Design of an axial flux permanent magnet motor for an energy efficiency competition vehicle

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Abstract. *The environmental issue had grown to be an important factor in areas like politics, economics and science. Nowadays, the so called green engineering is represented by many research groups all over the globe, developing sustainable projects. One of the most promising areas in this field is the design of electric vehicles. In Brazil, this activity is encouraged by an energy efficiency competition of prototypes developed by research institutions. In order to achieve a high performance, the energy conversion from the batteries to the tires in the vehicle must be very efficient. This paper proposes the design an electric machine on its state of art, making sure the project accomplishes a good placement in the competition. The prototype is a one passenger, lightweight, three wheeled vehicle, presenting very low aerodynamic and rolling resistance. Therefore, the power level of the motor is no challenge, being the design focused in the energy conversion efficiency. In order to minimize the mechanical losses, a direct coupling to the wheel was chosen. In the last decade, the development of permanent magnet machines has been intense, due to new techniques of manufacturing and low costs of the high energy rare-earth permanent magnets, which allied with the axial flux geometry, made the design of low speed high efficient machines possible. Although needing a larger diameter of installation, the motor present's low thickness, being very compatible with the wheel's inside geometry. So, to maintain the low mass and inertia of the vehicle, a high power density coreless geometry arrangement was designed. This feature eliminates the cogging torque and minimizes the losses generated at the stator cores. Another strategy was the use of Halfback magnet assembly, presenting a sine-shape flux distribution in the air gap, reducing the losses due space harmonics commonly present in permanent magnet geometry. The machine can be used as a brake as well, converting the kinetic energy of the prototype back to electric potential, increasing its autonomy. The electromagnetic, mechanical and control design was made in the COMSOL multiphysics platform, as a power tool, this finite element solver allows the structural solution to be used as an input of the electromagnetic (and vice versa), in each iteration. The machine batch test will take place in the beginning of 2011. The vehicle will compete in July, 2011, where the final validation will occur.*

Keywords*: Efficiency, Electric Vehicle, Hybrid, Electric Motor*

1. INTRODUCTION

This text describes the design of a state-of-the-art electromagnetic device, optimized to be as efficient as possible, to drive a competition vehicle. All the stages of the project are discussed, presenting the results and conclusions of the work. The resultant geometry is been manufactured and will be tested during this year.

2. CONCEPTION

The most important aspect of the project was the integration of the mechanical and electromagnetic design. A bidirectional iterative strategy was adopted, were the load and sizing results were used as entries for structural calculation and vice versa. This characteristic was the key to achieving a high efficiency machine.

The geometry converged for a high diameter, low air gap structure. The coils were disposed in the central stator and the permanent magnets in the external rotors. This configuration aims a low displacement in the air gap while the motor is been axially loaded.

The rotors are made of magnetic steel, having both mechanical and magnetic use. The attraction force between the two rotors made possible a boltless coupling of the machine. The torque is transmitted to the outer rim by pure friction with the rotors

Due to the low air gap goal, the coils were disposed inside a thin carbon fiber layer to improve its rigidity. An air gap of only 3mm (air, fiber, copper, fiber, air) was achieved. Figure 1 show a section view of the final geometry.

Because of the relative high diameter and to optimize the efficiency, the design was made to fit inside the vehicle wheel, being direct coupled to it.

