



**Politecnico
di Torino**

Design and Optimization of a Magnetic Gear

Stefano Savio

Polytechnic University of Turin

Department of Engineering Mechanical and Aerospace

Corso Castelfidardo, 39, 10129 Torino (TO)

2 May 2021

Summary

Introduction	4
Definition of parameters and model subassemblies	4
Starting a new study using EMWorks EMS Tool	9
Results obtained and conclusions.....	14
Bibliography.....	23

Introduction

The objective of this study is to show how a magnetic gearbox is designed and to calculate the transmitted torque values in a chosen case using EMWorks EMS simulation solution.

For the dimensioning of the gearbox, reference was made to some hypotheses presented by a group of researchers from the Faculty of Science and Technology of Vandoeuve, France (Gouda, 2011). In this research a magnetic reducer is modelled based on the geometries of the mechanical reducers normally mounted on electric vehicles. For these applications, the gear ratio is usually between 2 and 4, but in the present case we perform an analysis with $G_r = 7.5$,

For the modelling phase, I received support from EMWorks technical support team via emails and web meetings. Without such support and guidance, it would not have been possible to obtain accurate simulation results.

Definition of parameters and model subassemblies

Choice of transmission ratio $G_r = 7.5$. We chose the values p_1 , p_2 e p_3 following the considerations made in the previous chapter.

$$p_1 = 2$$

$$p_3 = 15$$

$$n_2 = 17$$

A number of considerations were behind the choice of these values:

Certainly, the focus was primarily on the magnetic flux density transmitted. It is observed graphically (Gouda, 2011) that, fixed a $n_2 = 17$ for the rotor gear box, in the air spaces between the inner rotor, outer rotor and the rotor gear box, magnetic field harmonics are

generated with different intensities depending on the number of polar pairs of the respective rotors. Obviously, the maximum values are chosen and based on these values (the values are defined p_1 e p_3).

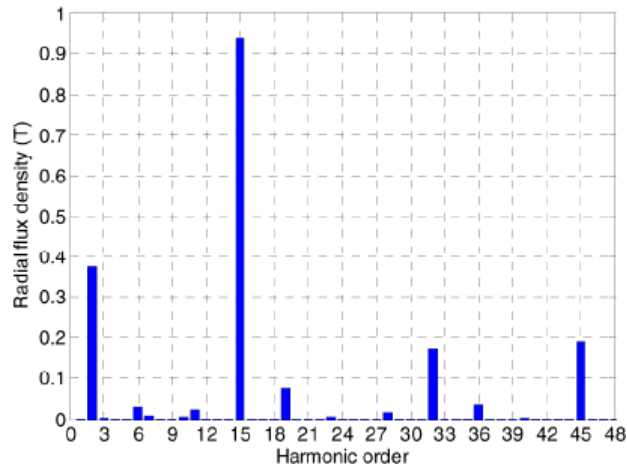


Figure 1, Radial magnetic field flux pattern in the air space adjacent to the outer rotor for a Gr=7.5 (Gouda, 2011)

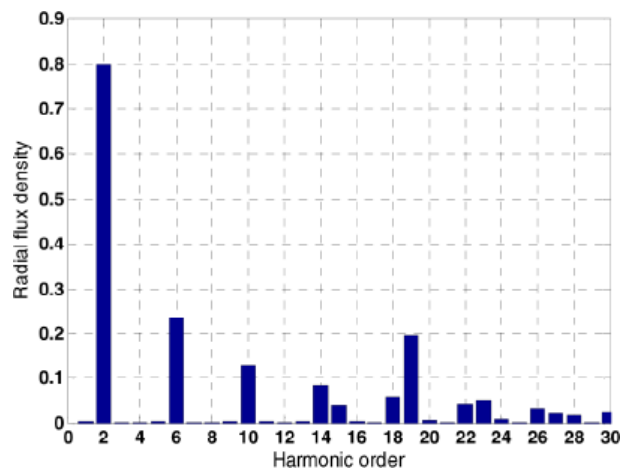


Figure 2, Radial magnetic field flux pattern in the air space adjacent to the inner rotor for a Gr=7.5 (Gouda, 2011)

After making this choice, it is recommended to make a quick check of the coefficient C_f to make sure that the wave effects are effectively reduced:

$C_f = \frac{2p_1 \times n_2}{MCM(2p_1, n_2)} = \frac{4 \times 17}{MCM(4, 17)} = 1$	(1)
---	-----

The value is equivalent to 1, which confirms that the number of magnetic pairs and blades chosen is adequate, with minimal oscillating effects.

The analysis and calculation of the transmitted torque is carried out using EMWorks EMS simulation tool, a *plug-in* for the Solidworks program able to simulate the trend and the generated magnetic field flux. It is used, for example, in the optimization of systems using electromagnetism, such as actuators, electric motors and transformers. (PERMANENT MAGNETS GEAR SYSTEM: 2D AND 3D ELECTROMAGNETIC SIMULATION INSIDE SOLIDWORKS, s.d.).

The software uses the Finite Element Method (FEM) which is a numerical technique that, starting from differential and partial equations, reduces, by approximation, the latter to algebraic equations.

This method has proven to be quite reliable in the study of engineering solutions.

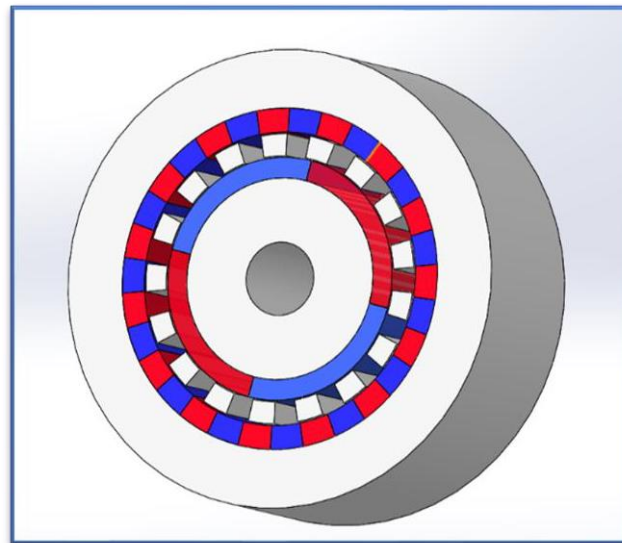


Figure 3, 3D model of the studied magnetic reducer

Below there's a table summarizing the parameters:

