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ANALYSIS OF SOME DESIGN PARAMETERS AND CONSTRUCTIVE SOLUTIONS FOR COAXIAL MAGNETIC GEARS

BY

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Abstract. This paper presents the torque focused design optimization and analysis of coaxial magnetic gears parameters when implementing some constructive and assembly solutions.

A theoretical investigation of several proposed solutions for mounting the permanent magnets on the surfaces of inner and outer rotors is held. The mounting of magnetic pieces on outer and inner rotors is considered as the benchmark models of magnetic gears do not display the actual torque capability provided by their constructed versions.

Design, geometry, and assembly of magnetic flux modulator are studied to determine some feasible solutions.

The impact of above-mentioned parameters on the torque capability are then studied and calculated with the help of finite element method

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(FEA) and the results are summarized and presented.

Keywords: magnetic gear, design parameters, constructive parameters, torque capability, optimisation.

1. Introduction

Magnetic gear design parameters have been previously investigated in a several dozens of scientific articles by way of varying one parameter individually or more parameters simultaneously. Most of the research on magnetic gears was done on theoretical models and did not analyse the assembly solutions and its subsequent impact on magnetic gear performance. Many experimental investigations on magnetic gear show reduced performances when compared with the previously held, theoretical investigation, due to the use of simplified magnetic gears topologies and calculation methods that are not taking into consideration the impact of all parameters on the calculation (Zanis *et al*., 2013; Molokanov *et al*., 2014; Rasmussen *et al*., 2005).

Previously, systematic design approaches to determine the optimal magnetic gear dimensions and optimal design procedure were analysed (Rahimi *et al*., 2018; Filippini and Alotto, 2017).

Analytical models which allow to estimate torque capability and material cost were previously presented by (Zhang *et al*., 2014). The investigations to determine the influence of design parameters on torque capability has shown the necessity to investigate multiple simultaneously rather than separately (Evans and Zhu, 2011). These and similar works are based on theoretical topologies, without considering the influence of the assembly solution on torque capability.

In this work, the magnetic field distribution in the coaxial magnetic gears and the torque capabilities are calculated and compared to a theoretical model with the finite element method (FEM). Instead of simplified and more agile calculation methods that cannot include all the particularities of the study, this paper's results are based on calculation methods that consider a bigger number of parameters that could be computed only with a 3D FEM.

The results of the investigation show that proposed solutions for magnetic gears topologies have a reduction of more than 10% of torque capability when compared to simplified, theoretical models. The compromise is still in a reasonable range for most of the topologies and the proposed constructive solutions could be a good start for an experimental prototype of magnetic gear.

2. Analysis of magnetic gear assembling solution and the simulation of their performance

2.1. Setup of the simulating environments

Magnetic gear torque simulation results were performed in EMS (EMWorks), which is an addon application of SolidWorks, and COMSOL Multiphysics applications. Both applications have 2D and 3D simulation capabilities and can compute geometries of high complexities. Also, they can provide simulation results in terms of magnetic flux density and transmitted torque on both, inner and outer rotors. Fig. 1 shows the configuration of the simulation environment in EMworks, and Fig. 2 presents a capture with the display of magnetic flux intensity after the simulation was calculated.

