Treball de Fi de Grau

Enginyeria en Tecnologies Industrials

Analytical design of a Synchronous Reluctance motor (SRM)

ANNEX

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ANNEX A

A.1. LUA scripts

Here is shown the script designed to analyse the geometry of the SRM every 5˚ rotated by the rotor for a complete 360˚ turn. In the example below an intensity of 1 A has been established to flow through the phases.

As already mentioned, if a more accurate analysis were to be run then the angle of rotation should be established as 1˚ in the sixth line of the code when defining the *for* loop. Moreover, in order to turn off the switcher of the i-th phase in the real maximum inductance position (rotor and stator poles totally overlapped), a full analysis of the solution should be inserted inside every *if* statement before the *mi_modifycircprop()*, *mo_showdensityplot()* and *mo_savebitmap()* functions. This analysis would take a lot of time and has been neglected since the beginning of the project.

```
showconsole()
open("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Arxius Femm i Dxf\\experimento7.FEM")
mi_saveas("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Arxius Femm i Dxf\\temp_carr_sinus_freq_19.FEM")
I=1
mi_seteditmode("group")
for angle = 0,360,5 do
        if angle == 0 then
                mi_analyze()
                mi_loadsolution()

                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot0.bmp")
        end
        if angle == 15 then
                mi_modifycircprop("A",1,0)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,I)
                mi_modifycircprop("D",1,0)
        end
        if angle == 20 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot1.bmp")
        end

        if angle == 30 then
                mi_modifycircprop("A",1,0)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,0)
                mi_modifycircprop("D",1,I)
        end
        if angle == 35 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot2.bmp")
        end
        if angle == 45 then
                mi_modifycircprop("A",1,I)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,0)
                mi_modifycircprop("D",1,0)
        end
        if angle == 50 then
                mo_showdensityplot(0,0,2,0,"bmag")
```

```
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot3.bmp")
 end
 if angle == 60 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,I)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
 end
 if angle == 65 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot4.bmp")
 end
 if angle == 75 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,I)
        mi_modifycircprop("D",1,0)
 end
 if angle == 80 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot5.bmp")
 end
 if angle == 90 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,I)
 end
 if angle == 95 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot6.bmp")
 end
 if angle == 105 then
        mi_modifycircprop("A",1,I)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
 end
 if angle == 110 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot7.bmp")
 end


if angle == 120 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,I)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
if angle == 125 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot8.bmp")
end
if angle == 135 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,I)
        mi_modifycircprop("D",1,0)
end
if angle == 140 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot9.bmp")
end
if angle == 150 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,I)
end
if angle == 155 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot10.bmp")
end
if angle == 165 then
        mi_modifycircprop("A",1,I)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
if angle == 170 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot11.bmp")
end
if angle == 180 then
        mi_modifycircprop("A",1,0)
```

```
        mi_modifycircprop("B",1,I)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
if angle == 185 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot12.bmp")
end
if angle == 195 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,I)
        mi_modifycircprop("D",1,0)
end
if angle == 200 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot13.bmp")
end
if angle == 210 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,I)
end
if angle == 215 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot14.bmp")
end
if angle == 225 then
        mi_modifycircprop("A",1,I)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
if angle == 230 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot15.bmp")
end
if angle == 240 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,I)
        mi_modifycircprop("C",1,0)


        mi_modifycircprop("D",1,0)
end
if angle == 245 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot16.bmp")
end
if angle == 255 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,I)
        mi_modifycircprop("D",1,0)
end
if angle == 260 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot17.bmp")
end
if angle == 270 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,I)
end
if angle == 275 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot18.bmp")
end
if angle == 285 then
        mi_modifycircprop("A",1,I)
        mi_modifycircprop("B",1,0)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
if angle == 290 then
        mo_showdensityplot(0,0,2,0,"bmag")
        mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot19.bmp")
end
if angle == 300 then
        mi_modifycircprop("A",1,0)
        mi_modifycircprop("B",1,I)
        mi_modifycircprop("C",1,0)
        mi_modifycircprop("D",1,0)
end
```

```
        if angle == 305 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot20.bmp")
        end
        if angle == 315 then
                mi_modifycircprop("A",1,0)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,I)
                mi_modifycircprop("D",1,0)
        end
        if angle == 320 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot21.bmp")
        end
        if angle == 330 then
                mi_modifycircprop("A",1,0)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,0)
                mi_modifycircprop("D",1,I)
        end
        if angle == 335 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot22.bmp")
        end
        if angle == 345 then
                mi_modifycircprop("A",1,I)
                mi_modifycircprop("B",1,0)
                mi_modifycircprop("C",1,0)
                mi_modifycircprop("D",1,0)
        end
        if angle == 350 then
                mo_showdensityplot(0,0,2,0,"bmag")
                mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot23.bmp")
        end
        if angle == 360 then
                mi_modifycircprop("A",1,0)
                mi_modifycircprop("B",1,I)
                mi_modifycircprop("C",1,0)
                mi_modifycircprop("D",1,0)
        end

        mi_analyze()


         mi_loadsolution()

         mo_groupselectblock(1)
         Parell_tensor=mo_blockintegral(22)
         mo_clearblock()
         mo_groupselectblock(1)
         mo_groupselectblock(2)
         mo_groupselectblock(3)
         mo_groupselectblock(4)
         mo_groupselectblock(5)
         mo_groupselectblock(6)
         mo_groupselectblock(7)
         Magnetic_field_energy=mo_blockintegral(2)
         mo_clearblock()
         currentA,voltsA,fluxA=mo_getcircuitproperties("A")
         currentB,voltsB,fluxB=mo_getcircuitproperties("B")
         currentC,voltsC,fluxC=mo_getcircuitproperties("C")
         currentD,voltsD,fluxD=mo_getcircuitproperties("D")
         arxiu=openfile("intens_flux_22.txt","a")
         write(arxiu,angle," ",Parell_tensor," ",Magnetic_field_energy," ",currentA," ",currentB," ",currentC," ",currentD," ",fluxA," ",fluxB," ",fluxC," ",fluxD," ","\n")
         closefile(arxiu)
         mi_selectgroup(1)
         mi_selectgroup(3)
         mi_moverotate(0,0,5)
end
mi_moverotate(0,0,-5)
mo_showdensityplot(0,0,2,0,"bmag")
mo_savebitmap("C:\\Users\\Lluís\\Desktop\\ETSEIB\\4t curs - 1r quatrimestre\\TFG\\Fotos\\sim2.2\\screenshot24.bmp")
mo_close()
```

Fig A.1: LUA script

ANNEX B

B.1. Improvement of the geometry

B.1.1. First Geometry

The current geometry of the SRM is such that the density flux generated in some parts of the stator is very high and can cause the temperature to increase and even a loss of properties from the stator's material (see ***Fig 18.1*** and Fig ***18.2***) can eventually occur, reducing the reluctance output torque and subsequently reducing the overall performance of the motor. In order to know the intensity of the magnetic field in the critical points of the geometry the FEMM post-processor allows to draw a red line (called contour line from now onwards) along which the program calculates the total intensity of the magnetic field for every point of the line. Thus, the program gives a graph of the density of the magnetic field as a function of the distance of the contour line starting always from its left end.

The nominal current has been set up for all the geometries.

Contour
Red line

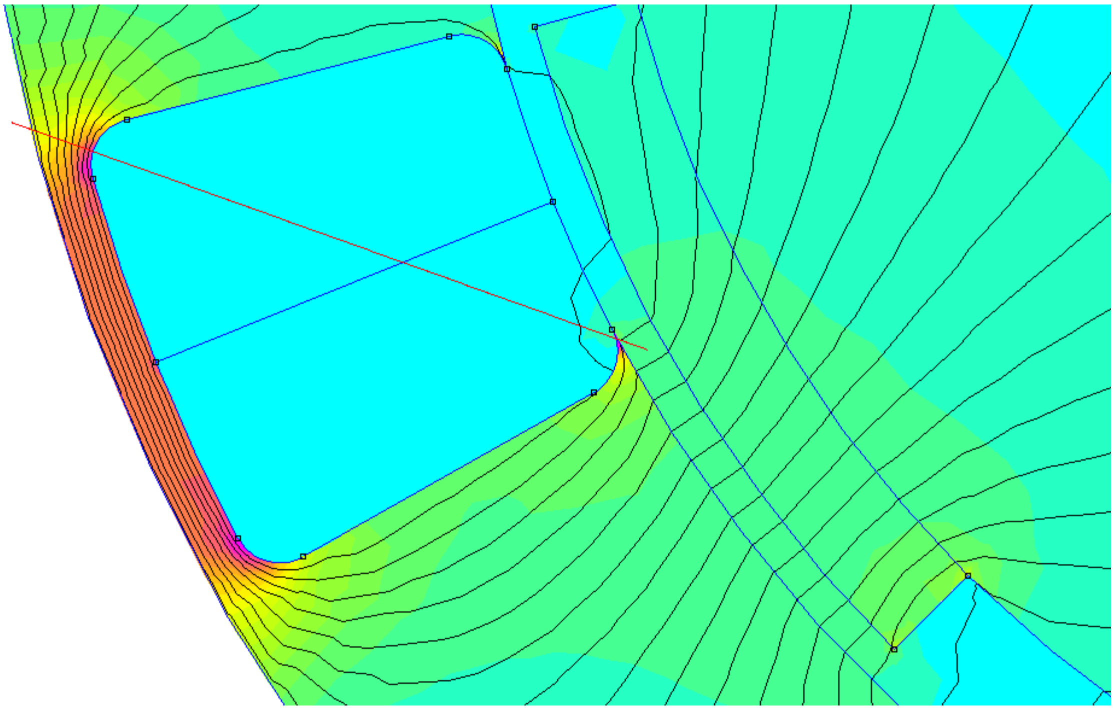

Fig B.1: The flux density lines are very saturated

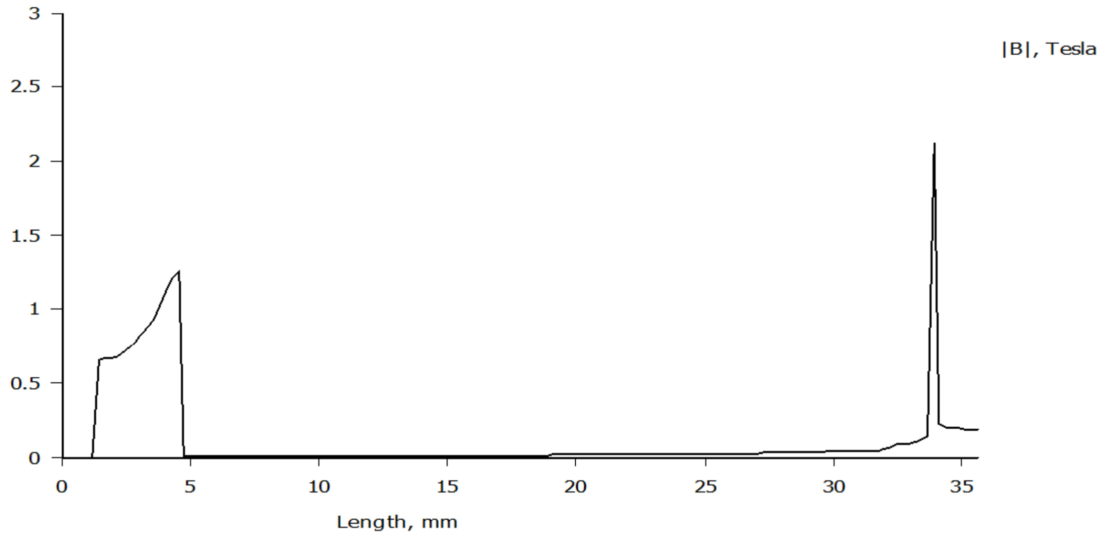

Fig B.2: Graph of the flux density that crosses the contour line drawn in the ***Fig B.1***. The x-axis length goes from left to the right, following the path of the contour red line.

Since we obtain that values over 2 T are being generated in the stator and the hysteresis curve (see ***Fig B.3*** and ***Fig B.4***) from Vanadium Permedur shows that for values over 2,2 T the material is working under saturated conditions, then it is cautious to re-design the stator geometry in order to reach lesser values of flux density in the model because with time materials can easily lose their magnetic properties and the increase the magnetic losses of energy. The sharp edges of the stator are useful in order to keep the copper wire confined within the stator slots. However, the density of the magnetic field is very high in those sharp ends. Future work regarding the smoothing of those edges could be carried out.