Description	Value (mm)
Inner radius of outer rotor iron die	93
Outer rotor radius	125
Outer radius of inner rotor iron matrix	55
Internal rotor shaft radius	20
Thickness of internal rotor magnets	11.2
Thickness of external rotor magnets	13
Total air space	2
Axial length	100
Metal gear box thickness	12
Polar pairs on the internal rotor p_1	2
Polar pairs on the external rotor p_3	15
No. of metal gear box blades n_2	17

Table 1, Description of the construction parameters of the magnetic gear unit under examination

The next step is the creation of the sub-assemblies starting from the previously built components: this step is fundamental and necessary so that the model placed in rotation shows correctly the moment transmitted to the respective rotors. They will then go to identify:

- the "HS Rotor", i.e. the high-speed rotor consisting of the two pairs of magnets and the inner metal rotor in which the shaft will be housed;
- the "LS Rotor", consisting of the external metal housing and 15 pairs of magnets;
- the *pole pieces*, the metal gear box;

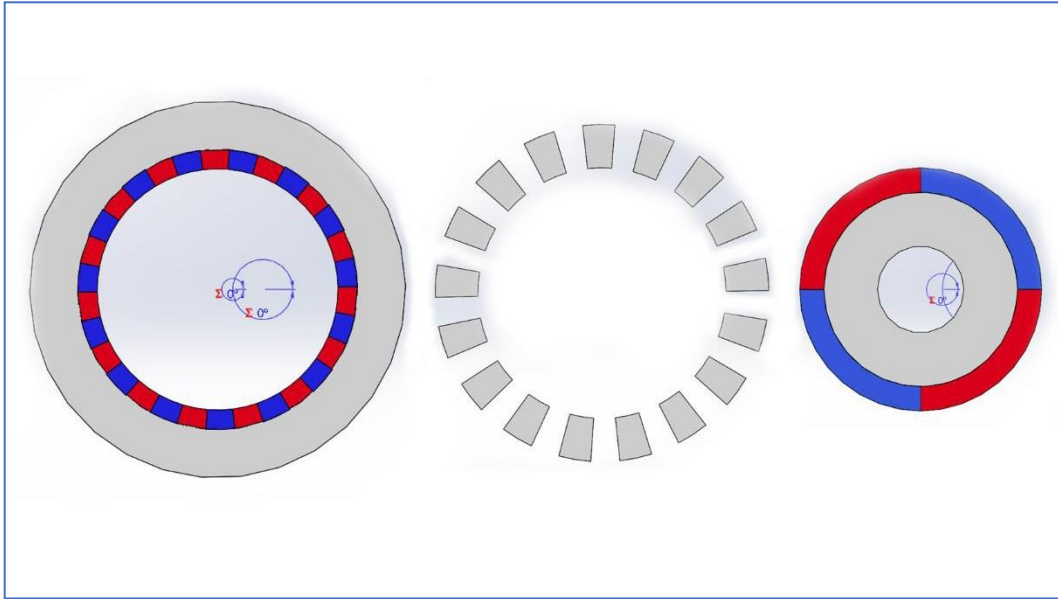


Figure 41, From the left you can see the outer rotor, the metal gear box and the inner rotor

Finally, an air box should be added. That is an additional volume that encompasses the entire model: this is essential in the transition from simple Solidworks modelling to the actual analysis using EMS software, because it is the space needed for the magnetic field to propagate; its absence would generate incorrect simulations, as experienced.

In anticipation of what will be clarified later, 2 orientation angles are defined, respectively for the inner and outer rotor, with respect to reference planes.

Starting a new study using EMWorks EMS Tool

Once the preliminary design phase has been completed, it is possible to start a new practice using the dedicated panel. It is a new study, and you will need to select the box indicating the study on magnetism and then choose to start the study with parameterization. This last point is essential in this case and for all situations where you need to observe different results regarding the variation of certain parameters.

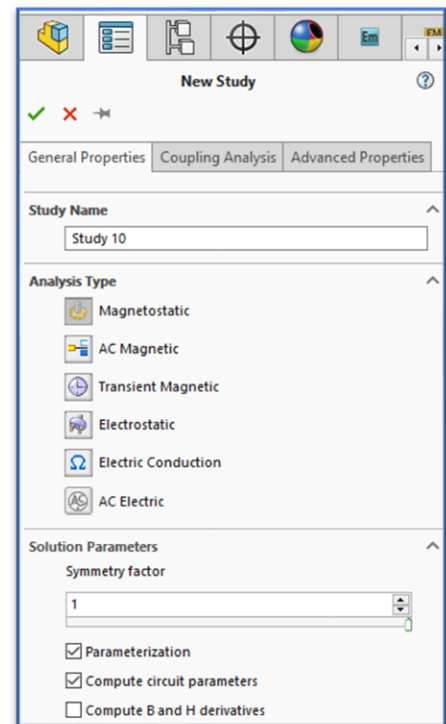


Figure 52, Panel dedicated to starting a "New Study" using EMS

To obtain a transmitted torque profile, we will need to rotate the outer and inner rotor and calculate the actual magnetic field value in each angular position. To make this step automatic, we will choose as parameters the two previously defined angular constraints, so that we can "rotate" the two parts independently of each other and thus also define their speed.

Among the parameters chosen in this study was also the air thickness present among the components: as will be illustrated later, this was fundamental to show how much the air thickness affects the transmitted torque value.

After successfully starting a new study and importing the previously selected parameters, you now need to define the different materials for each component.

During a first approach it was chosen generic *Mild* steel for the metal gear box, but from the obtained magnetic field images it is evident that the saturation point has been reached throughout the structure. Such result was obtained because an ideal material with linear magnetization was chosen. This clearly would have made the calculation unrealistic and inaccurate, so the choice fell on a material with a non-linear magnetization curve, an AISI 1010.