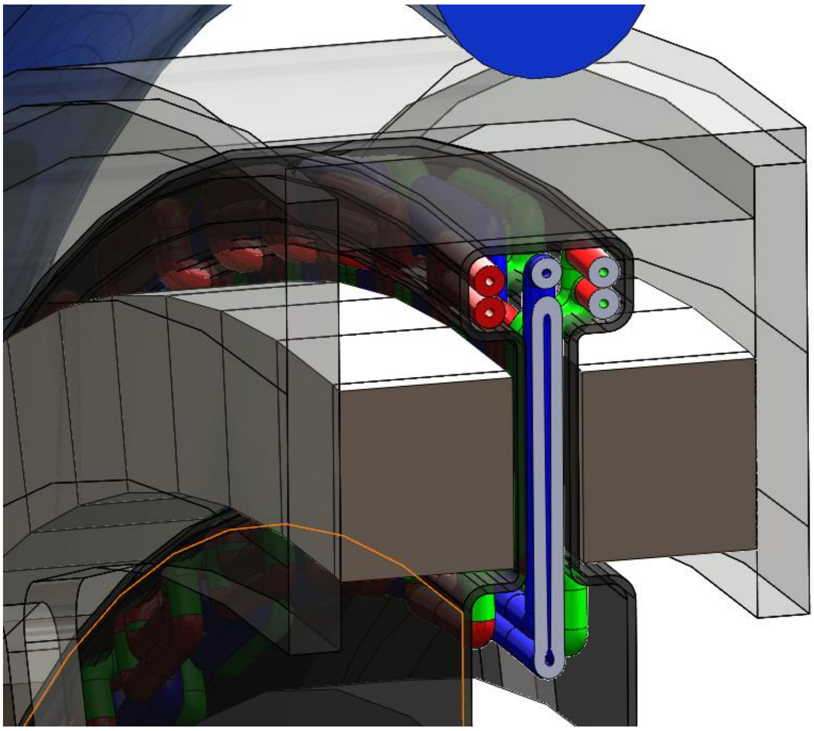

Figure 1 – Section view of the magnet-coil arrangement.

3. ELECTROMAGNETIC SIZING

In the past decade, some works [Gieras, 2008; Parviainen, 2005; Aydin, 2004] demonstrated the advantages of the *Axial Flux Machine* (AFM) in relation to the *Radial Flux Machine* (RFM). The AFM is capable to concentrate higher power density with a lower effective volume. Allied to the low cost of the high energy permanent magnets, these characteristics made the AFM the best topology alternative [Liberty, 2004].

Improving this topology with low total losses, the machine known as "*Coreless*" was adopted. Due its non-magnetic core, the losses in rotor discs, permanent magnetic and stators are eliminated. There is also no cogging torque normally presented in slotted cored machines. Only the Joule losses were representative in the machine conductors. The rated power needed for the vehicle is 250W on uphill, 15 km/h speed propulsion.

3.1. Magnetic Project

The basis machine project involves a good magnetic sizing, low losses and structural compatibility, and since there is no literature involving these aspects, they are all present in this paper.

The option to use rare-earth permanent magnets involves the high energy of this material with a high reminiscent value of 1.3 T, and its low cost since the fabrication method becomes cheaper [ResearchInChina, 2010]. This choice make possible to produce a high power density machine in low space volume.

Besides of a high flux magnetic material, the *Halfback* magnets arrangement made possible the increase of the total amount of flux directed to the conductor. The advantage of using the *Halfback* array is also related to "where to" redirect the flux lines, making possible to produce a smoother sine wave flux density line in the air gap, which reduces considerably the losses due to space harmonics and contributes for a high efficient machine.