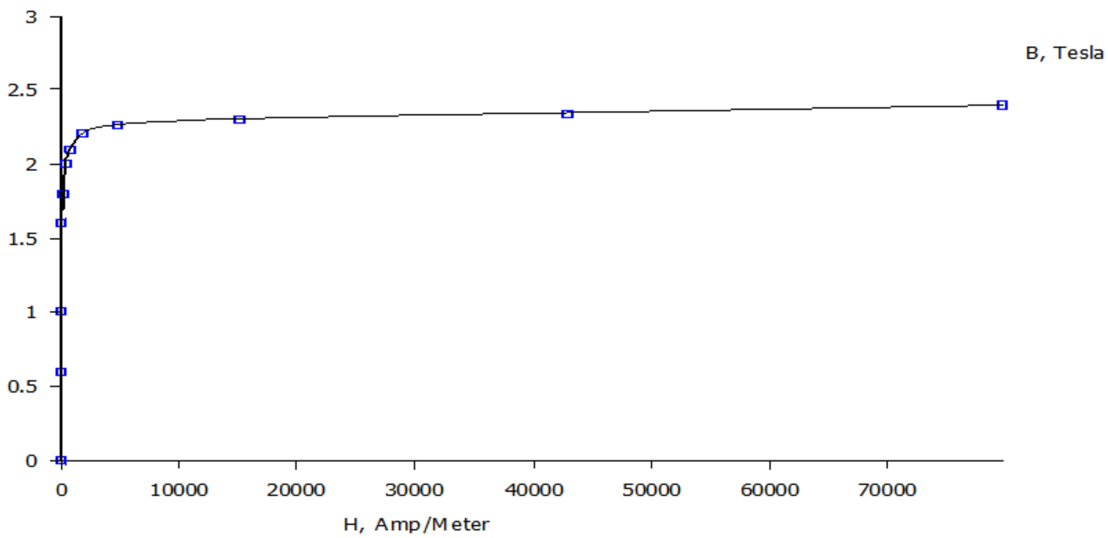

Fig B.3: Vanadium Permedur B-H curve

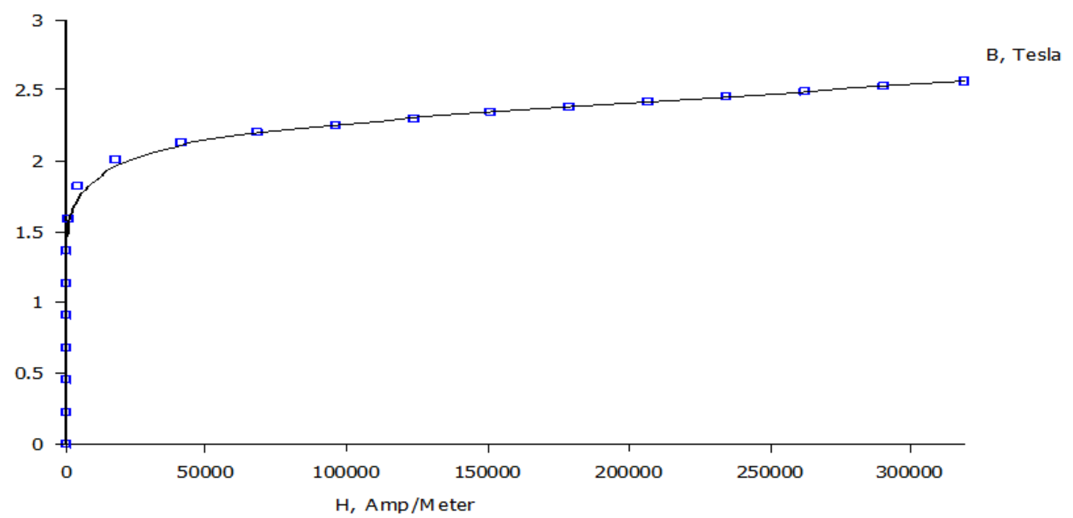

Fig B.4: Pure Iron B-H curve

B.1.2. Second Geometry

The saturated space between the slot and the outer diameter of the stator has been modified; now it has 10mm (see ***Fig B.5***). The number of turns of copper wire is the same, although the occupational factor of the slot has changed to $F_o = 0{,}44$.

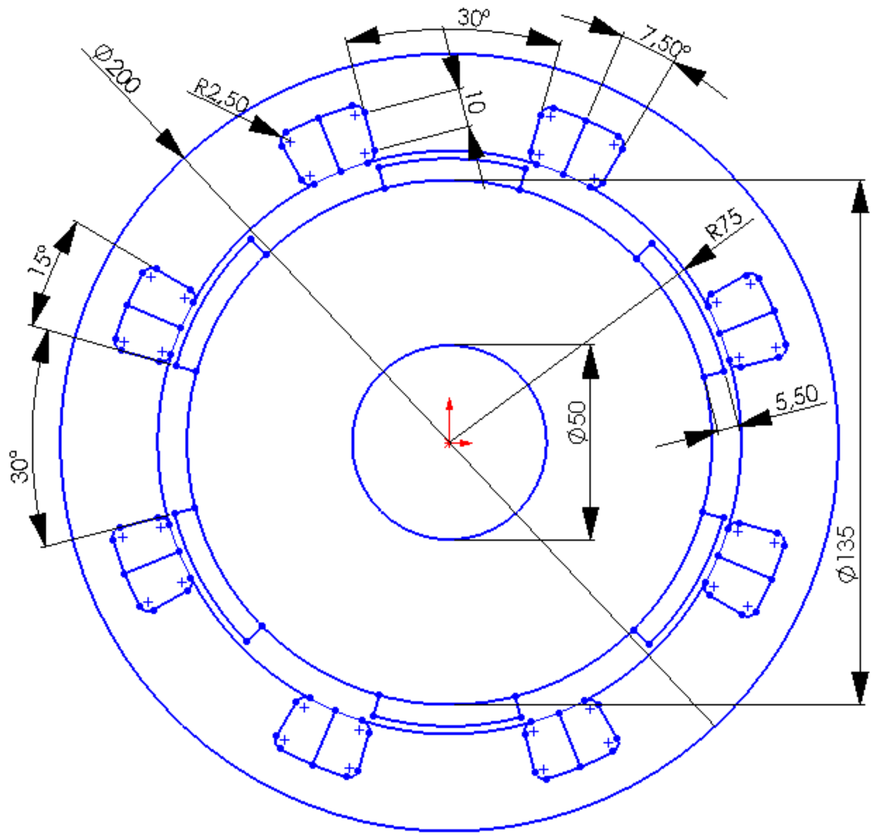

Fig B.5: Second geometry proposed for the 8/6 SRM

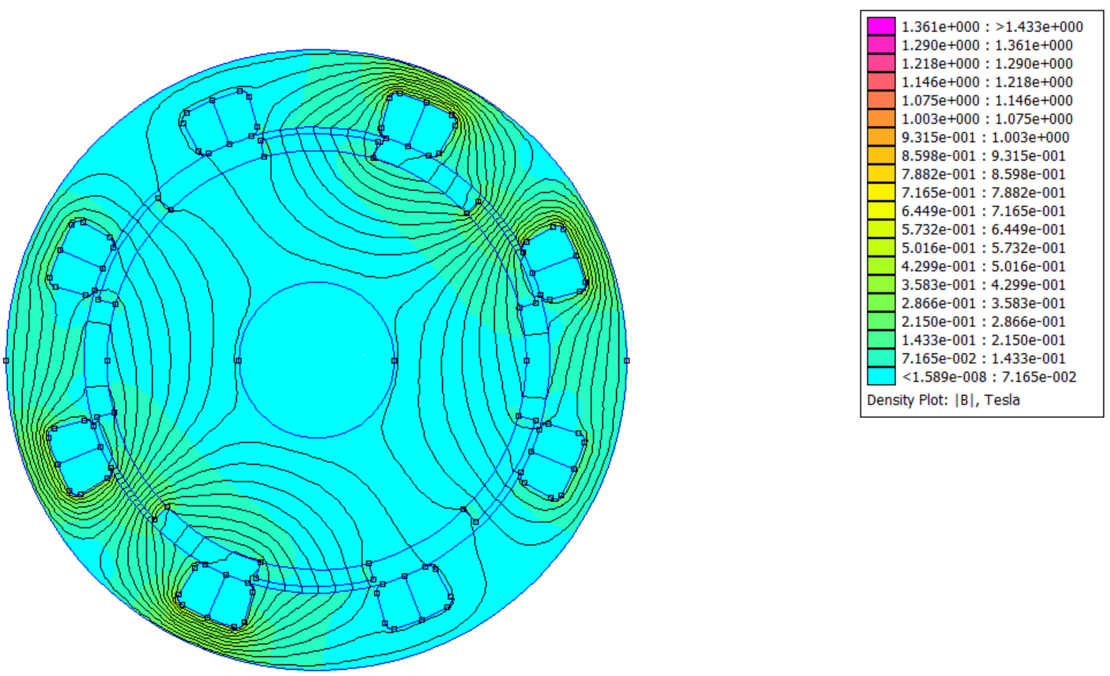

Fig B.6: Flux density lines as soon as phase B is energized with the nominal current, and legend

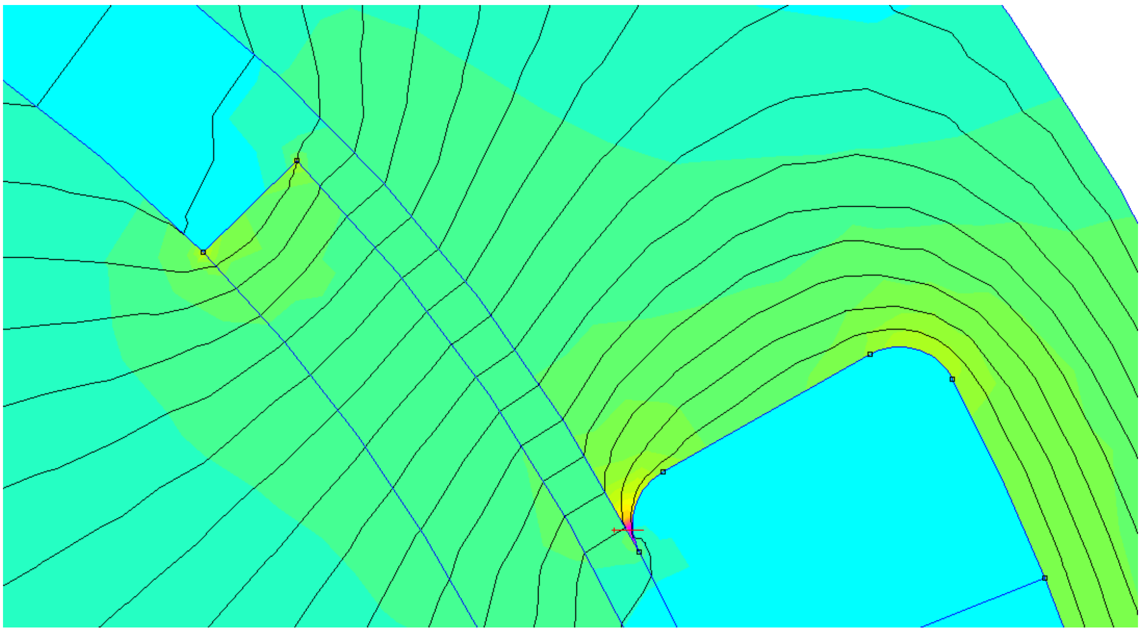

Fig B.7: Flux density lines as soon as phase B is energized and contour red line

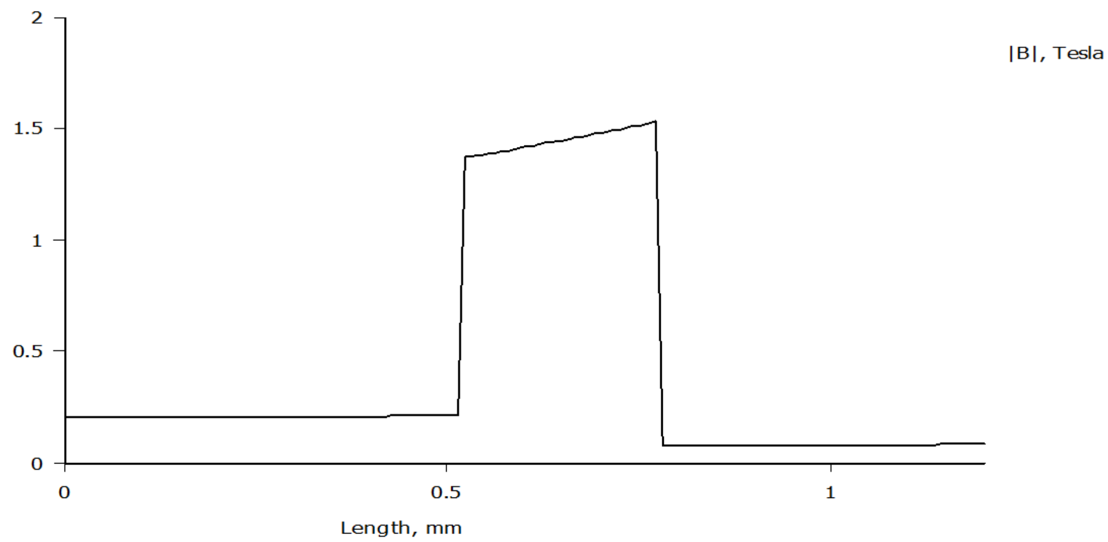

Fig B.8: Graph of the flux density that crosses the contour line drawn in the ***Fig B.7***

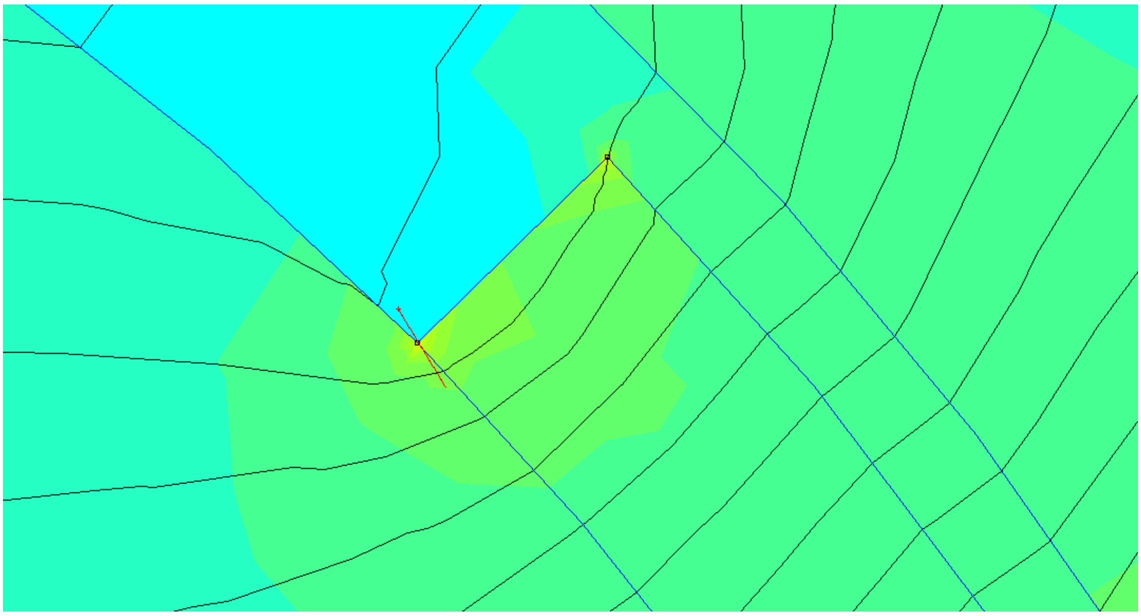

Fig B.9: Flux density lines as soon as phase B is energized and contour red line

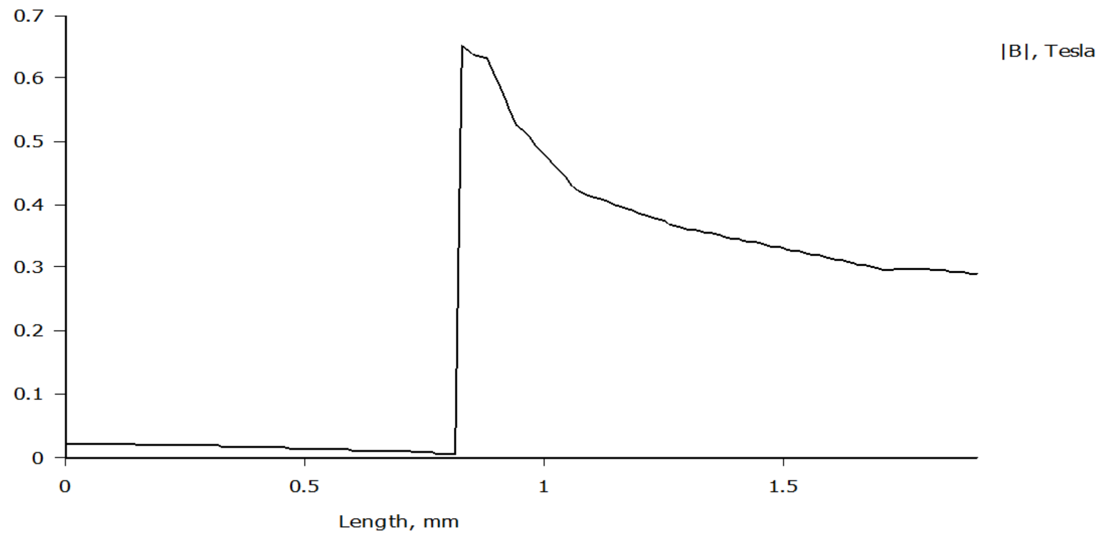

Fig B.10: Graph of the flux density that crosses the contour line drawn in the ***Fig B.9***

From the graphs of the FEMM software can be seen that the maximum value of intensity of magnetic flux is around 1,5 T and is given as soon as the i-th phase is energized. The sharp edges of the stator poles work very saturated. However, this value is contained in the linear part of the hysteresis diagram for both stator and rotor's material, and this part of the geometry has remained unchanged because it is useful in order to maintain the copper wire inside the stator slot.