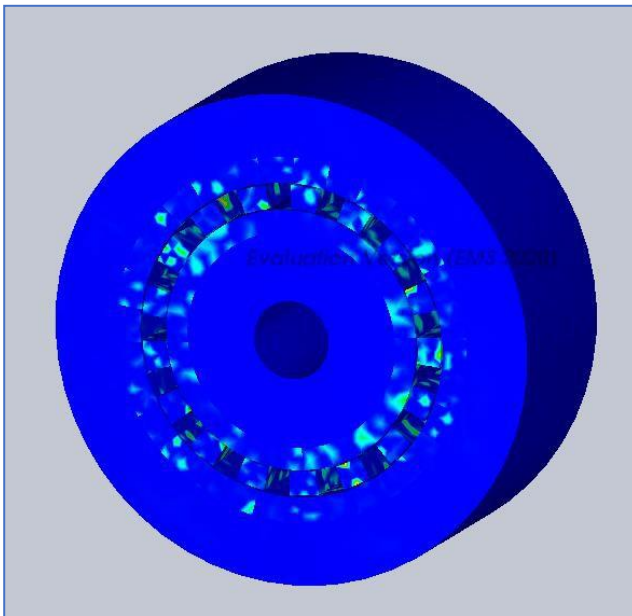


Figure 6, magnetic field flux representation with the choice of "Mild Steel" material for the metal gear box

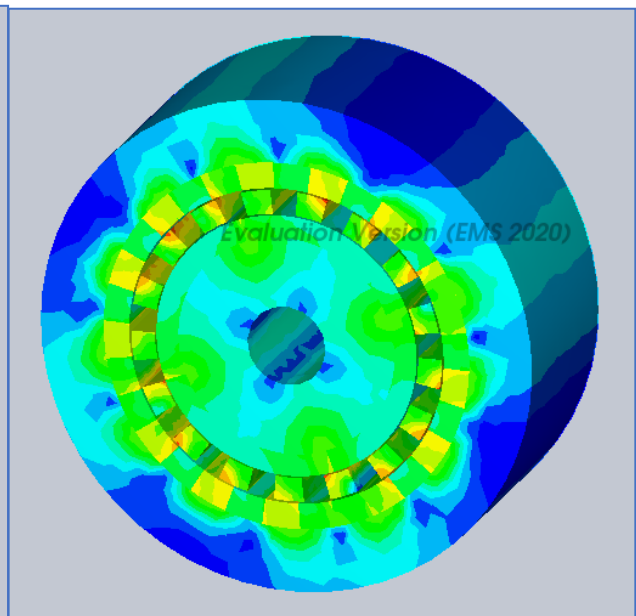


Figure7, Magnetic field flux representation with the choice of a non-linear material "AISI 1010" for the metal gear box

The definition of the permanent magnets on the inner and outer rotor deserves a separate discussion.

After inserting the N4212 magnets, the definition of the magnets cannot be considered finished until the direction of action of the magnetic field for each of them is also correctly indicated, choosing the "Cylindrical" and the actual direction "Radial", the whole system being axial-symmetrical.

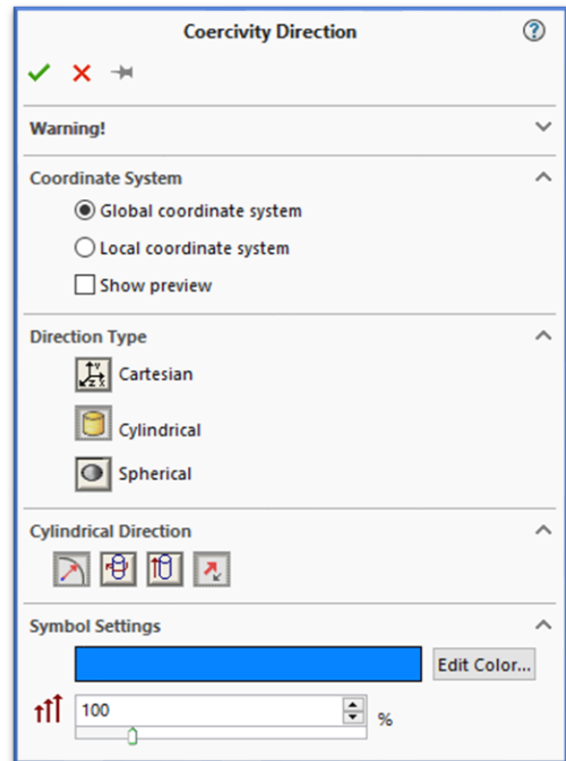


Figure 8, Magnetic material definition panel on EMSWorks

This choice is crucial because an incorrect modelling of the field flux generated by the magnets would lead to wrong conclusions.

Before moving to the simulation part, it is still important to define the "virtual work", i.e., the values of force and/or torque that we are interested to calculate. From the dedicated drop-down menu, we will go to select the elements that we would like to calculate their field of forces.

Through an intuitive graphic representation, it is possible to verify if the correct element of the transmitted torque has actually been chosen.

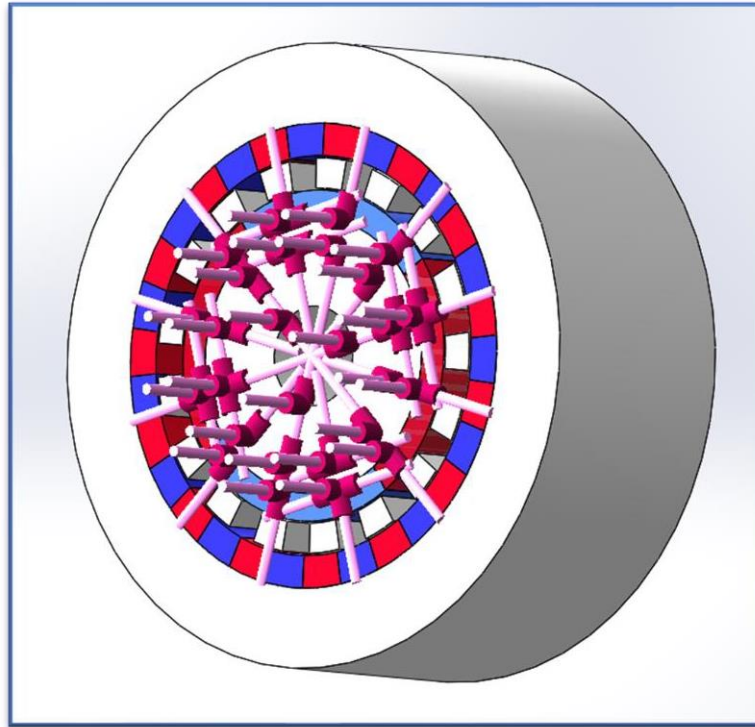


Figure 3, Viewing the structure under examination affected by torque

Once you have defined the key elements for starting a proper study, the last step is to define scenarios through parameterization. Scenarios constitute different spatial situations in which the different components are located. Having defined the angle constraints with respect to reference planes, it is possible to simulate the movement of the rotors and thus obtain results on the torque exchanged.

You can now start the computation. The EMS software is equipped with a *mesher* (based on the construction of tetrahedral elements) that operates automatically by increasing the number of tetrahedra in the geometrically more complex areas of the component.