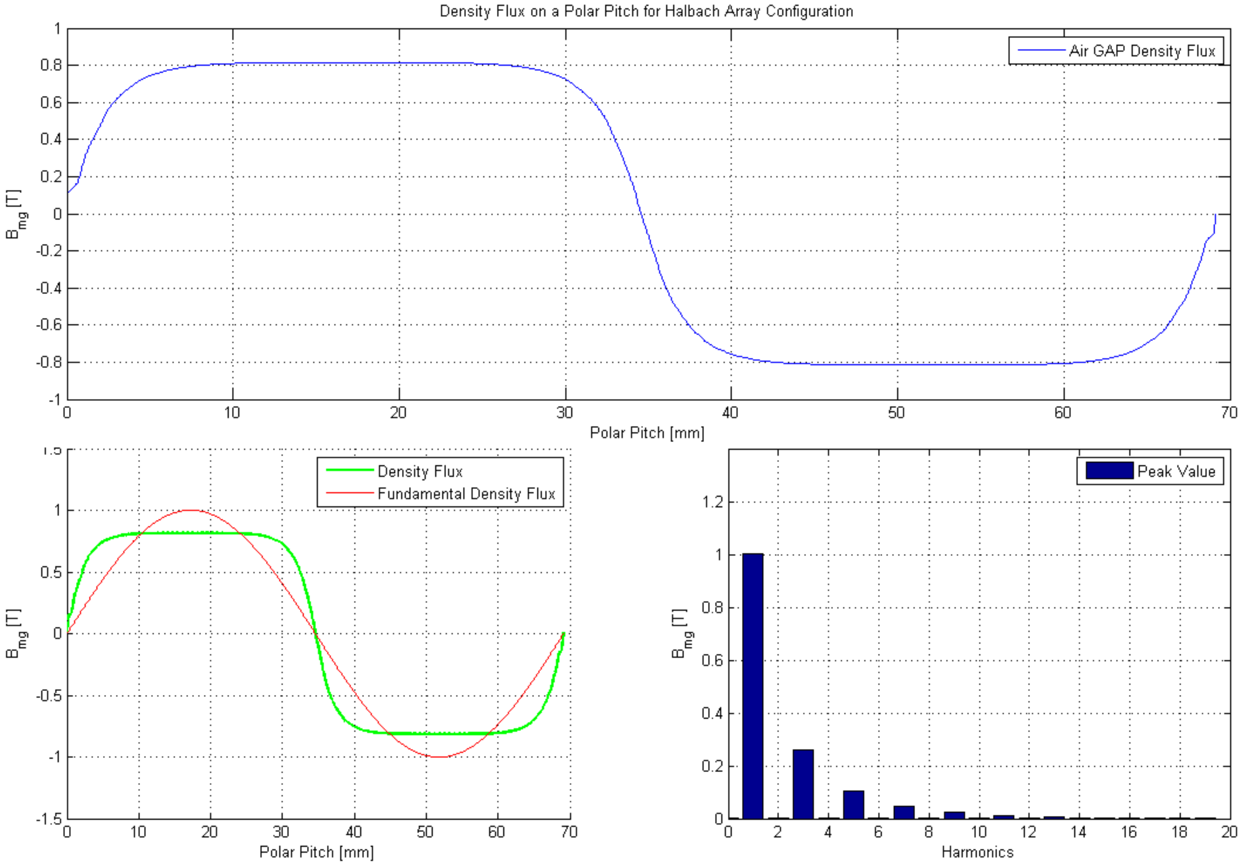

Figure 2 – PM magnetic flux with simple NS configuration.