When the rotor pole is totally overlapped with the stator pole the highest values for the magnetic flux intensity are around 0,55 T, but the motor materials are still working in linear conditions (see ***Fig B.11*** and ***Fig B.12***).

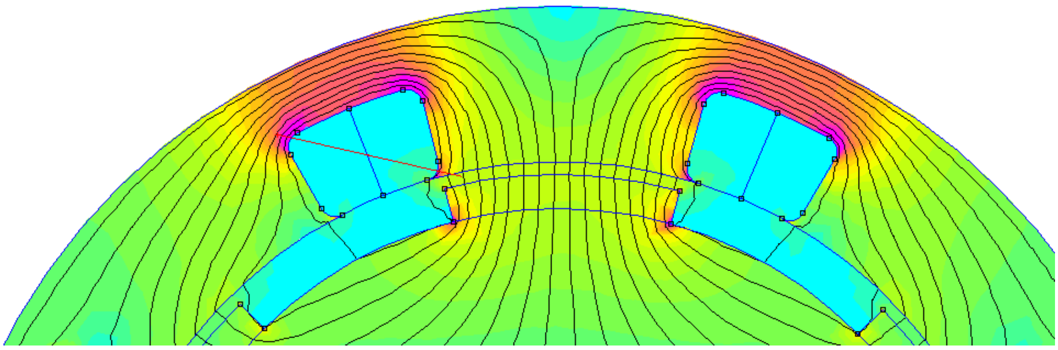

Fig B.11: Flux density lines when phase A is energized and the rotor pole is totally overlapped with the stator pole, and contour red line

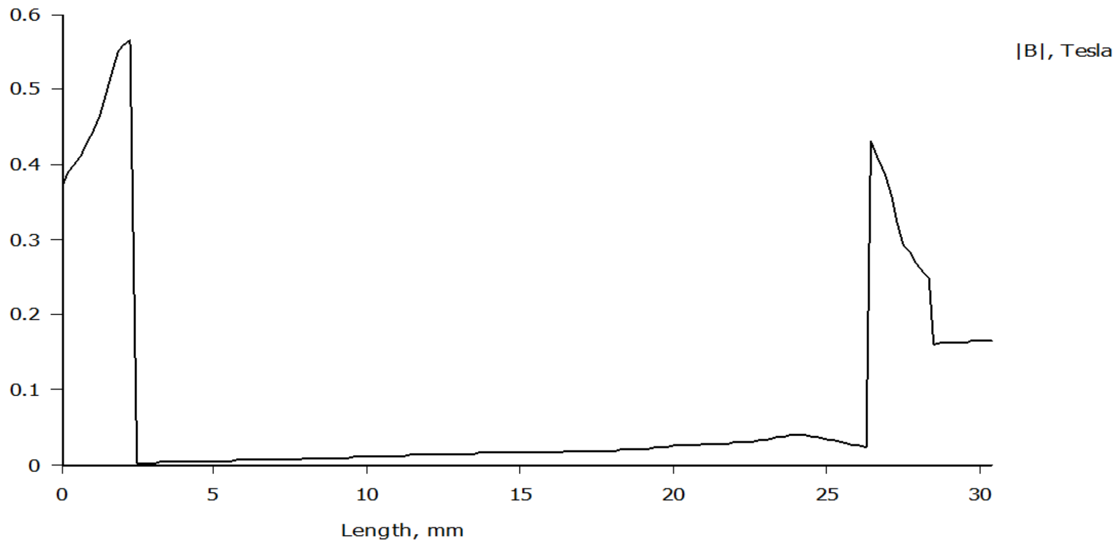

Fig B.12: Flux density lines crossing the contour line drawn in the ***Fig B.11***

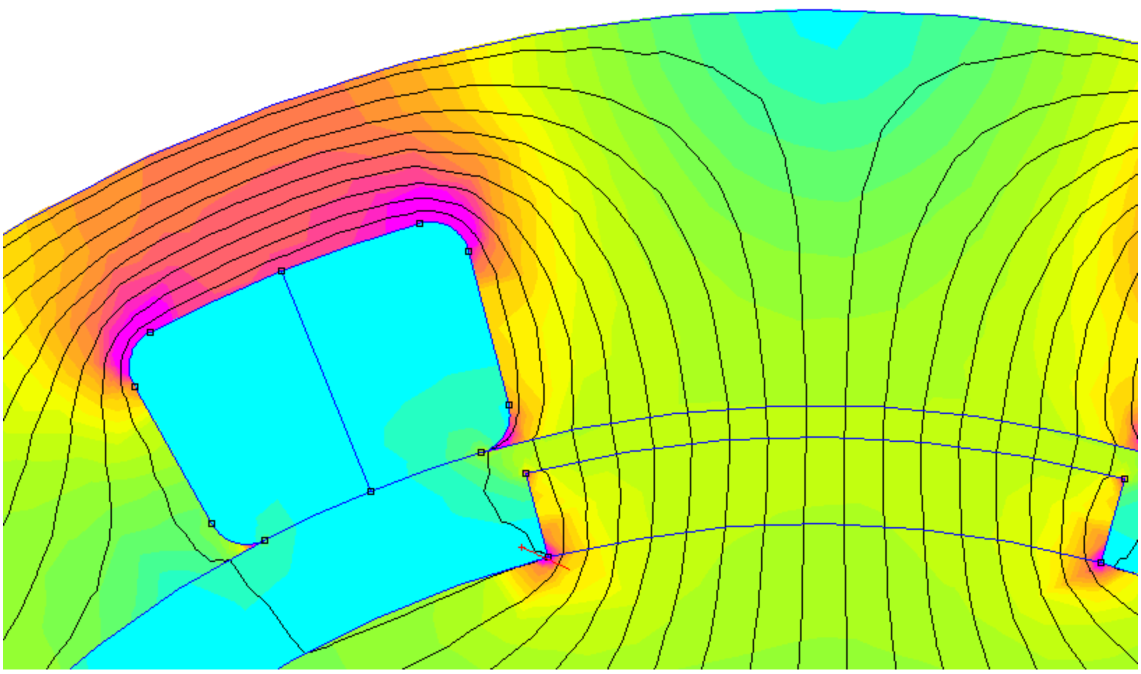

Fig B.13: Flux density lines when the rotor pole is totally overlapped with the stator pole and phase A is energized, and contour red line

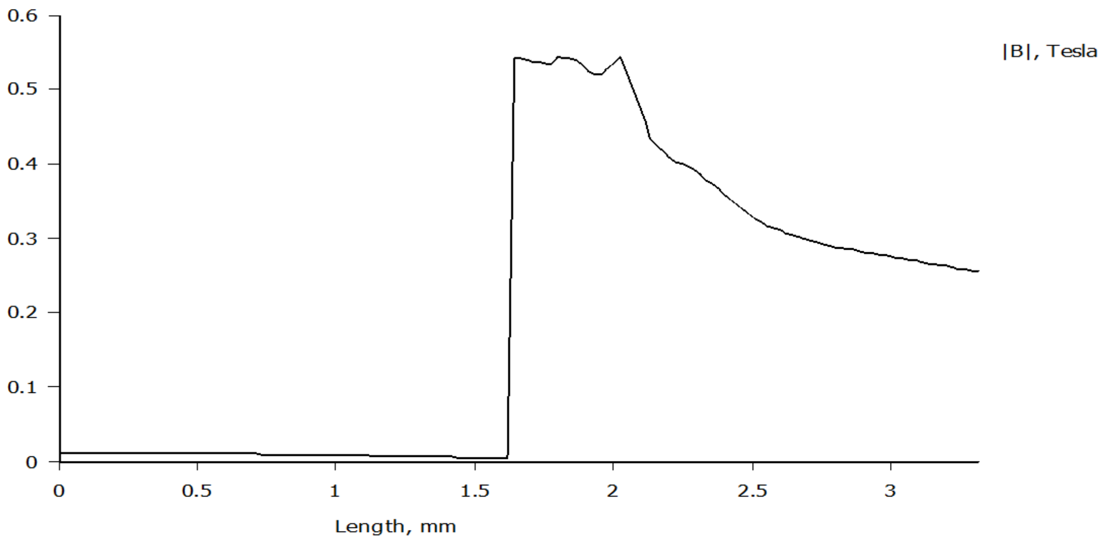

Fig B.14: Flux density lines crossing the contour line drawn in the ***Fig B.13***

B.1.3. Third geometry

In order to increase the saliency ratio, four flux guides per rotor pole have been implemented with the same measures as in the fourth geometry. The air gap has been doubled to 4 mm (shown in ***Fig B.15***). The flux barriers help to guide the flux density lines and concentrate them in a smaller region the space, that is to say, increments the density of the magnetic flux thus triggering a higher output torque. The U-shape of the flux barriers have been chosen according to the ease of the rotor manufacturing and the high performance over other type of flux barrier shapes **[1]**.The is 2 mm left from the outer flux barrier to the outer diameter of the rotor in order to avoid non-feasible rotors from a constructive point of view.

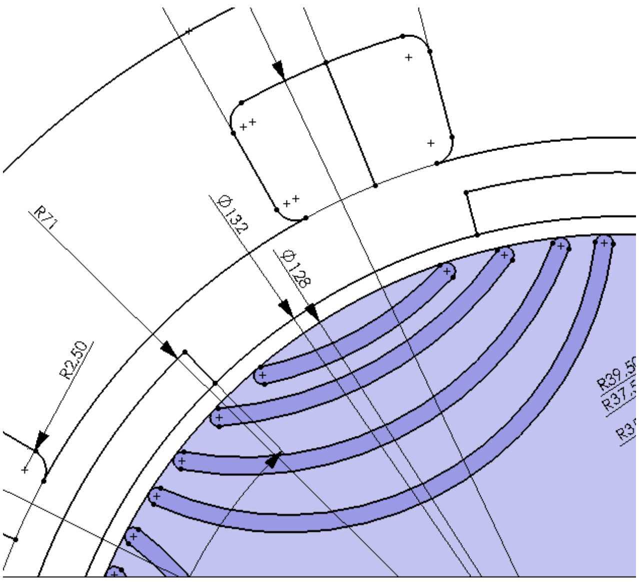

Fig B.15: Third geometry proposed with four flux barriers per rotor pole

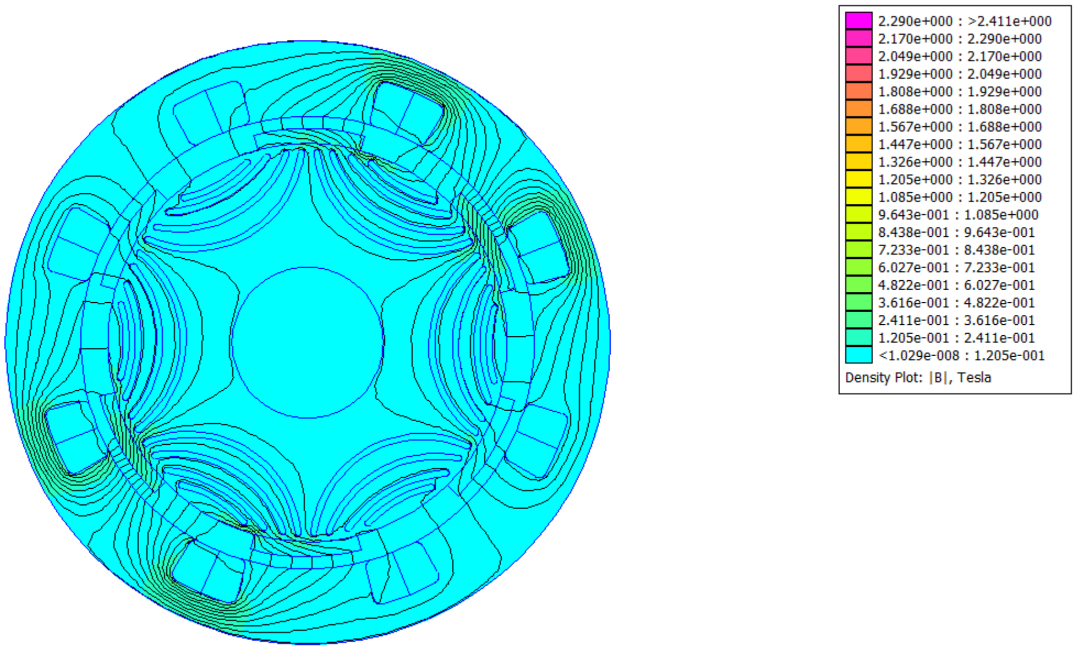

Fig B.16: Flux density lines for the third geometry as soon as phase B is energized, and legend