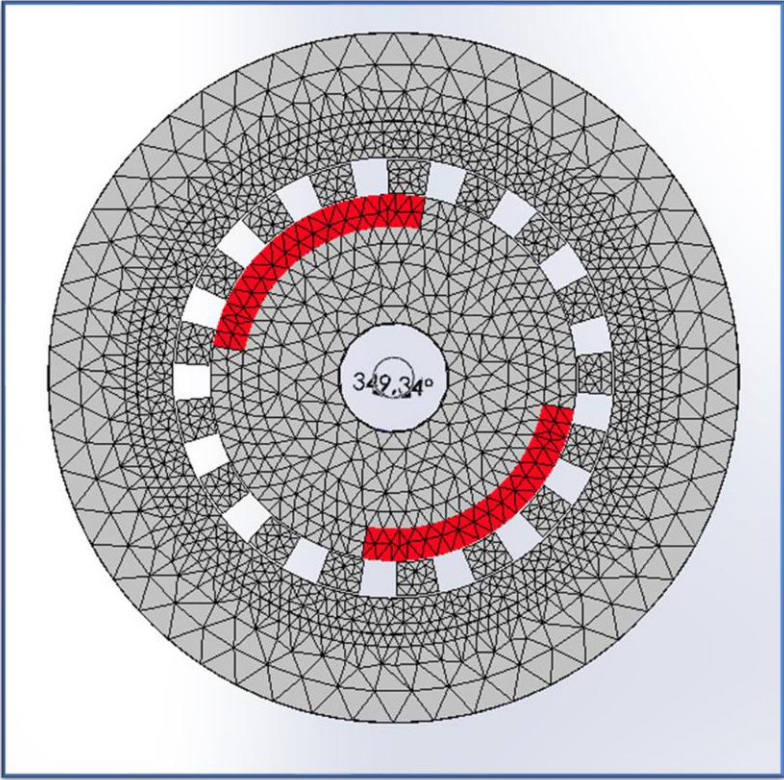


Figure 4, Displaying the model after executing the "mesh" command

Results obtained and conclusions

According to the guidelines described above, 3 studies have been carried out and significant results have been obtained with regard to torque transmission.

The first study carried out was based on a model (different from the one presented above) characterized by an internal rotor with a much smaller diameter and an *air gap of 4 mm*, (see figure on the left). To note, in the figure on the right, the almost halved size of the metal gear box and the significant increase in the size of the magnets on the inner rotor.

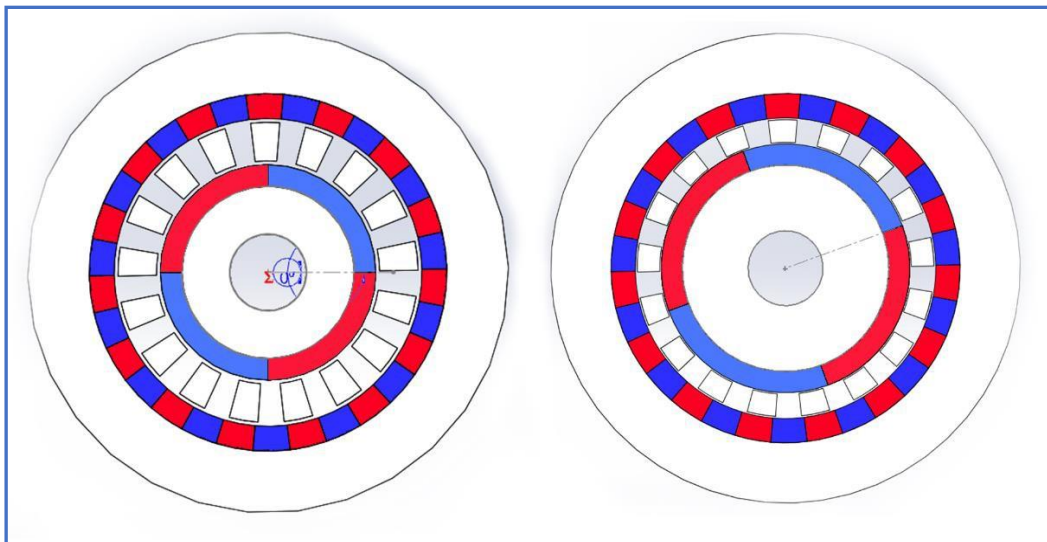


Figure 5, First and second version of the magnetic reducer

The first significant result is obtained by keeping the outer rotor and the metal gear box fixed and rotating the inner rotor between 0° and 180° .

In the graph below, scenario no. 8 corresponds to the angle of the internal rotor that maximizes the transmitted moment which barely reaches 24 Nm.

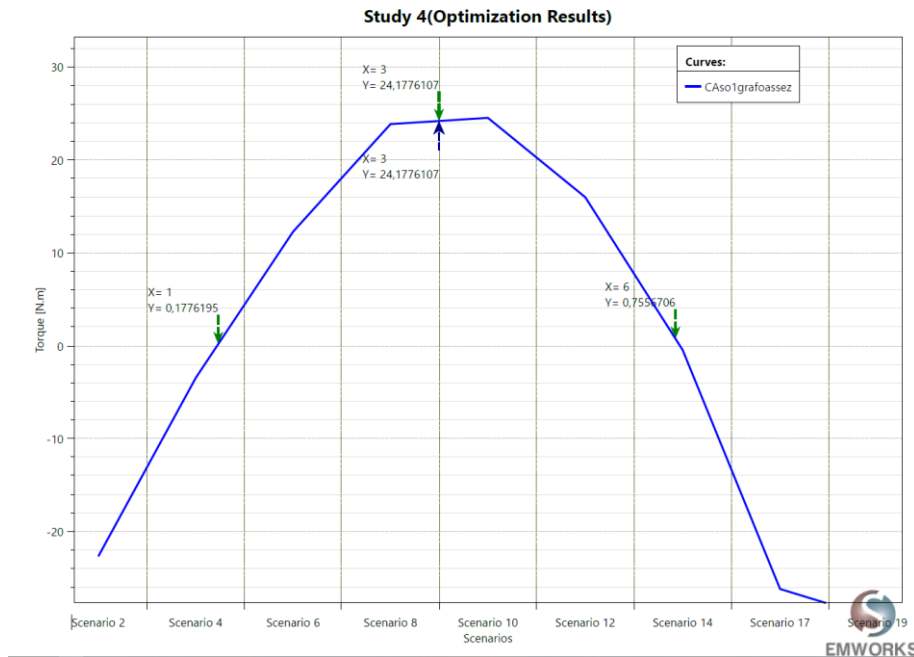


Figure 6, First model, transmitted torque trend keeping the outer rotor stationary

The results were not as expected and it was necessary to modify the model by halving the air space between the components from 4mm to 2mm, increasing the radius of the internal rotor and decreasing the thickness of the metal gear box.