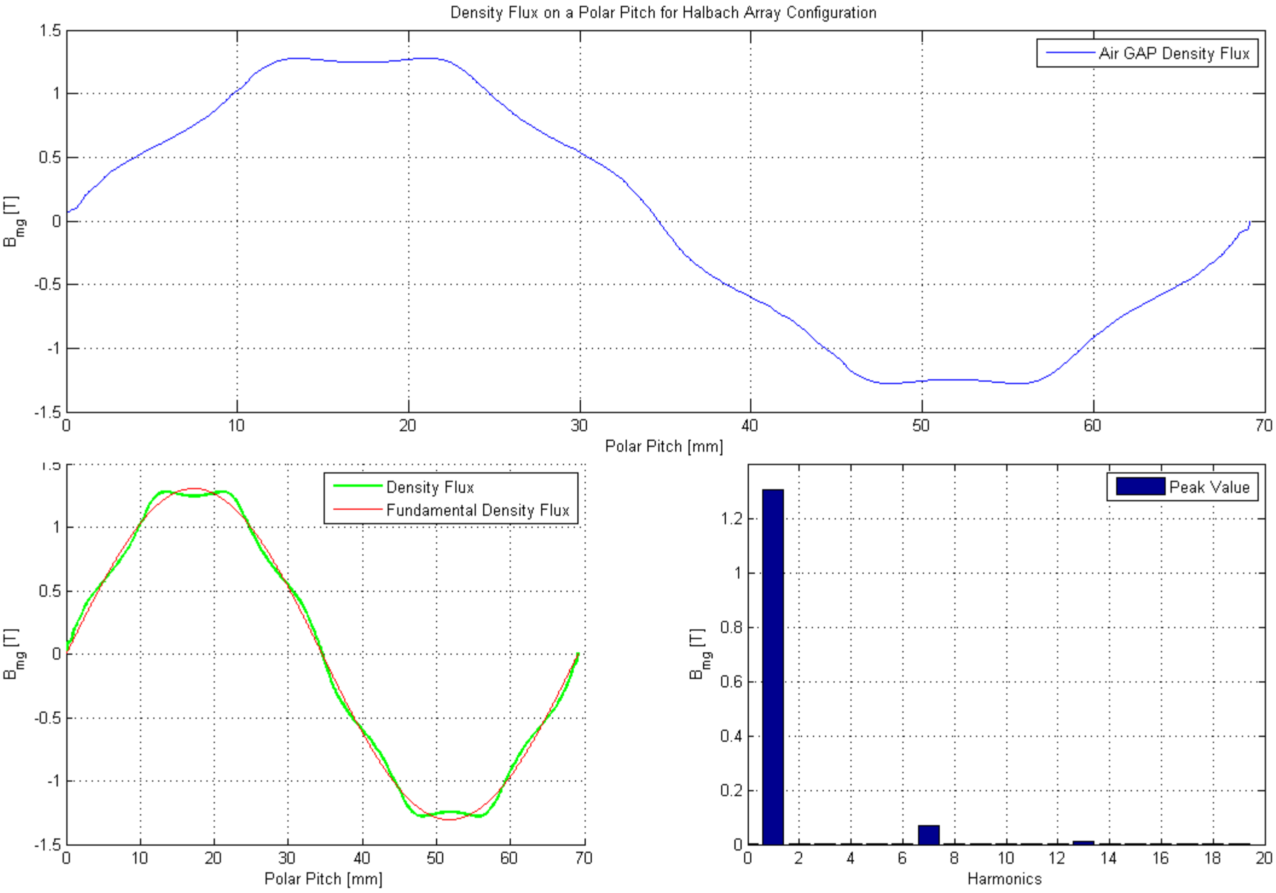

Figure 3 – PM magnetic flux with Halfback Array configuration.

In order to demonstrate the advantage of choosing this array, magnetic circuit simulations with and without the *Halfback* topology are presented. For the first simulation was considered only the vertical magnetization direction, placed in North and South position, which in this case is clear that the magnetic flux density has a square profile, as shown in Figure 2. In the second study, as shown in Figure 3, was placed six PM with 60° magnetization direction displacement with an optimized length. This situation is clear the sine shape and wave harmonics reduction are considerably high. This new format simplify the inverter control system that will be used to drive the machine which contributes for lower losses from the inverter operating as PWM (pulse width modulation) which can operate in lower frequencies; lower losses in the machine coils which appear from inside circulation current from multiples for the third harmonic; reducing possible cogging torque that may appear in higher drive frequency.

Both simulations were made considering a 3 millimeter air gap. The gap distance concern was also an optimal project design to increase the flux density, which was characterized as the healthiest geometry relation between the PM and air gap length before cause strong distortion on the flux density wave.

