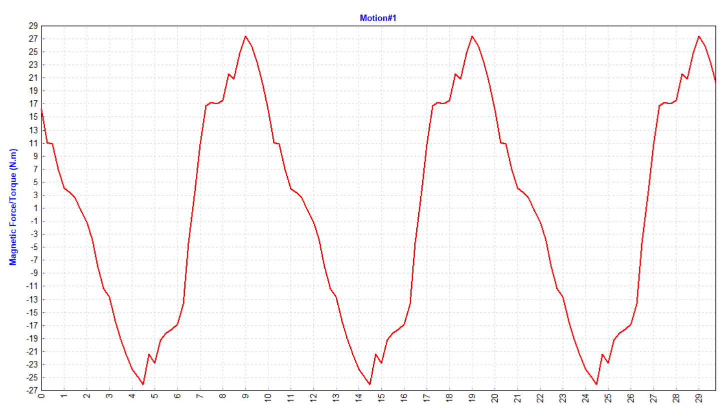

Figure 45: Reluctance torque versus angle delta

5.5 Calculation of the No-Load and the On-Load Flux Density distribution for a prespecified rotor position

The magnetic field distribution is the key parameters in electrical machines. All the quantities are derived by the components of the magnetic field i.e. radial and tangential. Here we will present a method to calculate the magnetic field at a no-load position and at an on-load position. This is a spatial waveform and for every rotor position or for every position of the stator magnetic field, varies. Initially, negate the value of currents in the coils. Then change the initial rotor at 22.5. Click on the tab Solver and then Static 2-D. After the solver finishes, then go to the Field tab, click on Bx smoothed and then press Update View. Press on the tab Tools → Field Circle Graph and create a circle with center (0,0) and radius 241.5 (approximately the middle of the air-gap). Acquire the data of the Value of Bx smoothed. Repeat the process for By smoothed. Store the two columns in an excel file named Bsmoothed and input the data on MATLAB on a numeric matrix format.Then run the code given. The no and on - load field distributions for the radial (normal) and tangential component is given on Figures 46 and 47.

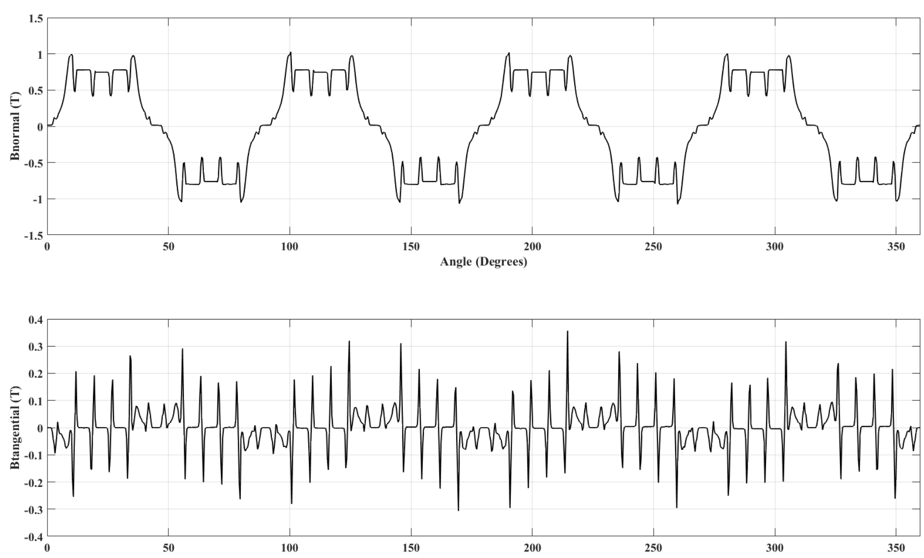

Figure 46: No-load magnetic field distribution

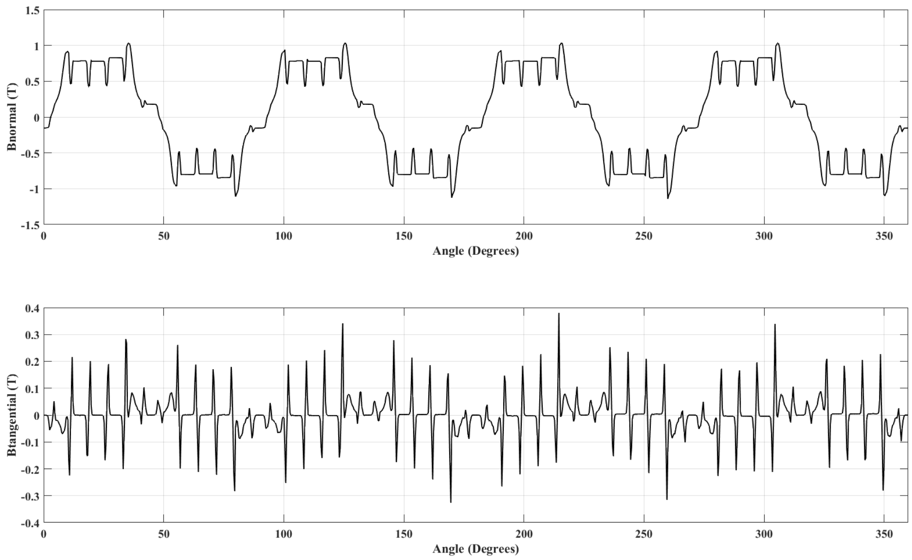

Figure 47: On-load magnetic field distribution