The final model thus obtained provides a higher torque of more than 36.4 N, which is more consistent with the study assumptions made at the outset. It is observed that the transmitted value is close to zero near scenarios 4 and 14, with internal rotor rotation angles of 100° and 200° , and is maximum for an angle of 160° .

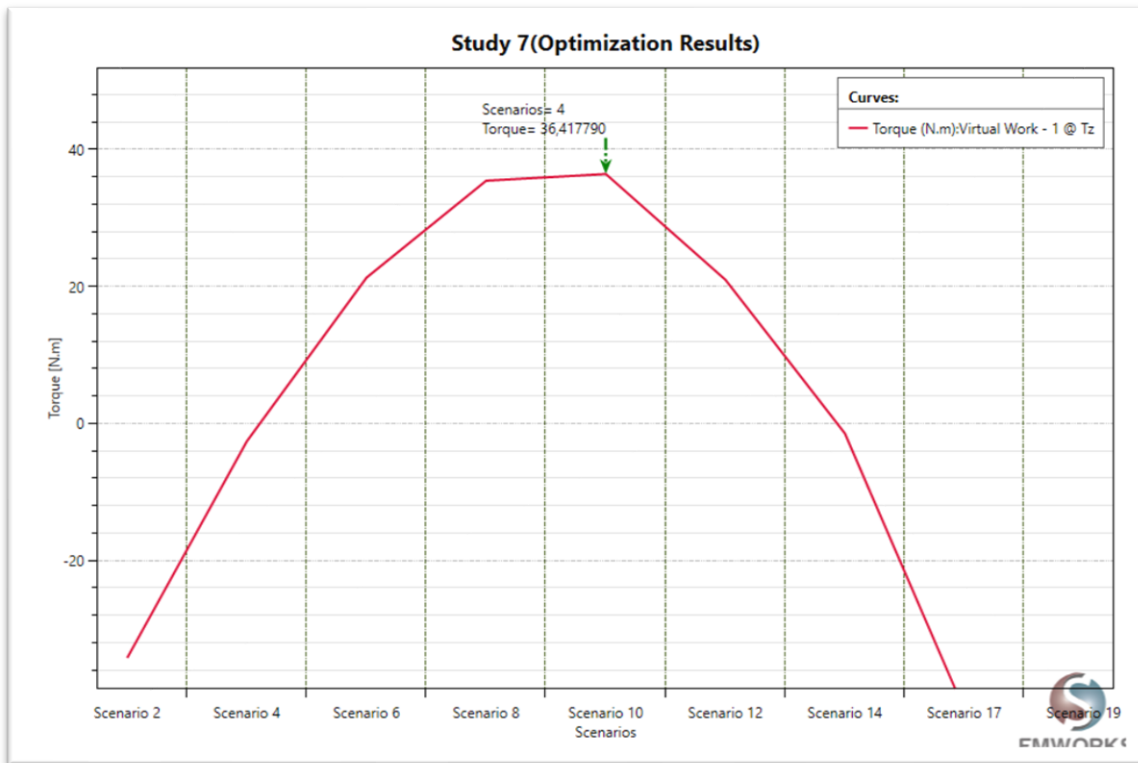


Figure 7, Final model, transmitted torque trend keeping the external rotor stationary

Through the graphic representation of the magnetic flux we can observe a high magnetic field flux resulting from the interaction between the two rotors.

It is worth mentioning that in the second image, scenario #9, there is a significant increase in color at the corners of the *pole pieces*. This is consistent with what was previously described: in that specific position, the internal rotor guarantees the maximum transmitted moment, directly related to the intensity of magnetic flux passing through the metal gear box.