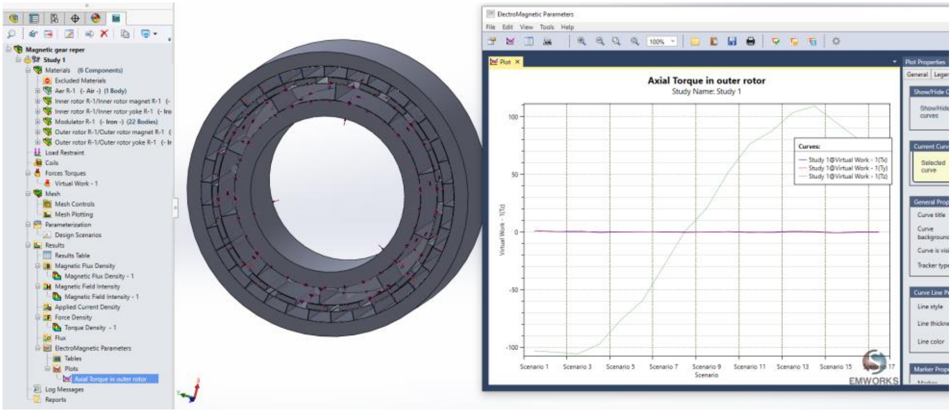
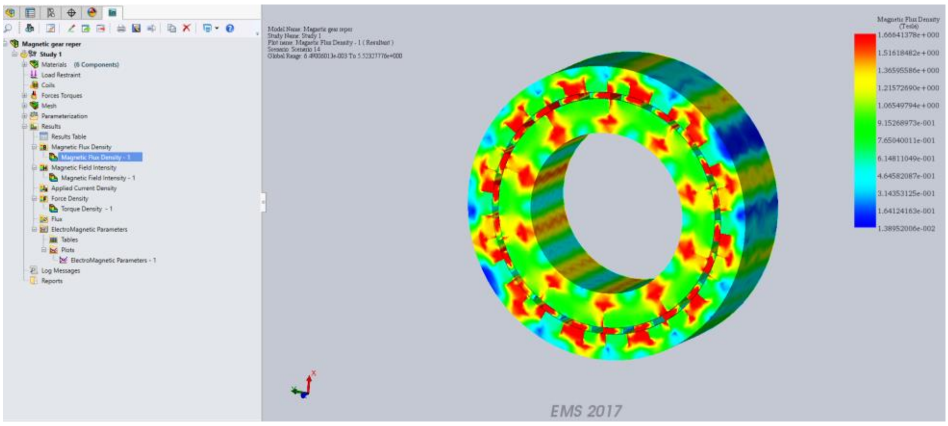


Fig. 1 – Configuration of the simulation environment and the plot of results for analysed magnetic gear with EMWorks.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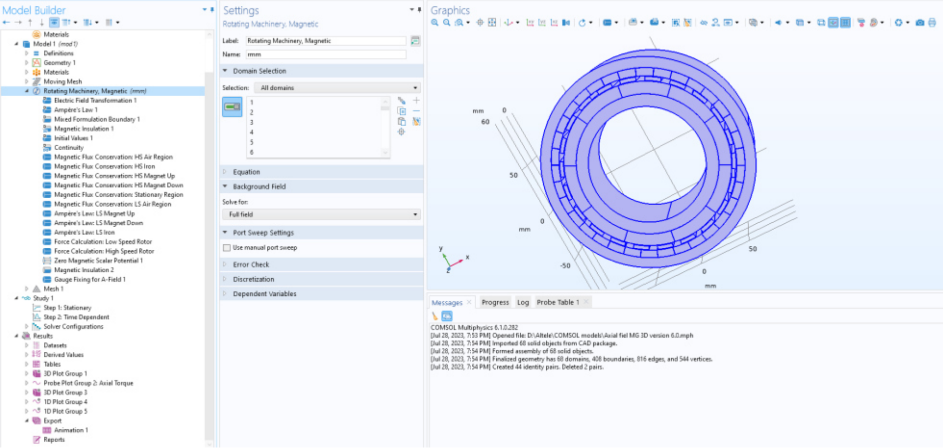
Study Name: Study 1
Plot name: Magnetic Flux Density - 1 (Resultant)
Scenario: Scenario 14
Global Range: 6.49006013e-003 To 5.52327776e+000

Fig. 2 – Plot of magnetic flux density for the analysed magnetic gear with1 EMWorks.

After constructing CAD model with SolidWorks and computing the simulation with EMS, same 3D model was imported in COMSOL, and the environment set with the similar parameters for the simulation as with EMS. Fig. 3 shows the configuration of the simulation environment in COMSOL Multiphysics.