3.2. Copper Sizing

Since the copper losses from Joule heating is the greatest machine concern, some studies were made to reduce this parcel. To decrease the current in the machine the option to elevate the final voltage seems to be trivial, but not so when it became a part of a mechanical compatibility, which may increase the coil length and increase the final effective air gap. This fact decreases the density flux and the machine power. By the other hand increasing the conductor radius reduces its resistance by the inverter quadratic as presented in Eq. (1), where σ, l and r are the electric conductivity, length and radius of the conductor.

$$R_{[\Omega]} = \frac{l}{\sigma \pi r^2} \tag{1}$$

Increasing the copper effective area reduces the losses by joule heating, but increases the contribution by eddy current that appears in larger volume material. The Litz Wire commonly known for skin effect losses reduction became an alternative to reduce the Eddy current contribution. The Eq. (2), which approximate the losses generated in the conductor demonstrate the litz wire advantage. The σ, ρ, f and m_{con}, are respectively the electric conductivity, the density, the rated operation frequency and the effective mass without connectors. The η_d is the distortion coefficients that can be approximated to a unit and B_{mx1}, B_{mz1} are the respective axial and tangential flux density over the conductor.

$$\Delta P_E = \frac{\pi^2}{4}\frac{\sigma}{\rho} f^2 m_{con} \eta^2 \left[B_{mx1}^2 + B_{mz1}^2\right] \tag{2}$$

While a normal glazed conductor may have an outer diameter of 1.5 millimeters, the internal litz with 55 strands can have approximate 0.089 millimeters diameter. This represents a decrease of 3.92 W to 0.24 W, a gain of almost 2% in the final efficiency.

3.3. Coreless Sizing

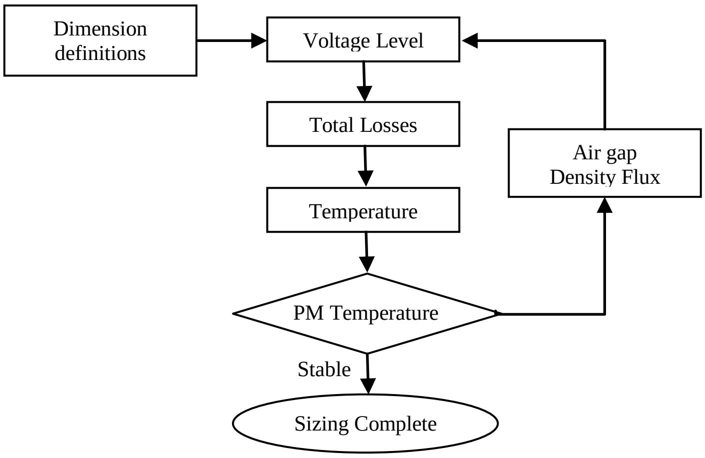

Figure 4 – Guided sizing for coreless axial permanent magnetic machine.

The *coreless* axial permanent magnet machine as a common machine spreads lot of possibilities and consequently the variables numbers for the machine sizing. In order to organize and describe the processes that guided the sizing, some starting points was taken as the outer diameter to fit the vehicle wheel, the PM and air gap length, as so the conductor adopted. This process interactively point to coils numbers, inner diameter, total losses and temperature rises as demonstrated in the block diagram presented in Figure 4.

For stationary case where the machine work at rated power and optimization study was developed which produced analytically 99.26% efficiency. The sizing results are shown on Table 1.

Table 1. Sizing and dimensions for a 250W coreless machine.

Proprieties	**Value**
Outer Diameter	329 mm
Voltage	7 V
Torque	10.4 Nm
Power	250 W
Current	20.6 A
Rotation	229.8 rpm
Frequency	57.4 Hz

3.4. Power Density

In electric machines that use rare earth PM, the first concern is about the temperature. Since the NdFebB are unstable material, the temperature rise can cause its demagnetization and consecutively the machine inactivity. The attention for this capability may represent a high excursion of power that can be drained for the equipment.

In order to minimize the temperature elevation, the mechanical design was directed to cause a thermal isolation between the coils and the magnets. With the intent to demonstrate how much power can be applied from this prototype an approximated thermal circuit using thermal resistances were mounted and the temperature rises simulation were obtained for different power values.