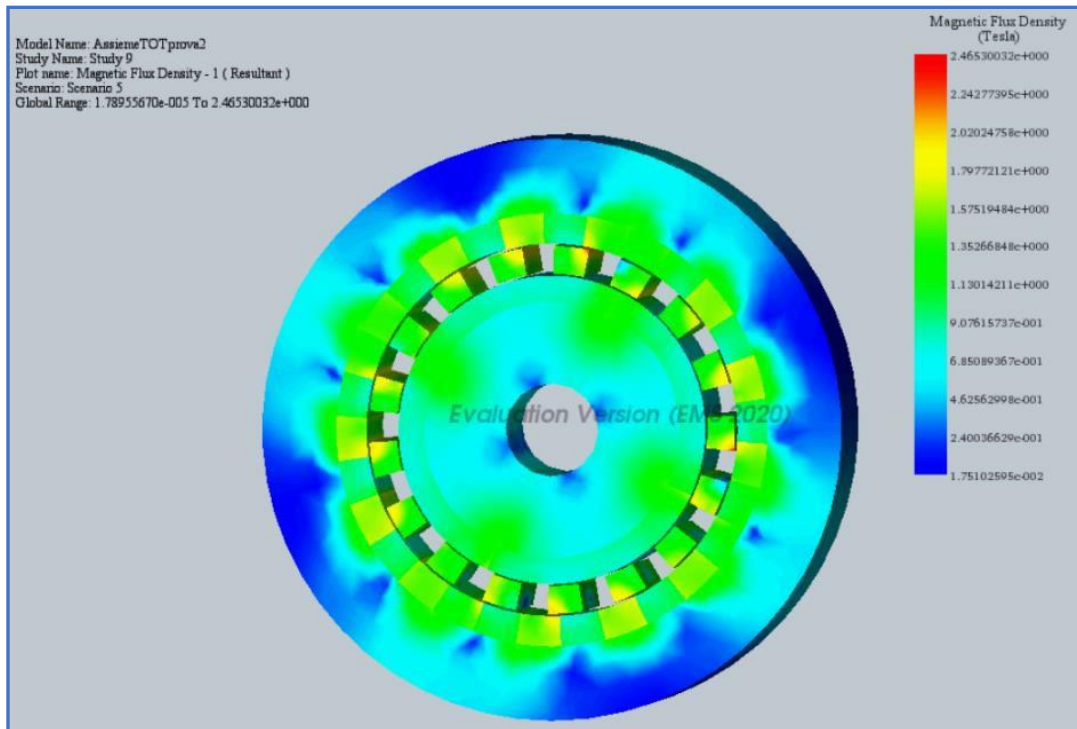


Figure 8, Magnetic field flux representation, scenario no. 5

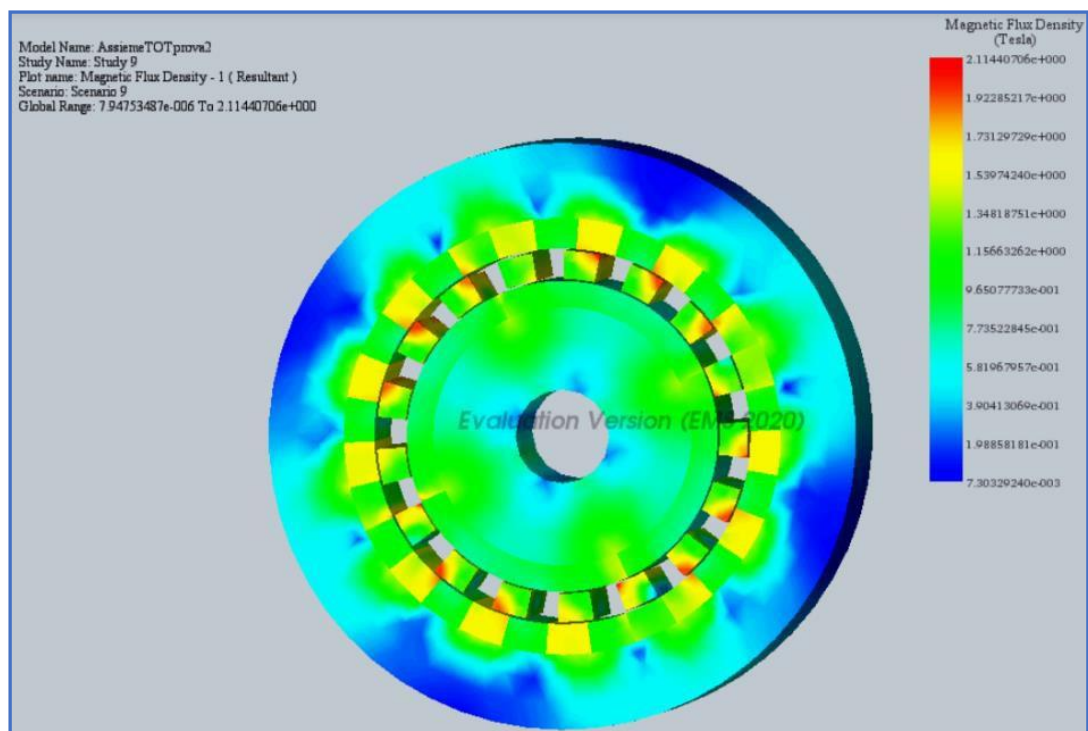


Figure 9, Magnetic field flux representation, scenario No. 9

These results have allowed us to confirm that the air space between the components is a fundamental characteristic to be considered when sizing a magnetic gearbox.

Before moving on to the evaluation of the torque transmitted to the external rotor, it is important to make a short digression focusing on the edge effects, i.e. the problems of oscillation and waviness of the torque.

These effects should not be underestimated and should be considered especially when selecting the gear unit bearings, as they will create torques in inappropriate directions, which must be compensated for.

The choice of a high number of *pole-pieces*, identified by the previously mentioned formula that guarantees the minimum possible oscillations, has allowed to obtain a roughly parabolic profile.

If this had not been the case, we would have had rather significant oscillation effects that would have led to a further loss of transmitted momentum.

As shown in the graph below, extracted from the study (Magnetic gear: 2D FEM simulation with EMWorks2D inside SOLIDWORKS, s.d.) an excessively small number of *pole-pieces* (in this case $p_2=5$) leads to peaks and ripples on the graph, signals of non-continuity in the transmission of magnetic field flux.

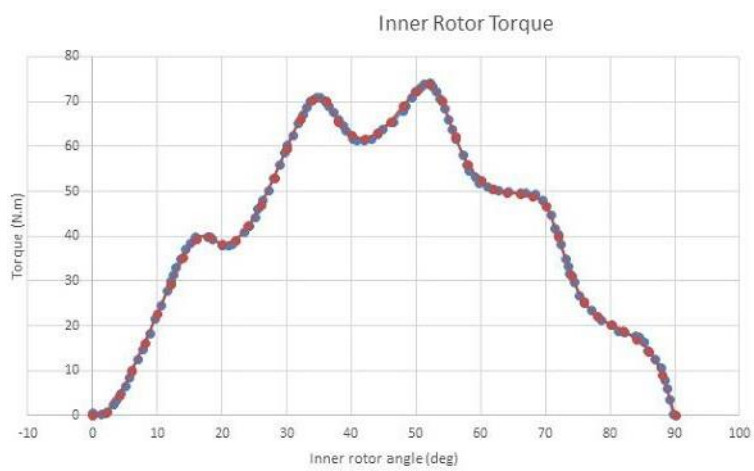
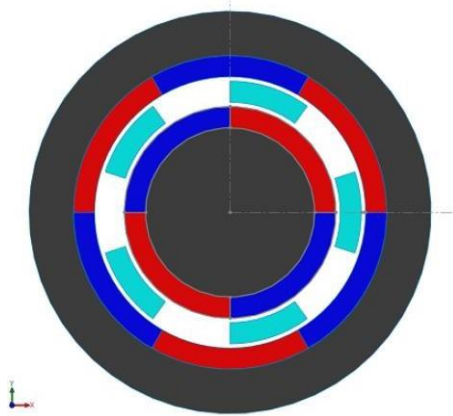


Figure 10, Magnetic gearbox with 5 pole pieces and respective transmitted torque representation while holding the external rotor fixed

However, the presence of ripples is not completely eliminated, especially on the internal rotor because it is rotating at a higher speed.

The first graph below shows the torques along the respective axes: the curve in blue represents the torque involved, while the breaks in green and red correspond to the oscillations along the x and z axes.