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Domain Selection

Selection: All domains

1
2
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6

Equation

Background Field

Solve for: Full field

Port Sweep Settings

☐ Use manual port sweep

Error Check

Discretization

Dependent Variables

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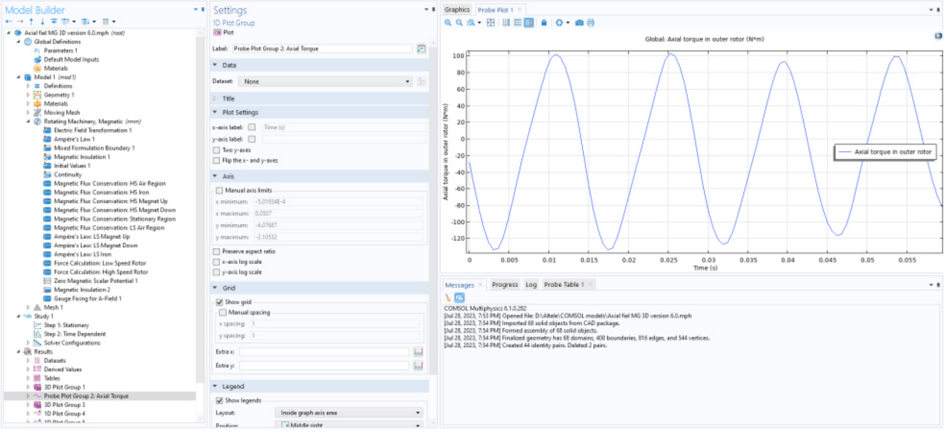
[Jul 28, 2023, 7:54 PM] Imported 68 solid objects from CAD package.
[Jul 28, 2023, 7:54 PM] Formed assembly of 68 solid objects.
[Jul 28, 2023, 7:54 PM] Finalized geometry has 68 domains, 408 boundaries, 816 edges, and 544 vertices.
[Jul 28, 2023, 7:54 PM] Created 44 identity pairs. Deleted 2 pairs.
```

Fig. 3 — Configuration of the simulation environment for analysed magnetic gear in COMSOL Multiphysics.

The outcome of both simulations delivered comparable values for the exit torque on outer rotor when applying similar parameters of the magnetic gear and of the simulating environment. Fig. 4 presents a plot of axial torque in outer rotor after the simulation was calculated in COMSOL Multiphysics.



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Label: Probe Plot Group 2: Axial Torque

Data

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Title

Plot Settings

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y-axis label: ☐

☐ Two y-axes

☐ Flip the x- and y-axes

Axis

☐ Manual axis limits

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x maximum: 0.0507

y minimum: -6.07687

y maximum: -2.10532

☐ Preserve aspect ratio

☐ x-axis log scale

☐ y-axis log scale

Grid

☑ Show grid

☐ Manual spacing

x spacing: 1

y spacing: 1

Extra x:

Extra y:

Legend

☑ Show legends

Layout: Inside graph axis area

Position: Middle right

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[Jul 28, 2023, 7:54 PM] Created 44 identity pairs. Deleted 2 pairs.
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Fig. 4 — Plot of axial torque in outer rotor for the analysed magnetic gear in COMSOL.

As the research moved on, the decision to prioritize the work in COMSOL was taken, as it offered certain advantages such as speed of computation, flexibility setting up the environment, possibility for the future works to add new conditions, variables, and scenarios. Besides, EMS last version was released a couple of years ago and is not compatible with newer versions of SolidWorks, meanwhile COMSOL has a full integration with CAD software and is updated constantly. This led the research to be conducted in COMSOL and EMS was used only when there was a necessity of additional verification of the result of a certain simulation.

2.2. Landmark magnetic gear