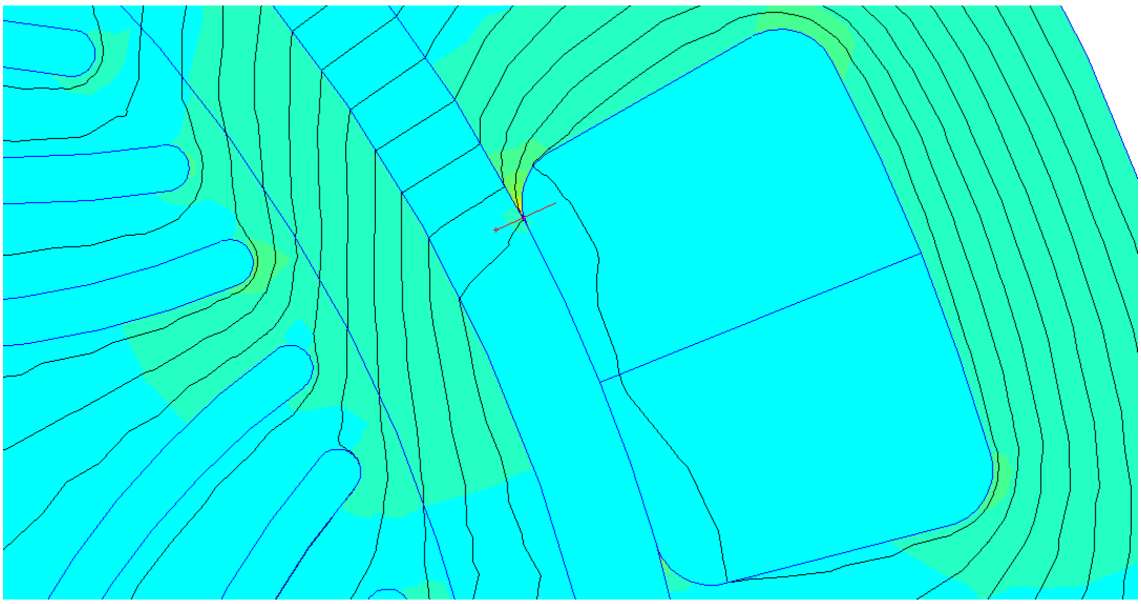

Fig B.17: Flux density lines as soon as phase B is energized and contour red line

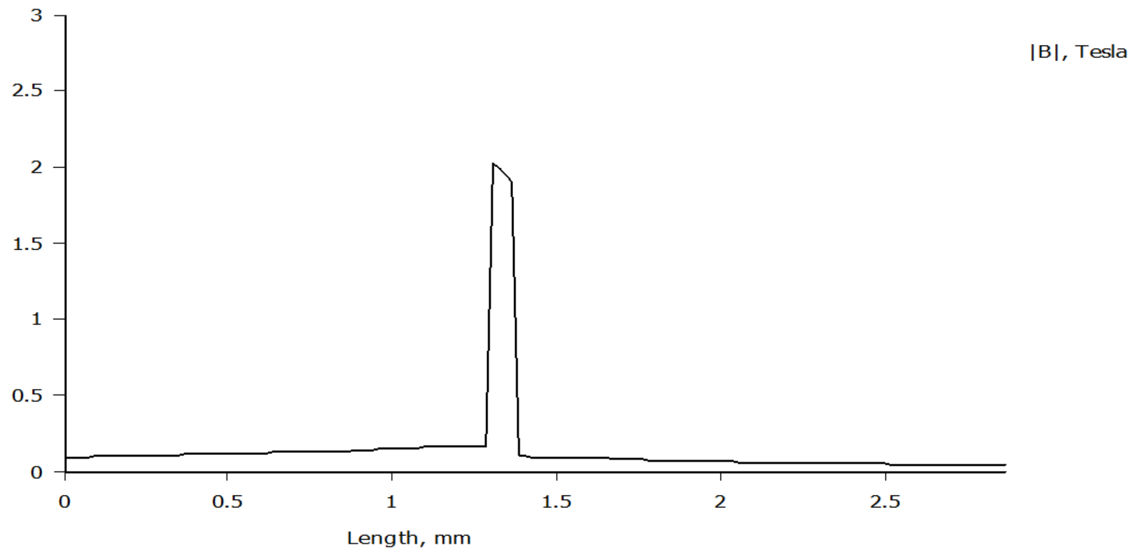

Fig B.18: Flux density lines crossing the contour line drawn in the ***Fig B.17***

It can be seen that the only part that works saturated is the sharp edge of the stator. This geometry is not useful since the output torque and the saliency ratio are very low. In order to increase them, the air gap should be smaller. Incrementing the air gap has been detrimental to the output reluctance torque.

B.1.4. Fourth geometry

A fourth geometry has been designed in order to increase the saliency ratio. The air gap has been reduced to 2 mm (see ***Fig B.19***) and the rotor's overall volume has been slightly increased by enlarging the rotor's outer diameter by 3 mm. In addition the length from the outer flux barrier to the outer diameter of the rotor has been diminished by 1 mm.

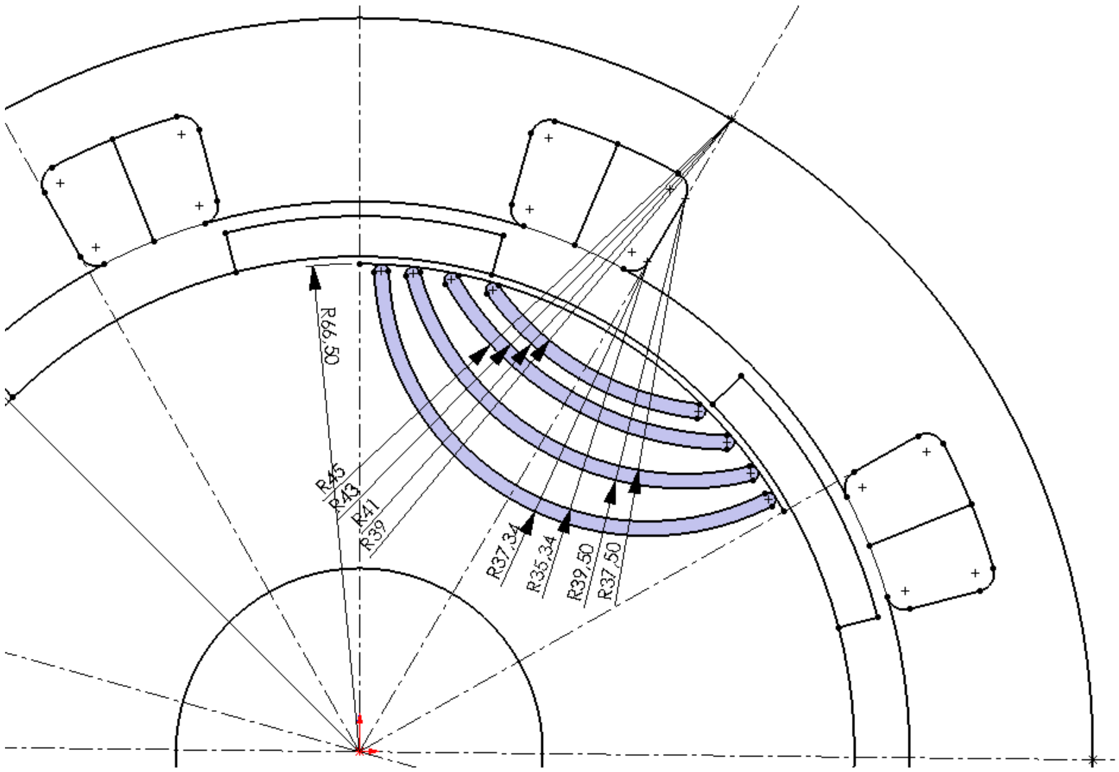

Fig B.19: Fourth geometry proposed with an air gap of 2 mm and the flux barrier's measures

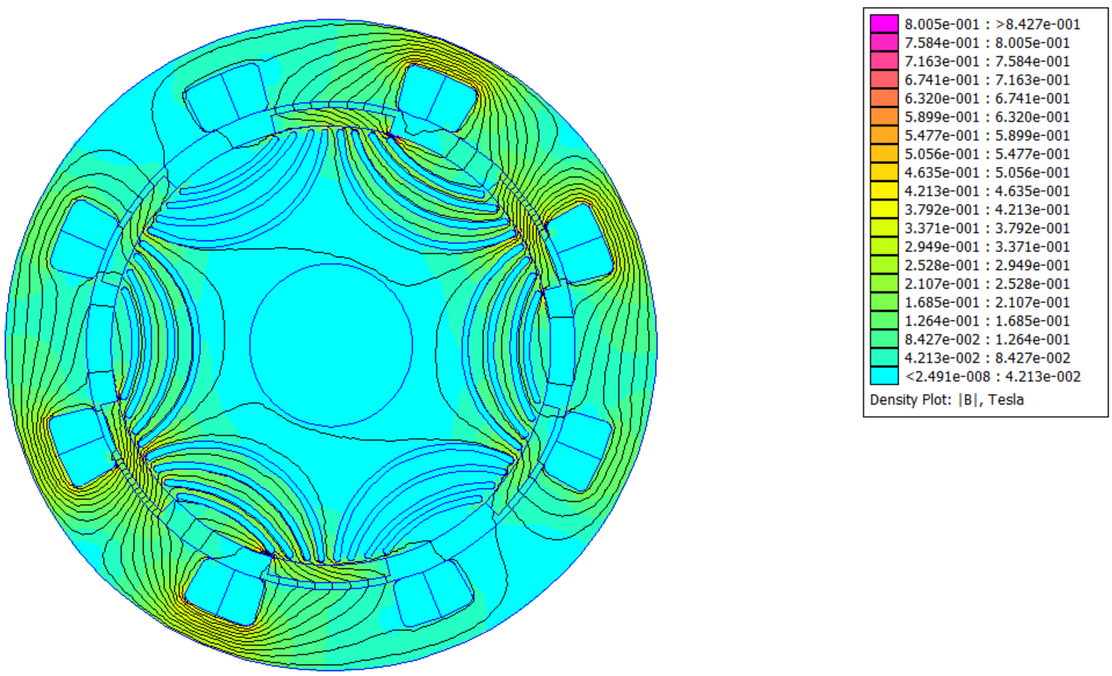

Fig B.20: Flux density lines as soon as phase B is energized with the nominal current, and legend

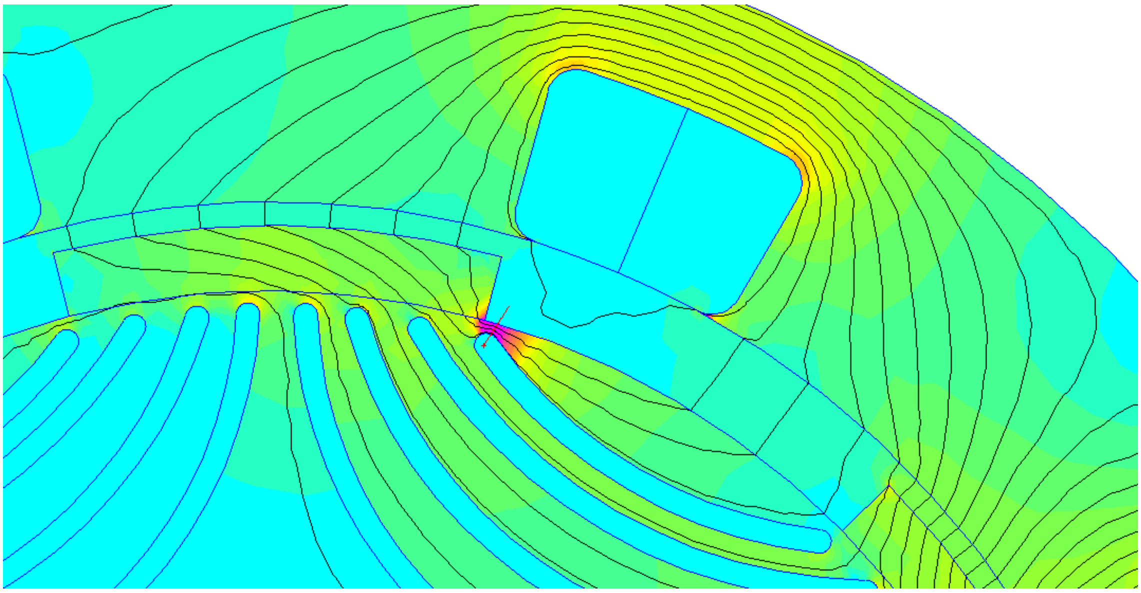

Fig B.21: Flux density lines as soon as phase B is energized and contour red line

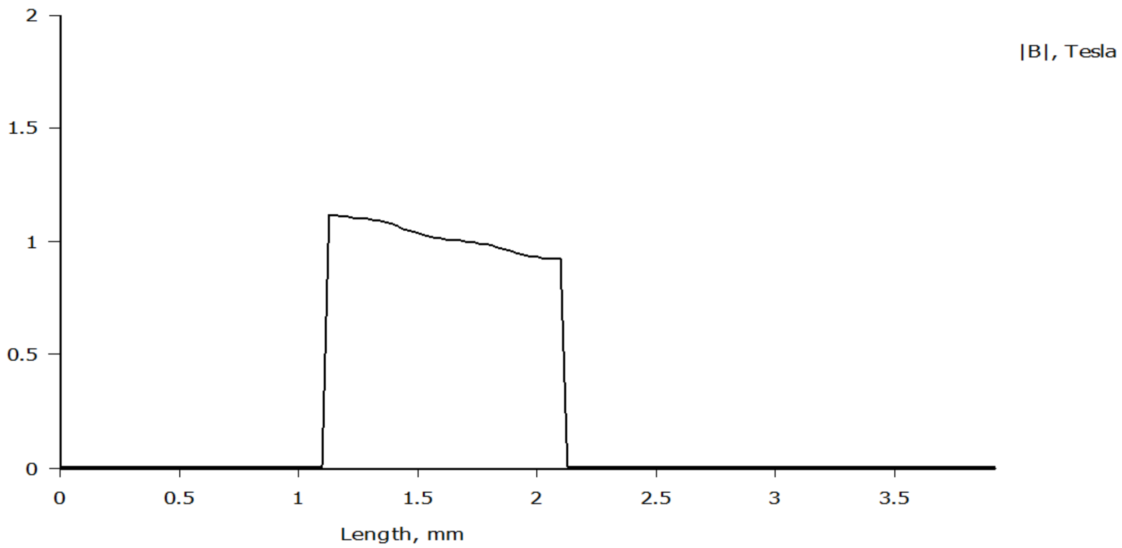

Fig B.22: Graph of the flux density that crosses the contour line drawn in the ***Fig B.21***