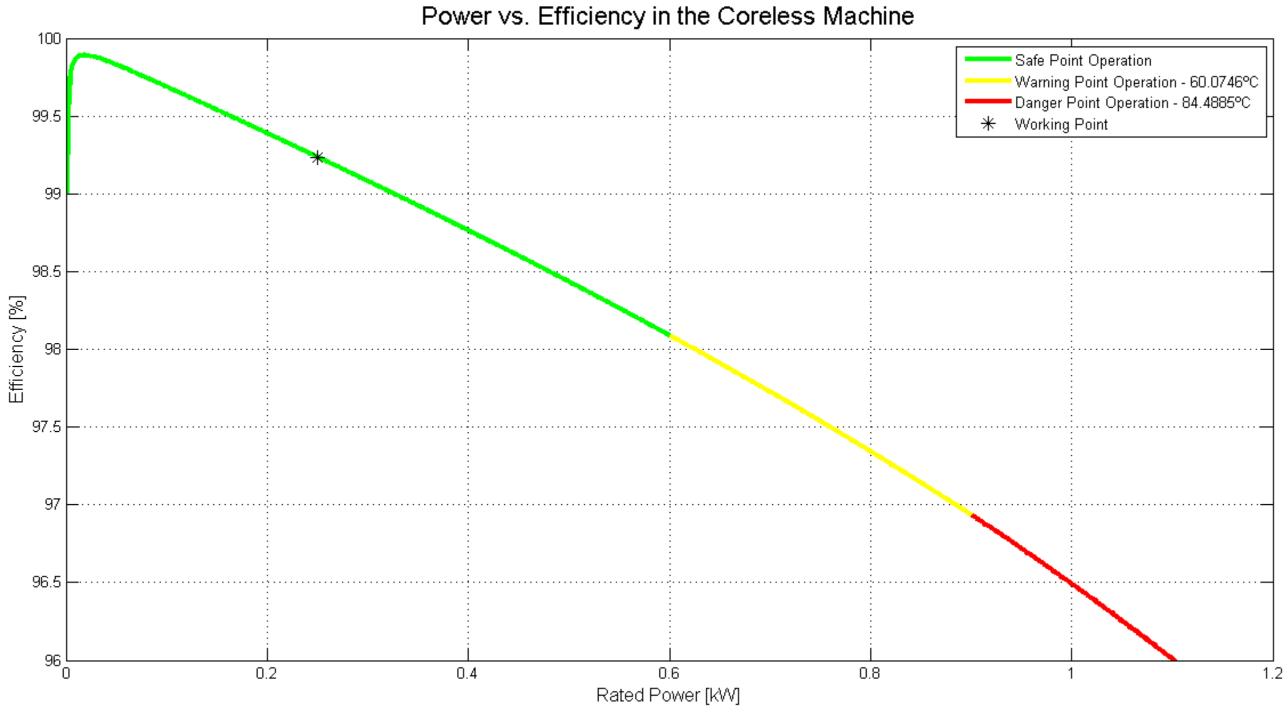

Figure 5 – Power capability restricted by the temperature rise

The simulation presented in Figure 5 show that this topology can maintain an extremely high level of efficiency including for greater power levels.

4. MECHANICAL DESIGN

During the development, the electromagnetic performance was put as first priority because it acts directly in the energy transformation efficiency. The mechanical design was made with the objective of sustain the electric and magnetic bodies, being optimized to present a low mass with high axial rigidity. Besides that, the structure works as wheel and hub, resisting all the road loads. The geometry was simulated extensively for each case of loading, separated and in combination. The final model can be visualized in Figure 6.

Figure 6 – Final model of the machine.

4.1 Stator

The stator consists in an assembly of the Litz wire coils, a carbon fiber enclosure and an aluminum torsion disc. Figure 7 shows von Mises tension FEA calculation to the disc. Due to its large diameter, the torsion loads are relatively low and the part was alleviated extensively. The coils are rolled together with the fiber lamination, forming a rigid block that is later bolted to the disc.