To evaluate the performance of each proposed constructive solution, the values and for the landmark Magnetic Transmission will first be obtained, which will be the comparison benchmark for the other constructive solutions. This theoretical model focuses on obtaining the optimal parameters of the input and output torque without analysing aspects such as the assembly method, the cost-effectiveness, and the reliability of the magnetic transmission. However, this will serve as a basic model for the constructive solutions analysed and proposed later, which will also consider the aspect.

To obtain the optimal model of the landmark magnetic transmission, this research uses iterative optimization based on FEA parametric analysis.

The Fig. 5 shows the analytical model and the benchmark magnetic transmission parameters to be optimized.

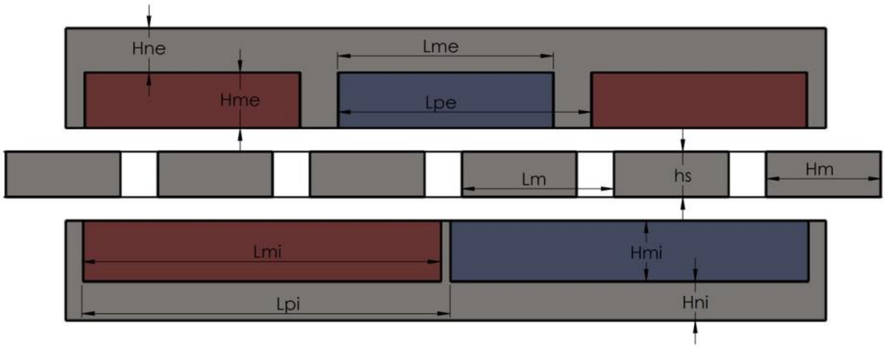

Fig. 5 – Parameters subjected to optimization in the linearized model of the landmark magnetic transmission.

Table 1 lists the optimization order of these parameters and their influence on transmission's performance, as well as the trade-offs for each parameter. The output torque is set as the optimization objective. After sufficient iteration of the sequential optimization process, the optimal dimensions of the theoretical magnetic transmission model can be obtained. The initial consideration from which the design of the benchmark transmission started was the measurement of its outer diameter of Ø200 mm and its axial length of 80 mm.

Table 1

Optimization process sequence and conflicting effects between parameters

Parameter	Contradictory effects on TM performance
The thickness of the ferromagnetic core of the outer rotor (Hne)	The saturation condition of the outer ferritic core as opposed to the volume and weight of MG.
Outer rotor magnet thickness(Hme)	The operating point of the outer magnets opposed to the volume of magnetic material on the inner rotor
The width (or arc length) of the outer magnetic poles (Lme)	The effective flux generated by the outer magnets opposes the modulating effect of the outer rotor.
The thickness of the modulator parts (hs)	The modulating effect of the counter space between the inner and outer rotors opposed to the distance between the two rotors
The width of the modulator pieces (Hm)	The modulation effect against the flow loss effect between the rotors.
The thickness of the magnetic parts of the inner rotor (Hmi)	The operating point of the internal magnets against the volume of magnetic material
The width (or arc length) of the inner magnetic poles (Lmi)	The effective flux of the internal magnets against the volume of magnetic material.
The thickness of the ferrite core of the inner rotor (Hni)	The saturation condition of the ferromagnetic core against its weight