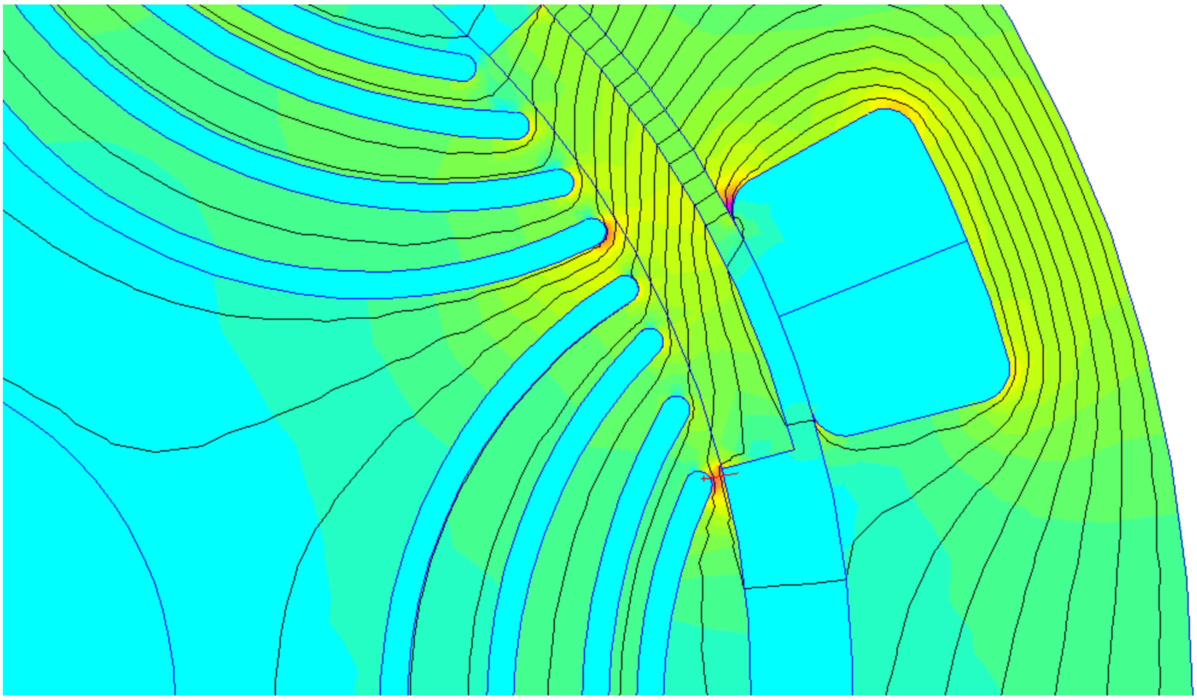

Fig B.23: Flux density lines as soon as phase B is energized and contour red line

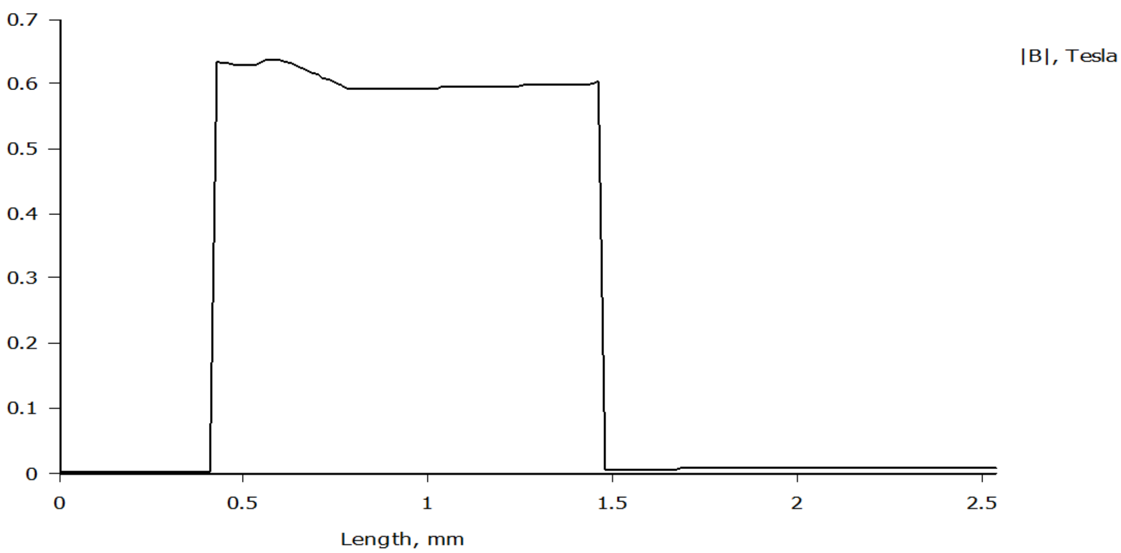

Fig B.24: Graph of the flux density that crosses the contour line drawn in the ***Fig B.23***

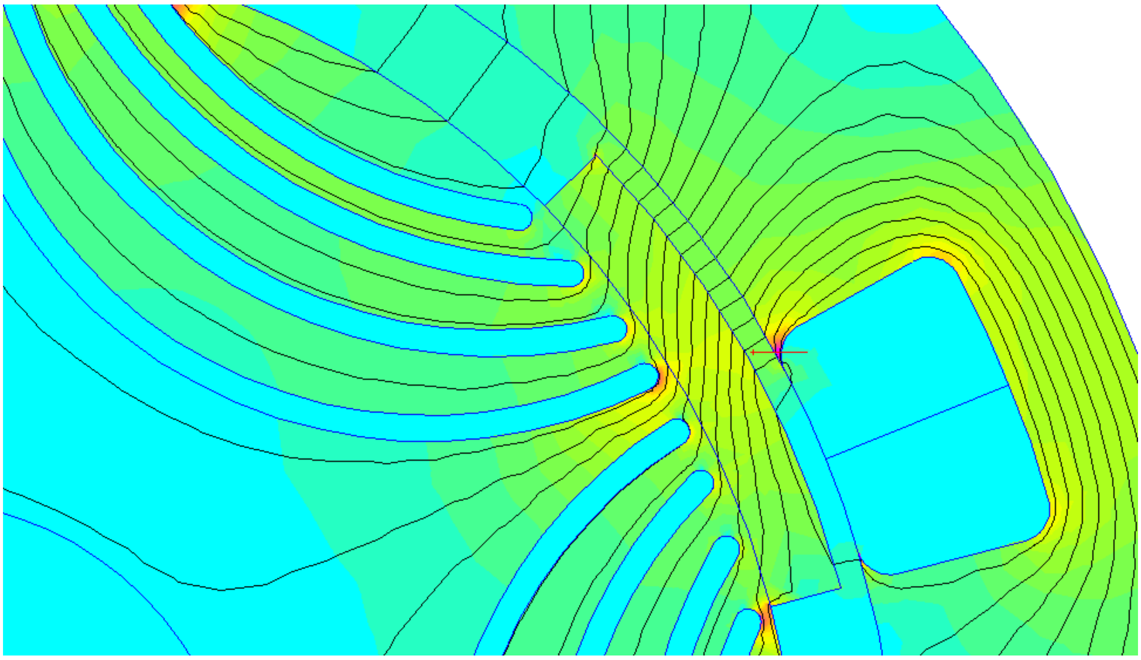

Fig B.25: Flux density lines as soon as phase B is energized and contour red line

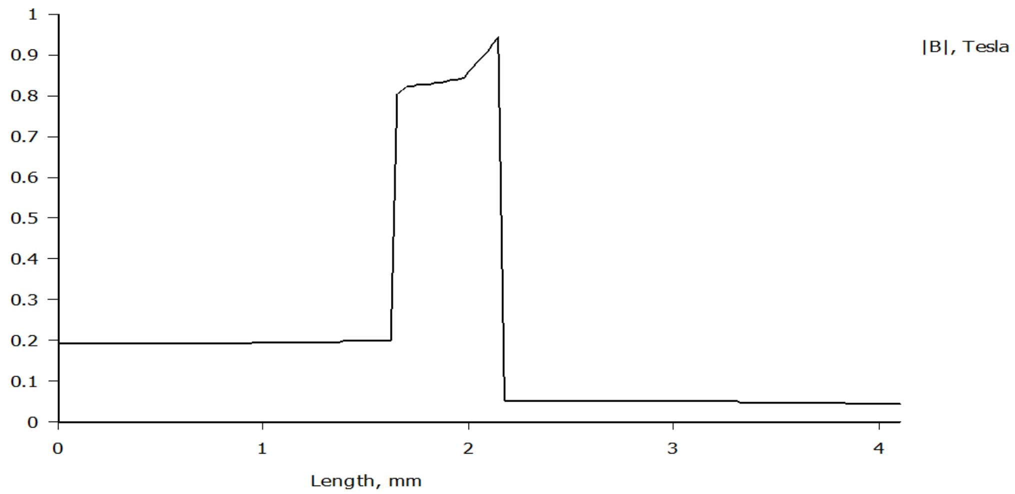

Fig B.26: Graph of the flux density that crosses the contour line drawn in the ***Fig B.25***

The highest values for the intensity of the magnetic field are around 1,1 T, which means that the materials of the motor are working under linear conditions. The torque in the instant where phase B is energized is a little bit higher than that obtained by the first and the second geometry in the same instant.

B.1.5. Fifth geometry

Finally, a fifth geometry has been designed in order to increase the saliency ratio. The air gap has been reduced to 0,2 mm (see ***Fig B.27*** and ***Fig B.28***) and the rotor's overall volume has been slightly increased by enlarging the rotor poles. Now their length are 8,8 mm, 3,8 mm larger than in the previous geometries.