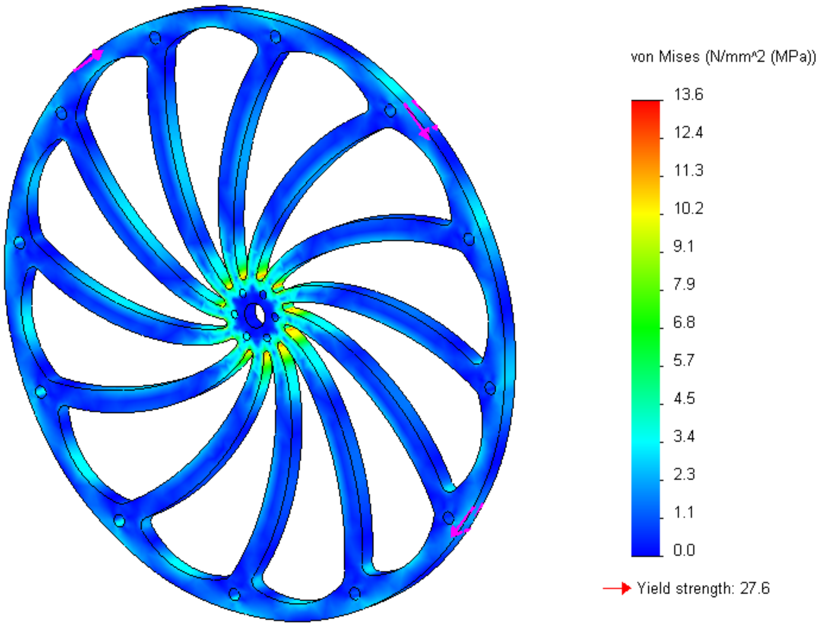

Figure 7 – Stator assembly model

4.2 Rotor

The rotor assembly has axial, radial and torsional loading. It is composed by two magnetic steel laser-cut plates, two steel bearing houses, an external aluminum rim and the Halfback magnets assembly, as can be seen in Figure 8. The magnets are attached to the plates using high strength polymeric composite. The plates and rim are fixed by the magnets attraction force, sparing the use of bolts. The bearing houses are welded to the plates.

Figure 8 – Section view of the rotor

Due to its complex loading, the rotor was simulated intensively. The principal preoccupation was the displacement in the air gap during lateral loading in curves. The plate thickness was optimized with this purpose. The axial deformation for 1g of lateral force calculated via FEA can be seen in Figure 9.

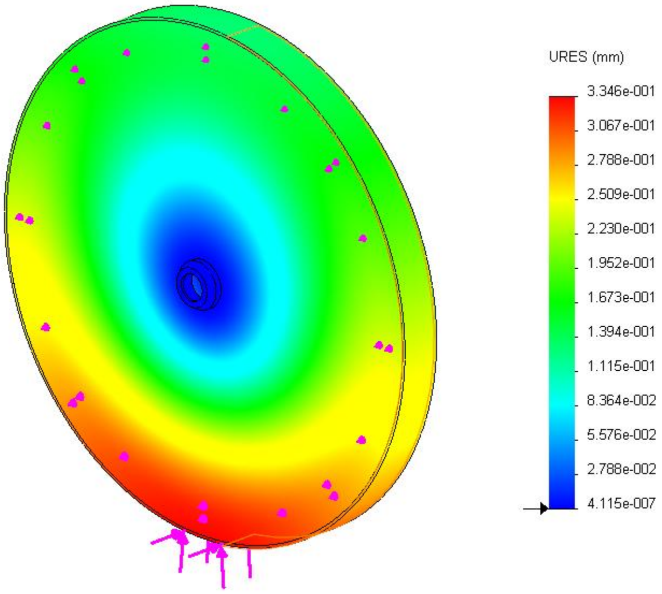

Figure 9 – Axial displacement in the rotor during a severe curve

5. ACKNOWLEDGEMENTS

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