The optimal parameters obtained using finite element analysis for the benchmark magnetic transmission model are illustrated in Fig. 6 and in Table 2.

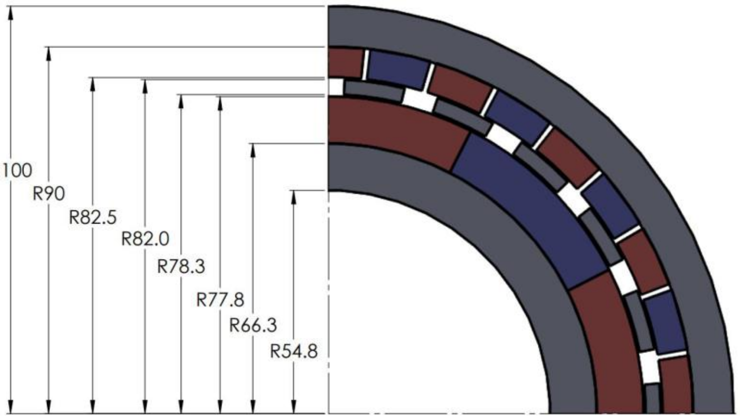

Fig. 6 – The dimensions of the reference magnetic transmission in millimetres.

Table 2

Additional parameters of landmark magnetic gear

Parameter	Value
The number of pole pairs on the inner rotor	5
The number of pole pairs on the outer rotor	17
The number of ferromagnetic pieces of the modulator	22
Transmission ratio	3.4
Axial length	80 [mm]
The space between the modulator and the inner rotor	1 [mm]
The space between the modulator and the outer rotor	1 [mm]
Magnetic material volume	$5.43 \cdot 10^{-4}$ m^3
Permanent magnets material	NdFeB
Remanence of magnetic material	1,21 T
Coercivity of the magnetic material	890 [kA/m]
Ferromagnetic material	Low carbon steel
Rotational frequency of inner rotor	500 [rpm] / 52.36 [rad/s]
Rotational frequency of outer rotor	147 [rpm] / 15.4 [rad/s]

The final transmission performance simulation results were obtained in COMSOL Multiphysics and when necessary, checked with SolidWorks EMS. The optimal design and configuration for the benchmark magnetic gear capability and torque transmission performance is displayed in Fig. 7:

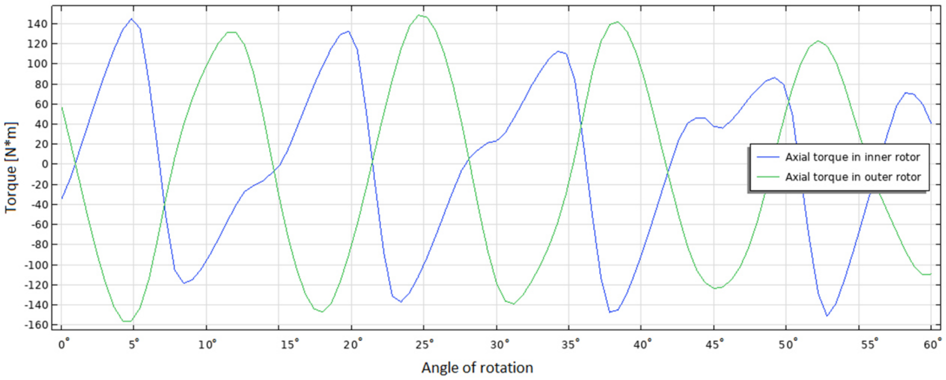

Fig. 7 – Obtained results for the landmark magnetic gear. Variation of inner and outer rotor torque over time

The computation result of the theoretical model for the optimised magnetic gear displayed a capability to transfer a torque of more about 140 N·m on the outer rotor while the torque applied on inner rotor reached about same values.

2.3. Constructive solutions proposed for the assembly of magnetic transmissions.

Most of the research on magnetic transmissions is done on theoretical models and does not analyze how to assemble them. Due to the favorable results in terms of the capacity of the transmitted torque, various constructive solutions, adapted to their possible use in different practical applications, the attention of current research is directed towards efficient and reliable ways of assembling magnetic transmissions that would preserve a value as higher as possible of the torque it can transmit through its rotors.

Starting from the landmark magnetic transmission analyzed in the previous chapter, possible solutions will be described for how to assemble the parts of the flux modulator and the permanent magnets on the inner and outer rotors.

2.3.1. Assembly solutions for flux modulator ferromagnetic parts