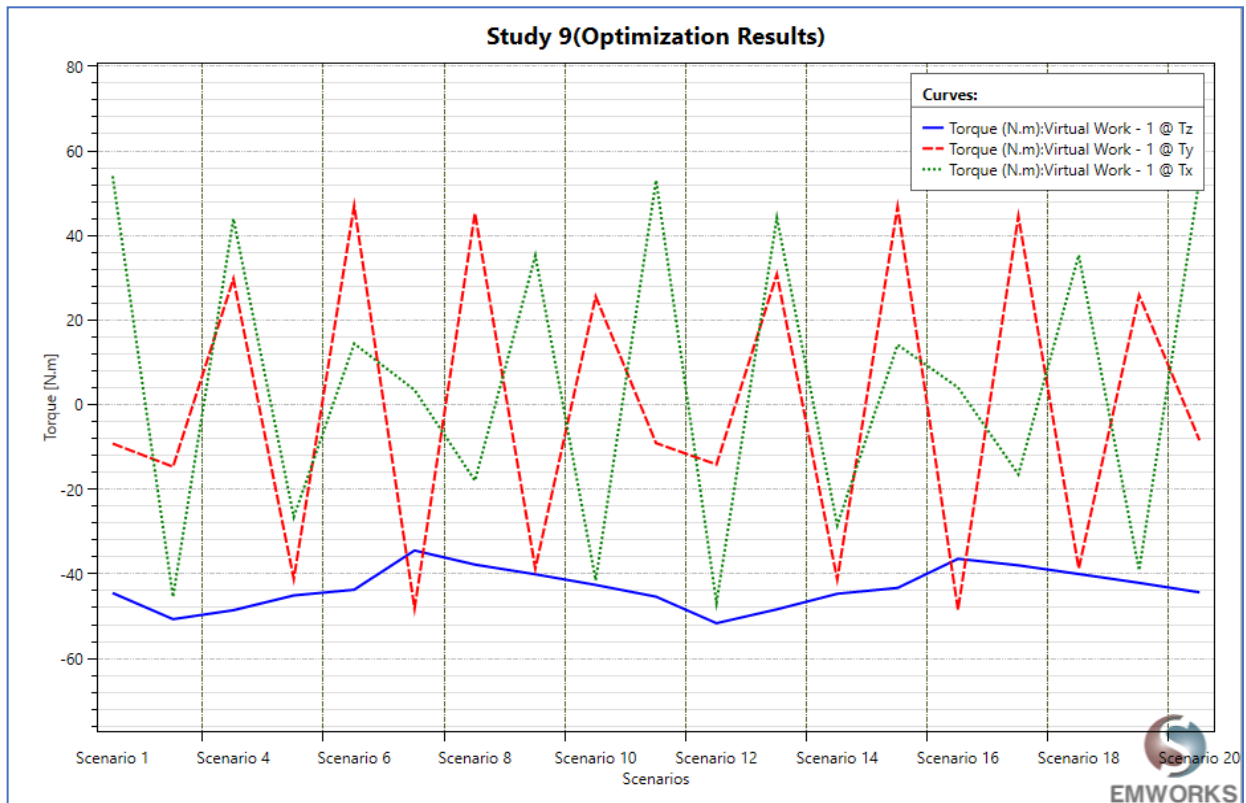


Figure 11, Torque behavior generated on the internal rotor along the z(blue), x(green), y(red) axis

It is also observed that the unwanted twisting effects on the outer rotor are practically null.

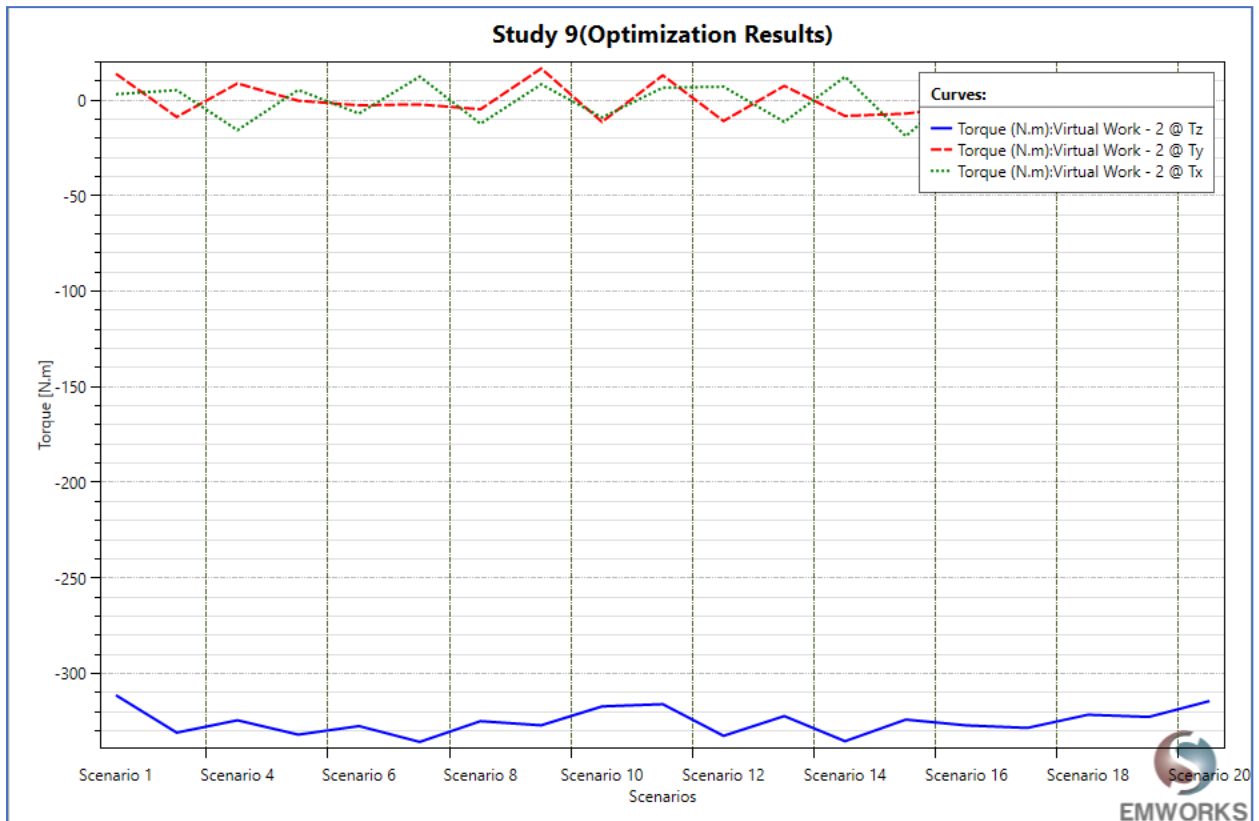


Figure 12, Torque trend generated on the outer rotor along the z(blue), x(green), y(red) axis

Let us proceed with the evaluation of the torque transmitted on the external rotor, following the guidelines described in the previously mentioned study (Magnetic gear: 2D FEM simulation with EMWorks2D inside SOLIDWORKS, s.d.). To make this evaluation, rotate both rotors in the opposite direction while keeping the metal gear box fixed.