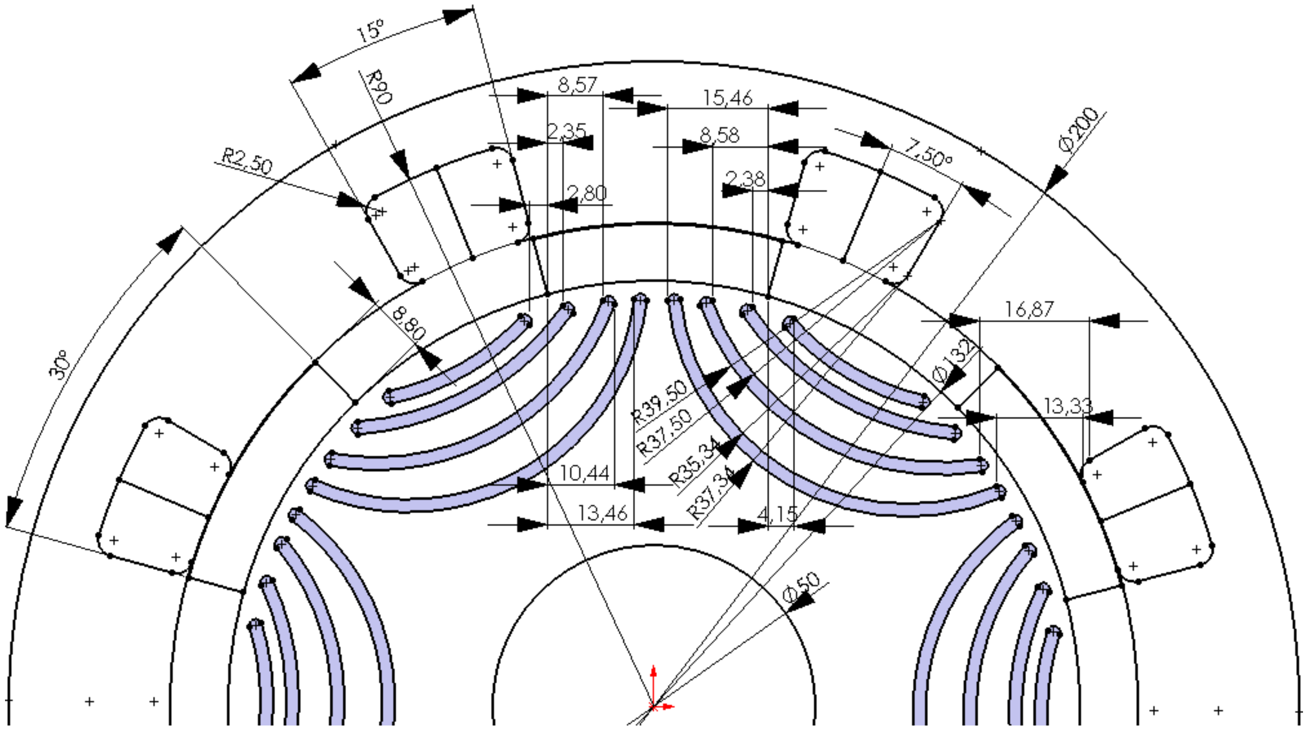

Fig B.27: Fifth geometry

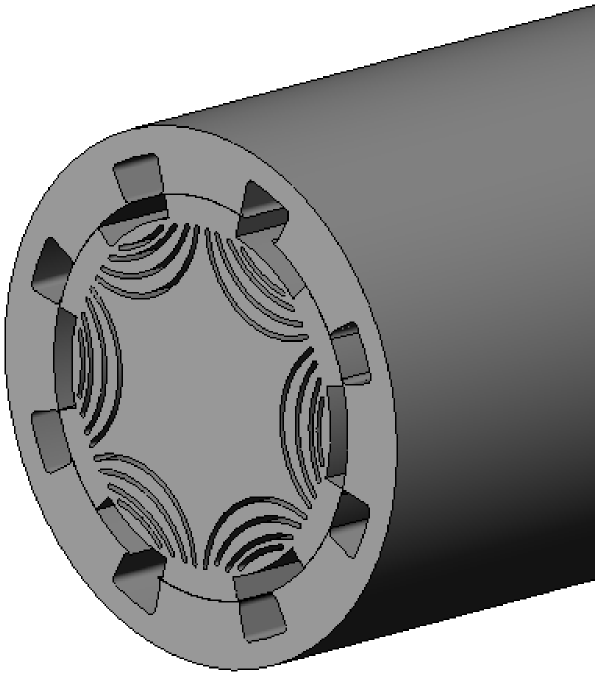

Fig B.28: 3D view of the fifth geometry without the non-magnetic shaft

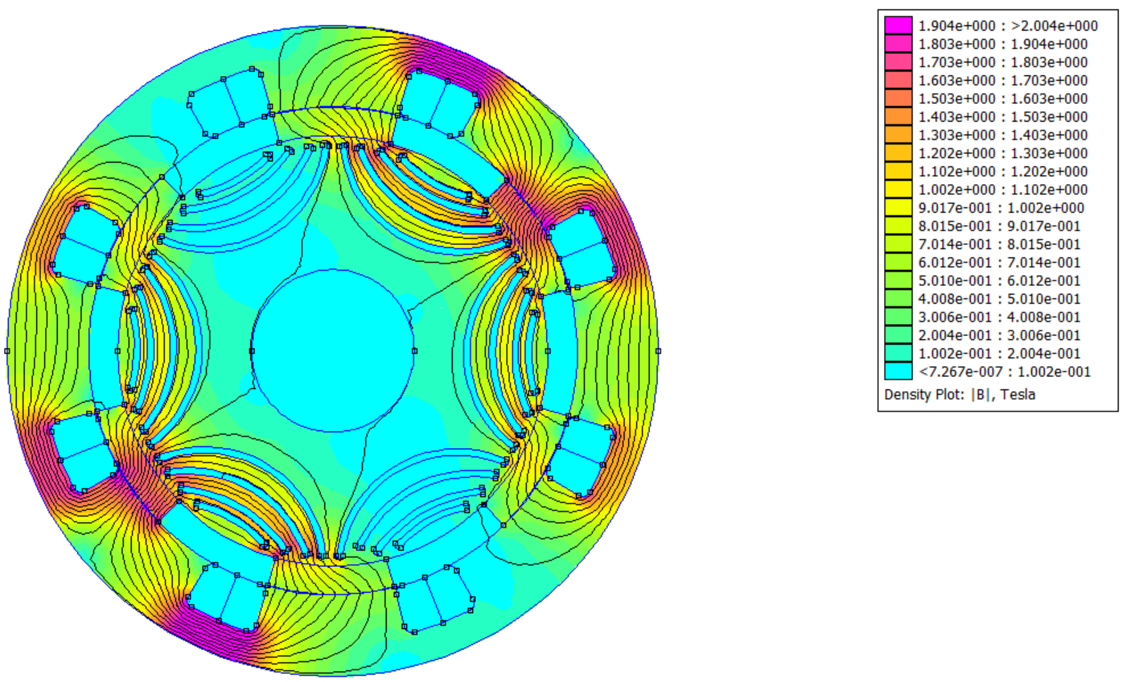

Fig B.29: Flux density lines as soon as phase B is energized and legend

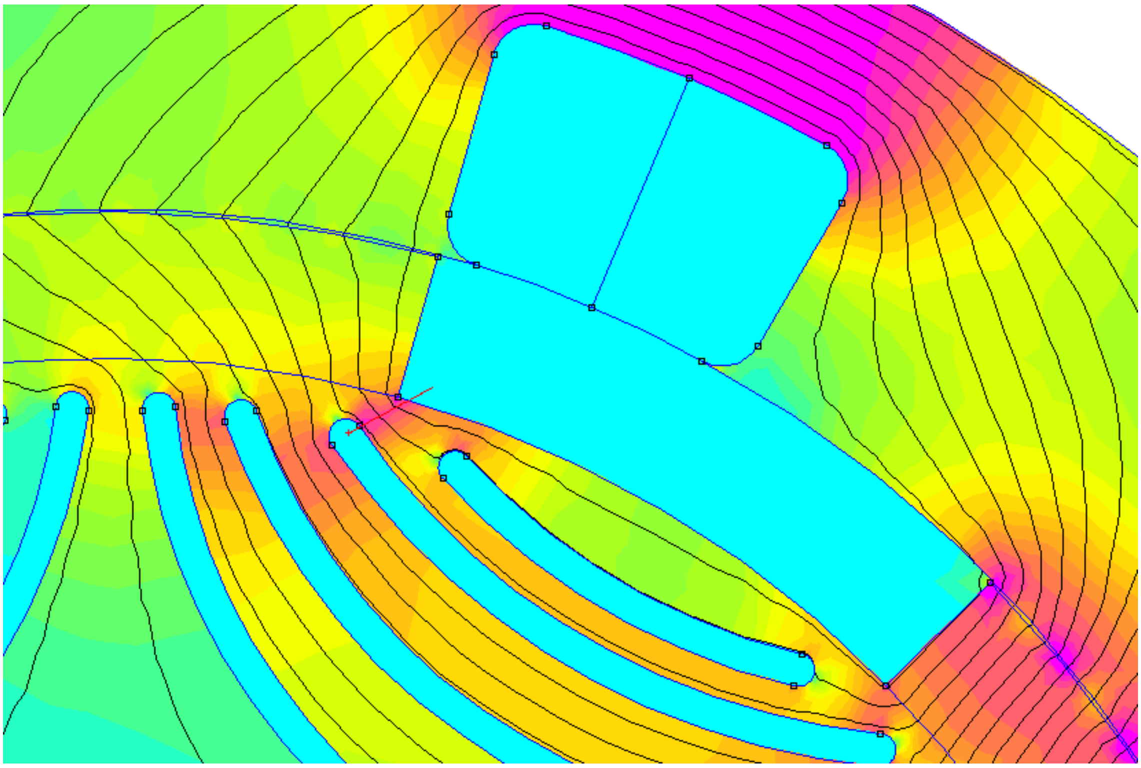

Fig B.30: Flux density lines as soon as phase B is energized and contour red line

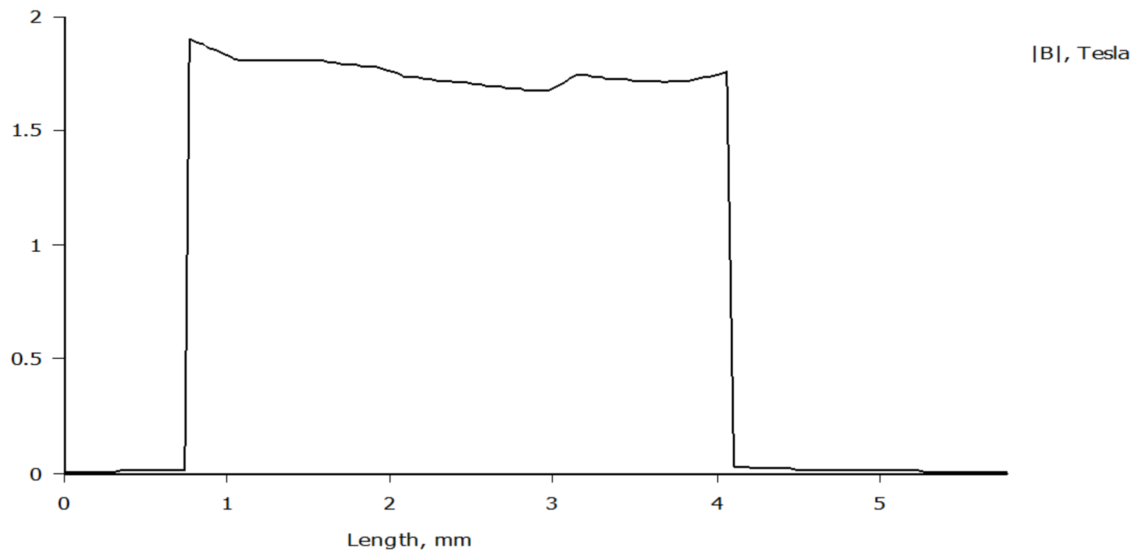

Fig B.31: Flux density lines crossing the contour line drawn in the ***Fig B.29***

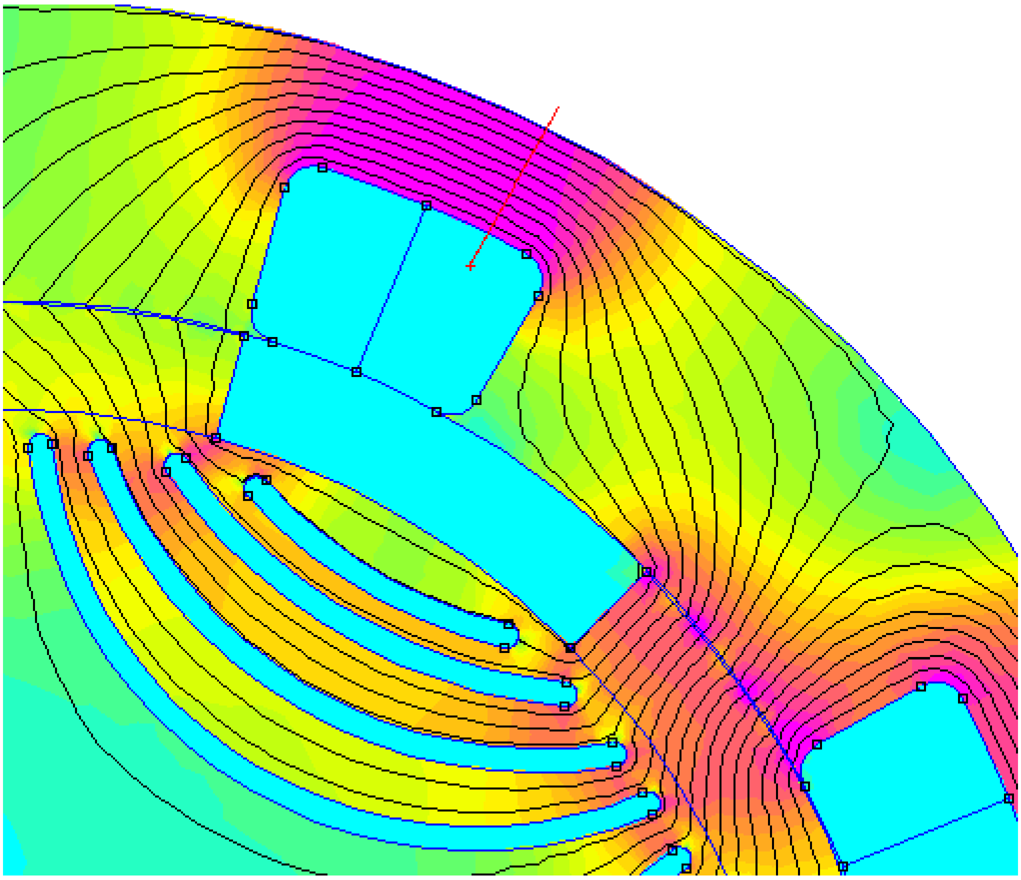

Fig B.32: Flux density lines as soon as phase B is energized and contour red line

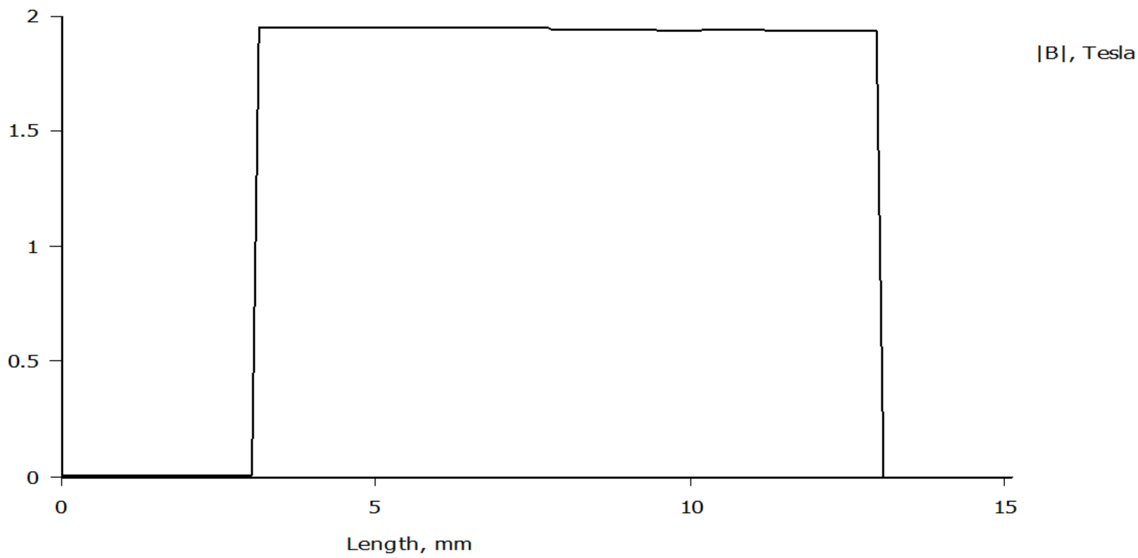

Fig B.33: Flux density lines crossing the contour line drawn in the ***Fig B.31***

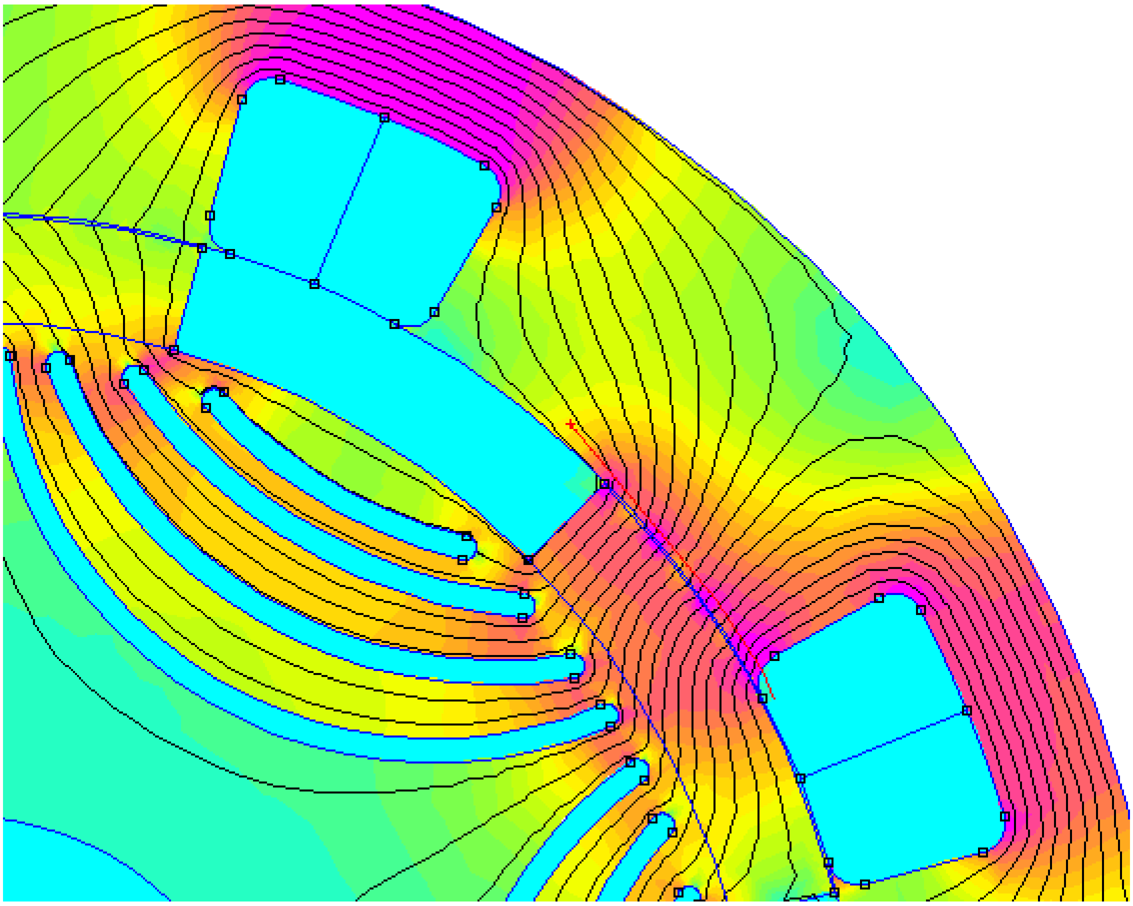

Fig B.34: Flux density lines as soon as phase B is energized and contour red line

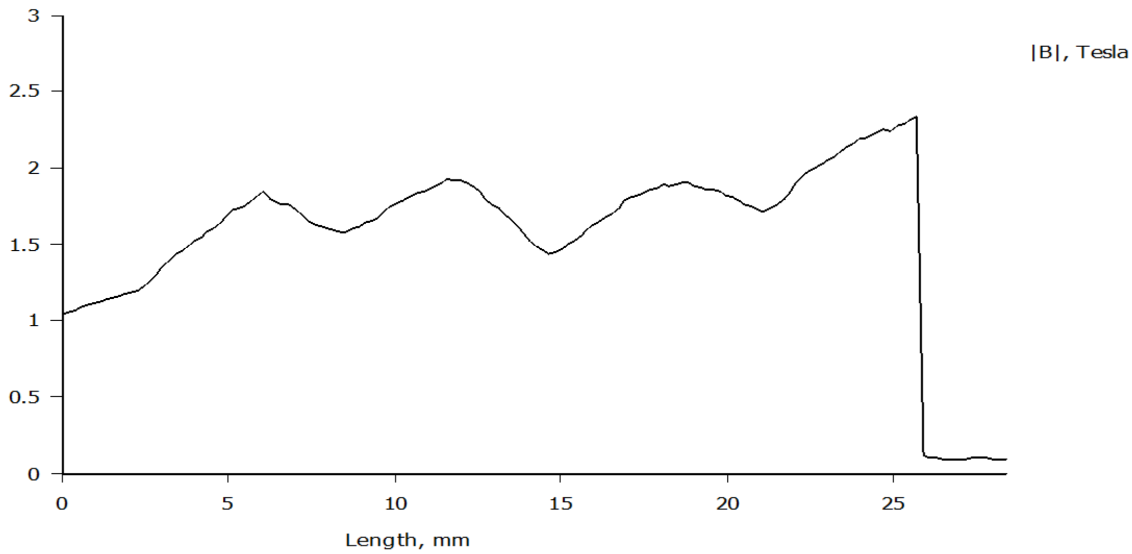

Fig B.35: Flux density lines crossing the contour line drawn in the ***Fig B.33***

The highest values of density of the magnetic field are between 2 and 2,5 T. This geometry is working quite saturated with the nominal current. However, this motor design shows the highest performance among the five geometries. Further study regarding the smoothing of the most saturated areas could be carried out.

B.2. Calculation of the number of turns, resistance of the magnetic copper wire, and phase inductance of the coil

The number of turns per stator pole has been calculated in order to achieve a coherent occupational factor F_o. Since the number of turns of the first SRM proposed geometry had to be the same as the number of turns of the second and final geometry for calculation comparisons, the number of turns have been limited by the slot surface of the second geometry, which is smaller than the first proposed ($S_1 = 0{,}251229 \cdot 10^{-3}\ m^2 > S_2 = 0{,}159232 \cdot 10^{-3}\ m^2$).

$$F_o = \frac{S_{occ}}{S_{slot}} = \frac{N \cdot S_{1\,wire}}{S_{slot}} = \frac{N \cdot 0{,}667\ mm^2 \cdot \frac{1\ m^2}{1000000\ mm^2}}{0{,}159232 \cdot 10^{-3}\ m^2} \approx 0{,}4 \rightarrow N = 100\ turns$$

The occupational factor of the first geometry therefore is a bit lower ($F_o = 0{,}265$) although in a reasonable range.

B.3. Variation of the components of the density of the magnetic field with the number of finite elements

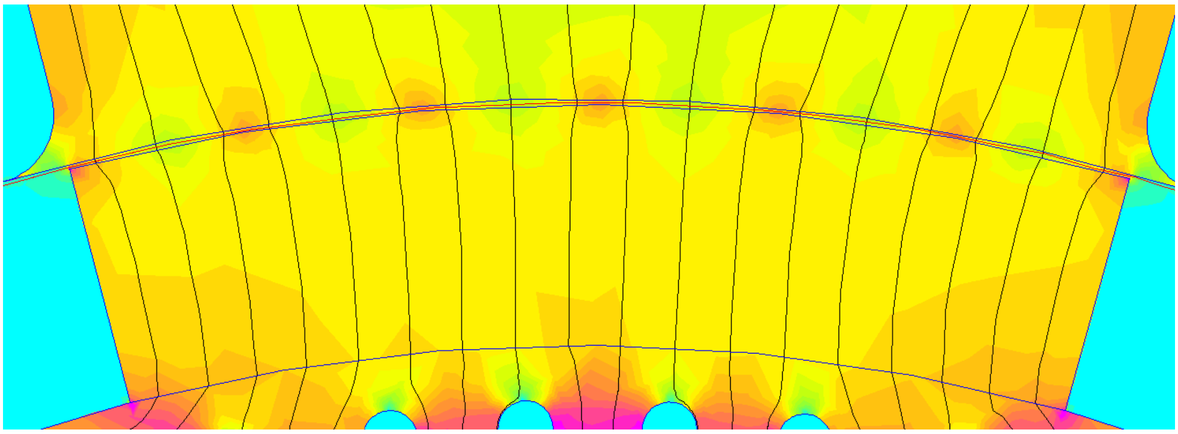

Fig B.36: Contour red line in the air gap of the fifth geometry for the position of maximum inductance when the nominal current is energised

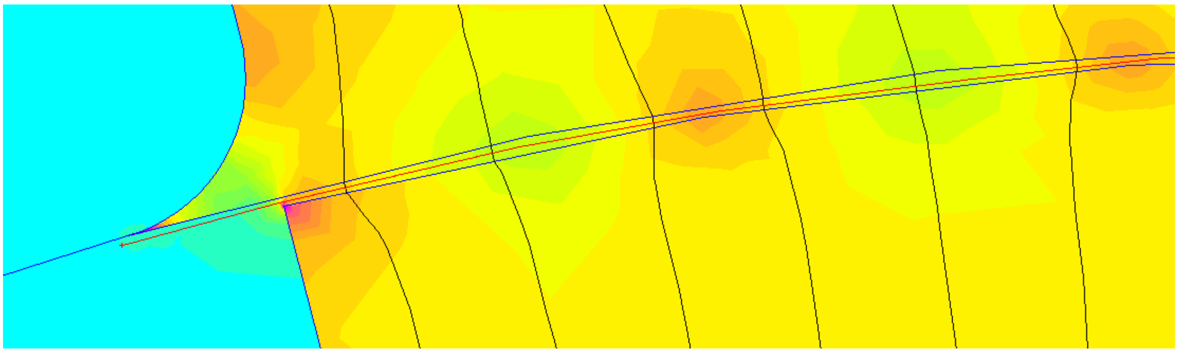

Fig B.37: Contour red line in the air gap of the fifth geometry for the position of maximum inductance when the nominal current is energised

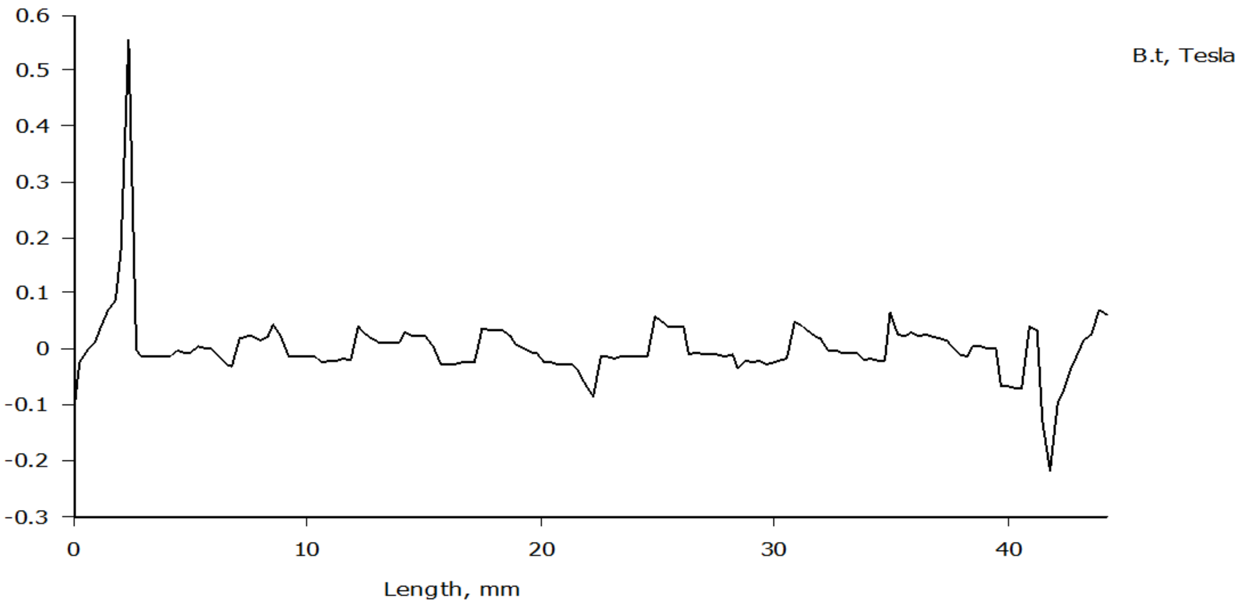

Fig B.38: Tangent component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 13.861 nodes.

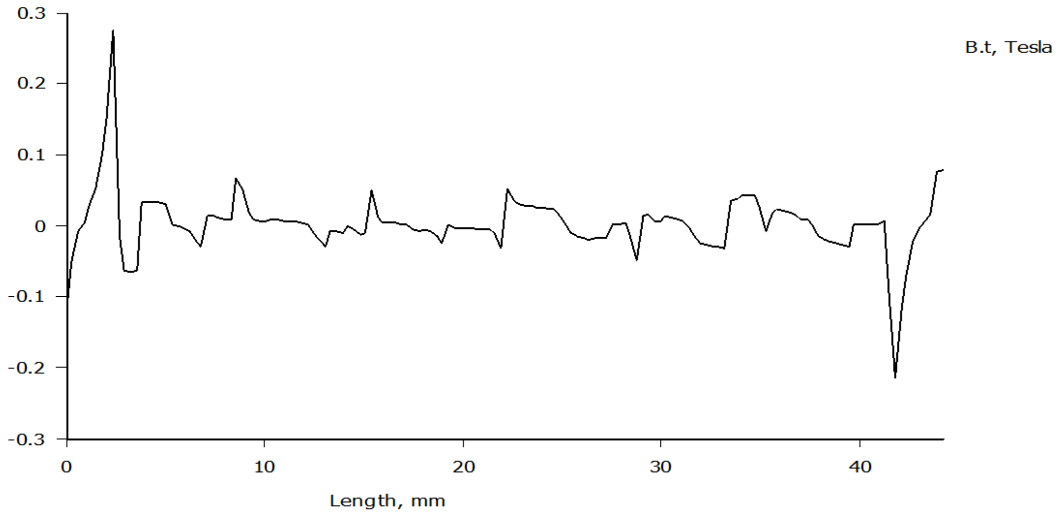

Fig B.39: Tangent component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.120 nodes.

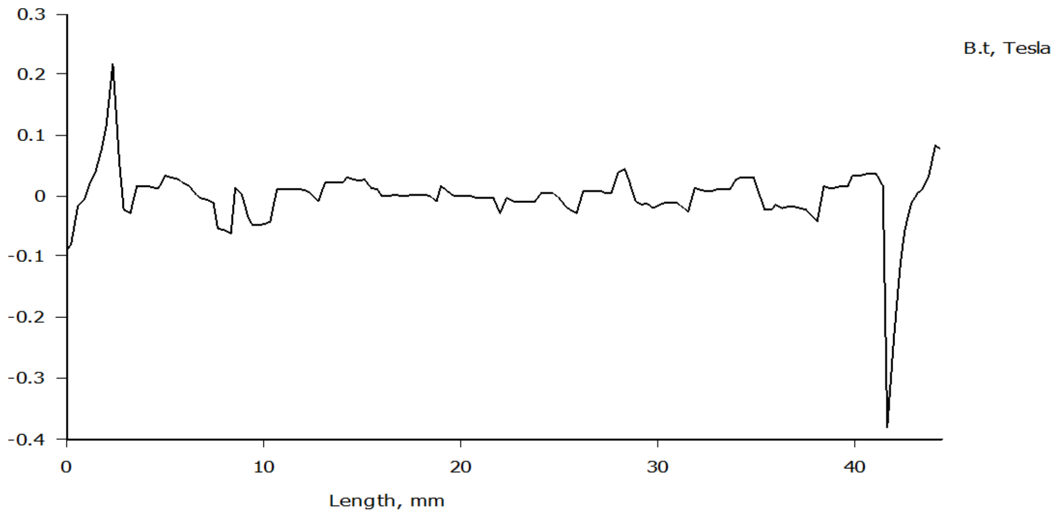

Fig B.40: Tangent component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.804 nodes.