The angle of the outer rotor is calculated using the formula:

$\varphi_0 = -\varphi_i \cdot p_i / p_0$	(2)
--	-----

By defining successive scenarios, you can simulate the relative movement of the two components and obtain an expression of the two torques. The starting position is chosen so that the angle at which the inner rotor delivers the maximum torque. In this way, turning faster than the outer rotor, it anticipates the outer rotor, and the transmitted field flow "draws" the outer rotor to itself, but never reaches it.

The result obtained is as follows:

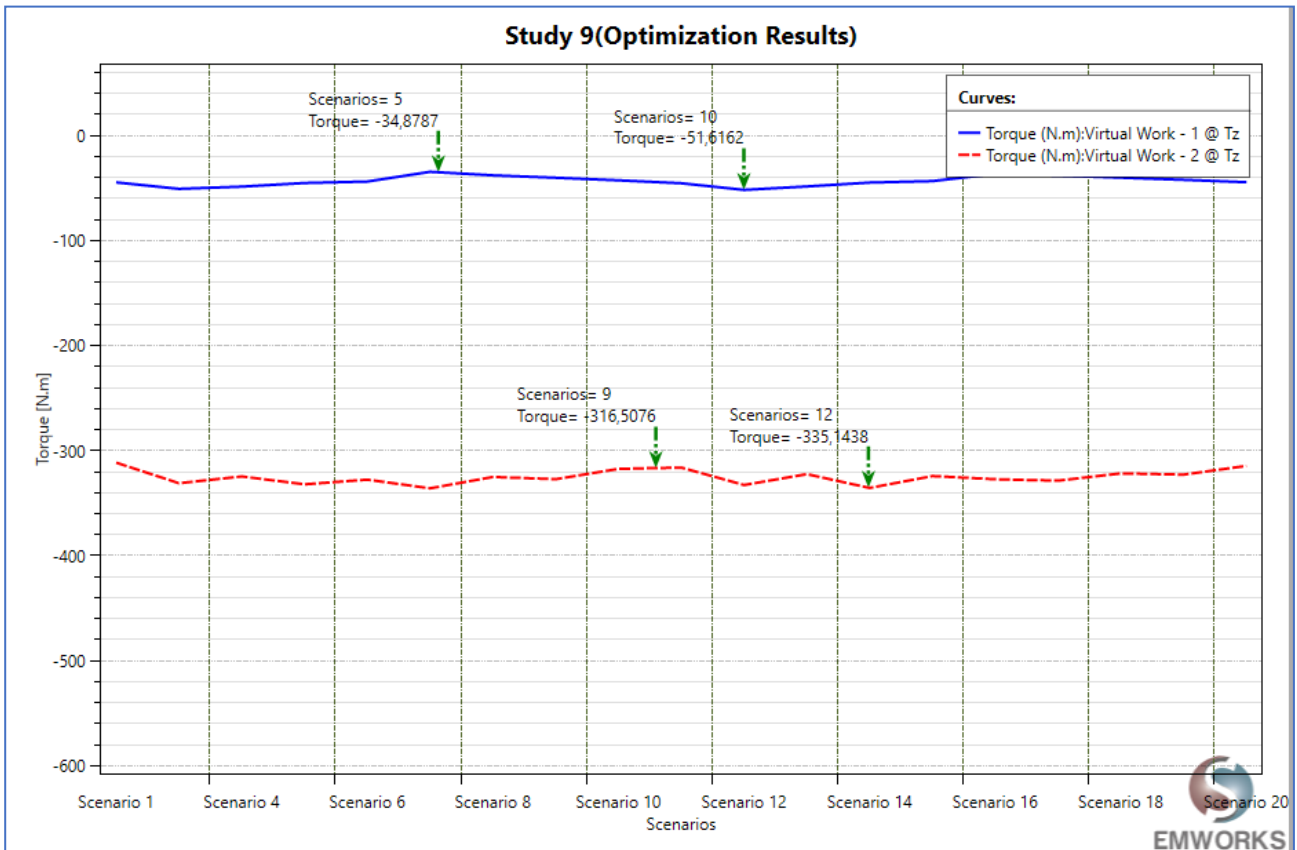


Figure 13, Torque trend on inner rotor (blue) and outer rotor (red) respectively

The inner rotor develops an average torque of 43Nm, while the torque generated on the outer rotor is about 325 Nm.

These results confirm that our modelling is effective because the torques perfectly reflect the initially defined transmission ratio of

$G_r = \frac{325}{43} = 7.55$	(3)
-------------------------------	-----

The result, so close to the value initially assumed, ensures that the oscillation of the transmitted torque, as graphically displayed, has significantly reduced.

Bibliography

- Gouda, E. &. (2011). Comparative Study Between Mechanical and Magnetic Planetary Gears. Institute of Electrical and Electronics Engineers.
- Howe, K. A. (2001). A novel high-performance magnetic gear. *IEEE Transactions on Magnetics*, (pp. vol. 37, no. 4, pp. 2844-2846).
- K. Atallah, S. D. (2004). "Design, analysis and realisation of a high-performance magnetic gear," in IEE Proceedings - Electric Power Applications, vol. 151, no. 2,.
- Magnetic gear: 2D FEM simulation with EMWorks2D inside SOLIDWORKS*. (n.d.). Retrieved from EMSWorks: <https://www.emworks.com/application/magnetic-gear-2d-fem-simulation-with-emworks2d-inside-solidworks>
- PERMANENT MAGNETS GEAR SYSTEM: 2D AND 3D ELECTROMAGNETIC SIMULATION INSIDE SOLIDWORKS*. (n.d.). Retrieved from EMWORKS: <https://www.emworks.com/application/permanent-magnets-gear-system-2d-and-3d-electromagnetic-simulation-inside-solidworks>
- Tlali, P. &.-J. (2014). Magnetic gear technologies: A review. Berlin: International conference on Electrical Machines, ICEM 2014.
- Toliyat, N. W. (2010). Analysis of the concentric planetary magnetic gear with strengthened stator and interior permanent magnet (IPM) inner rotor. *IEEE Energy Conversion Congress and Exposition*, (pp. 2977-2984). Atlanta.
- Wu, Y.-C. (2015). Design of an 8-speed internal gear hub with rotary control mechanism for bicycles.
- Yi-Chang Wu, C.-T. C. (2018). A novel bicycle rear hub transmission with a magnetic gear mechanism. Department of Mechanical Engineering, National Yunlin University of Science and Technology, Douliou, Taiwan, R.O.C.

<https://www.emworks.com>