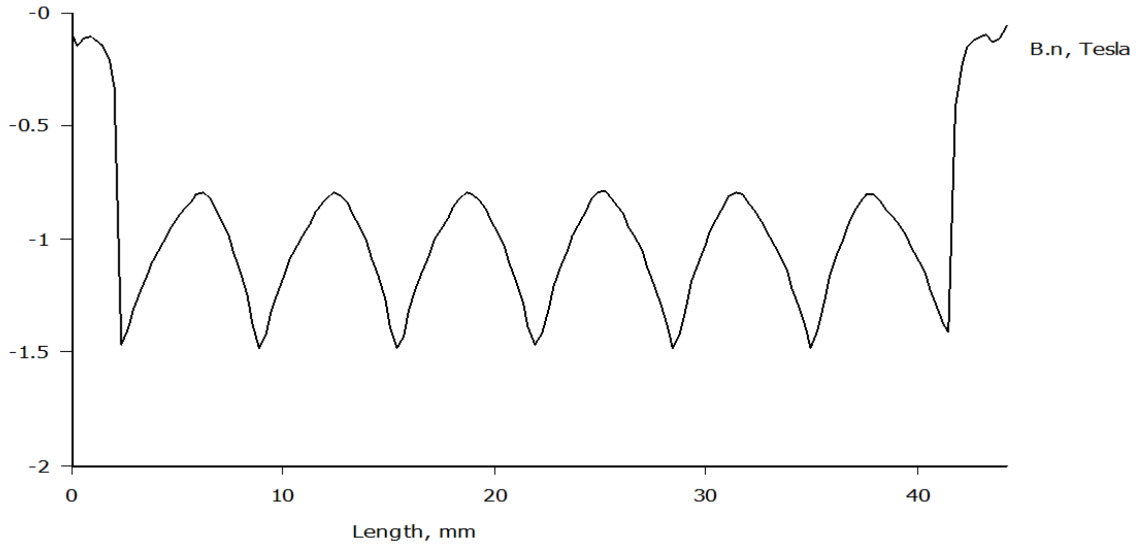

Fig B.41: Normal component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 13.861 nodes.

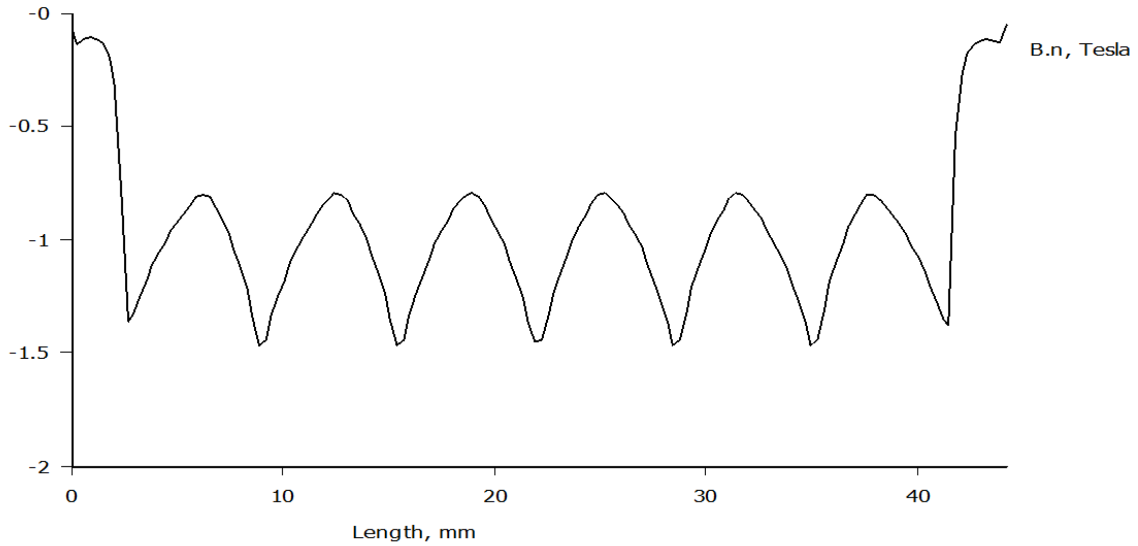

Fig B.42: Normal component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.120 nodes.

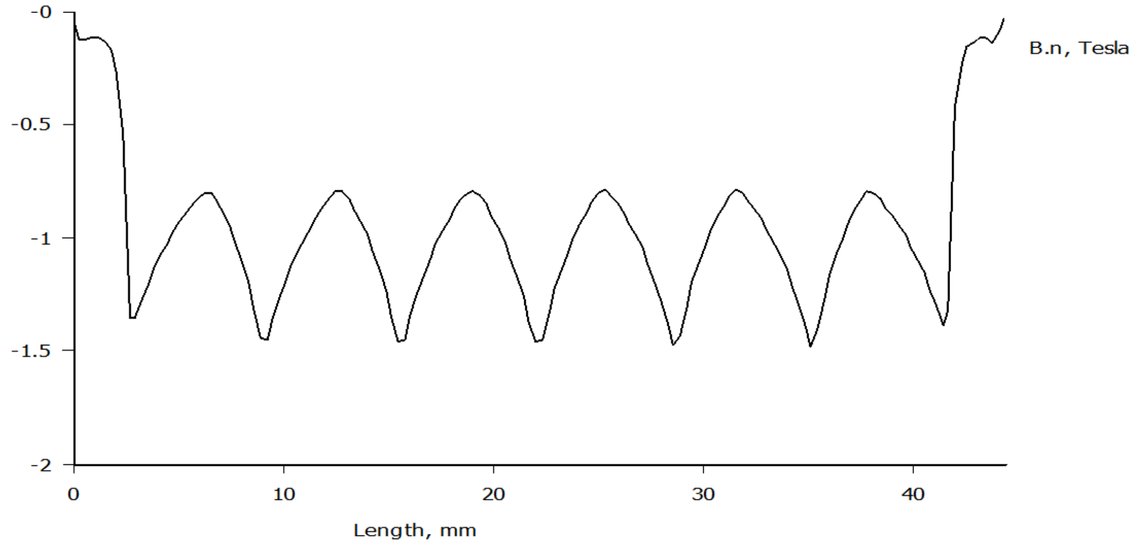

Fig B.43: Normal component of the density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.804 nodes.

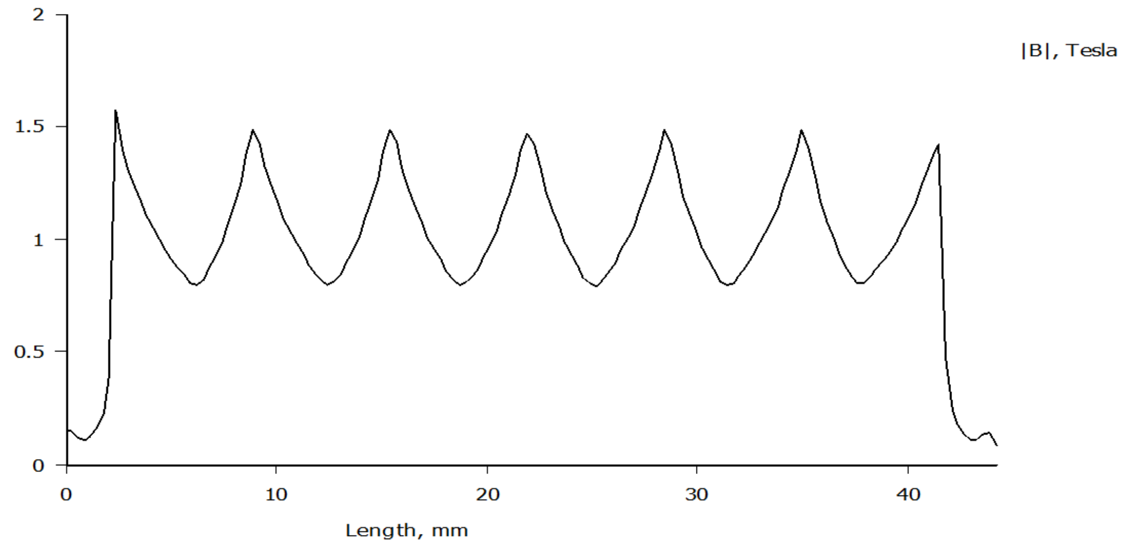

Fig B.44: Total density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 13.861 nodes.

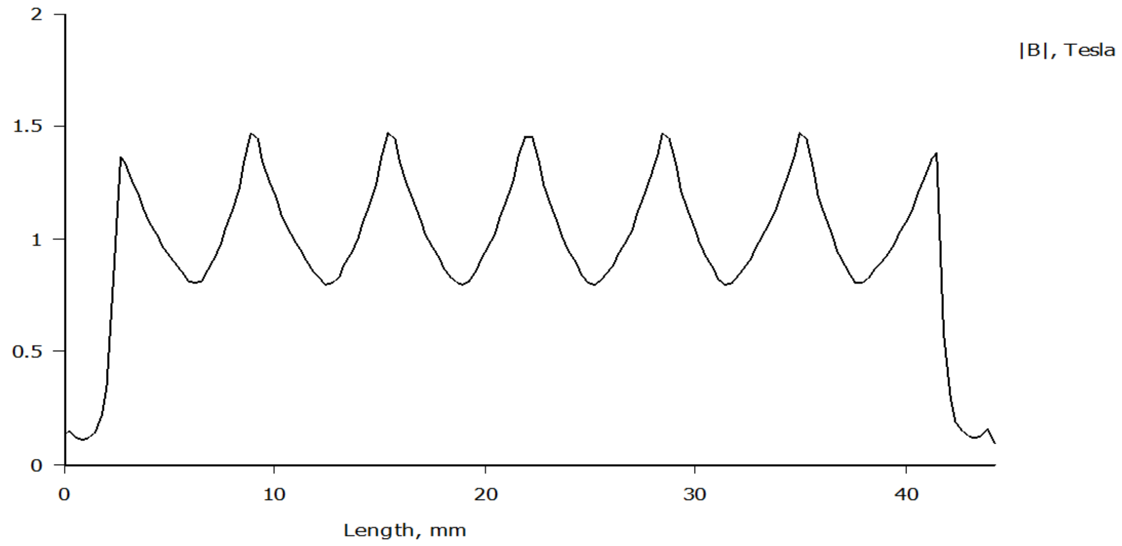

Fig B.45: Total density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.120 nodes.

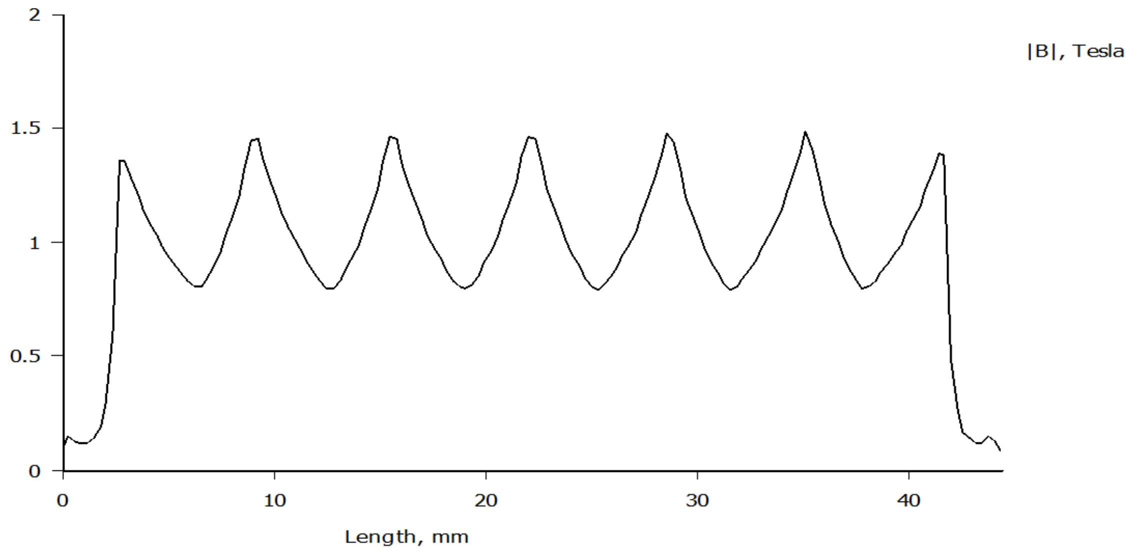

Fig B.46: Total density of the magnetic field in the air gap in the position of maximum inductance. The number of nodes for the finite elements is 15.804 nodes.

B.4. Calculation of the hysteresis and eddy current losses

Due to irreversible processes of magnetization a loss of heat occurs in the magnetic material. These losses are proportional to the area confined in the cycle of hysteresis of that material. The softer a magnetic material is, the smaller its area of hysteresis cycle and therefore the lower the losses due to alternate magnetization of the material.

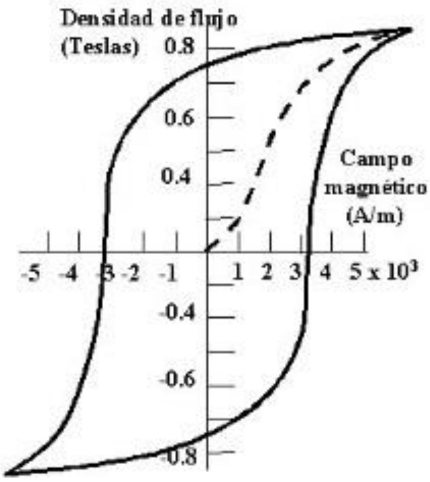

Fig B.47: Hysteresis cycle of a ferromagnetic material

The quantification of the losses due to the hysteresis cycle of the material can be approximated by the Steinmetz formula:

$$P_h = \frac{K_H \cdot f \cdot {B_{max}}^n}{\gamma \cdot 10^4} \ \frac{W}{kg}; \ n \begin{cases} 1{,}6 \ if \ B_{max} < 1\,T \\ 2 \ if \ B_{max} > 1\,T \end{cases}$$

K_H is the hysteresis coefficient that depends on the material characteristics and other parameters, the frequency equals 75 Hz (phase commutation frequency), γ is the specific weight of iron of the rotor and B_{max} accounts for the highest value of density of the magnetic field in the magnetization cycle considered.

The quantification of the losses due to the eddy currents can also be approximated by the following formula from Steinmetz:

$$P_{ed} = \frac{\sigma_E \cdot f^2 \cdot {B_{max}}^2}{\gamma \cdot 10^4} \ \frac{W}{kg}$$

σ_E is the eddy current coefficient that depends on the material characteristics.