The flux modulator, which is made of ferromagnetic material and is placed between the two rotors with permanent magnets, has a particularly important role in modulating the magnetic field and, respectively, in the ability to transmit torque from one rotor to another. When stationary, it ensures the efficiency of the transmission and the interaction of the magnetic field of the rotor through which the torque enters, to the one that takes over and through which the output torque is achieved which will rotate in the opposite direction to the input rotor. When allowed to rotate freely, and one of the rotors fixed, the modulator can serve as the rotor through which the torque output is achieved.

The geometry and the way the ferromagnetic parts of the modulator are assembled directly influence the performance of the magnetic transmission. One of the simplest ways to assemble the modulator is to connect them with bridges at the ends as shown in Fig. 8:

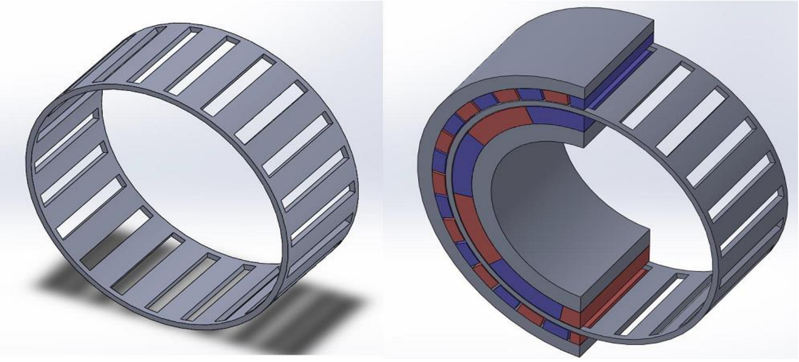

Fig. 8 – The bridged modulator and its representation in magnetic transmission.

The finite element analysis shows that when the bridges on the ends of the modulator are ferromagnetic, they prevent, on the portions around them, the efficient modulation of the flux, becoming points of concentration of the magnetic field. As a result, this phenomenon leads to a reduction of the transmitted torque by up to 29%. This effect is visible in the finite element simulations in the following Fig. 9 and the torque capability, and the torque capability of this design is displayed in Fig. 10.

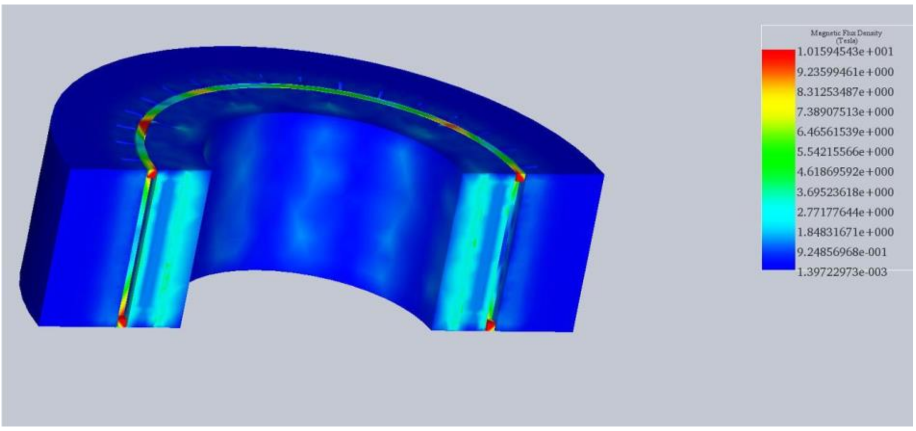

Fig. 9 – Sectional view of the Magnetic Field Density simulation. The red areas represent the highest concentration of flux on the modulator bridges which leads to a decrease in the torque capability of the magnetic gear.

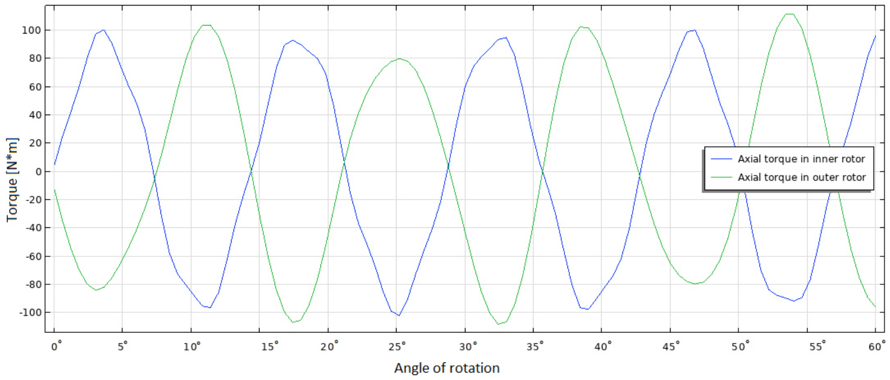

Fig. 10 – Torque capacity transmitted by inner and outer rotors of MG with bridged modulator.

A proposed solution in this paper is to increase the length of the modulator so that it will be longer than the magnetic rotors, this way the modulator bridges do not interfere with the magnetic field between the two rotors, and it is also proposed to connect them with non-magnetic material bridges, which will eliminate magnetic concentration on the transmission ends and ensure efficient modulation. Design changes of the bridged modulator are shown in Fig. 11.

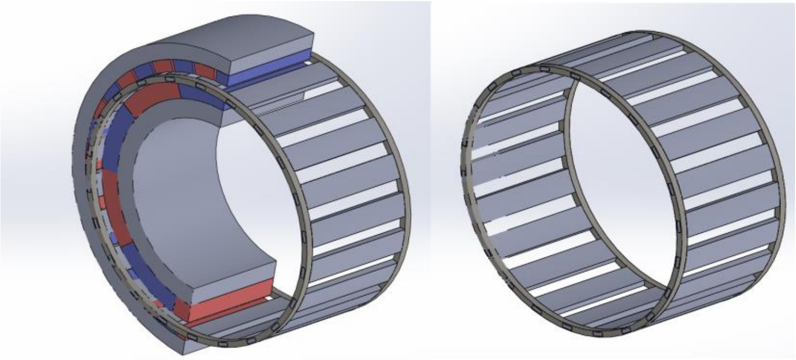

Fig. 11 – The constructive solution of the flux modulator with extended non-magnetic bridges outside the transmission.

The result of the implementation of this solution solves partially the flow losses, and the transmitted torque is improved by about 15% in comparison with MG with ferromagnetic bridge between modulator pole pieces, as presented in Fig. 12.

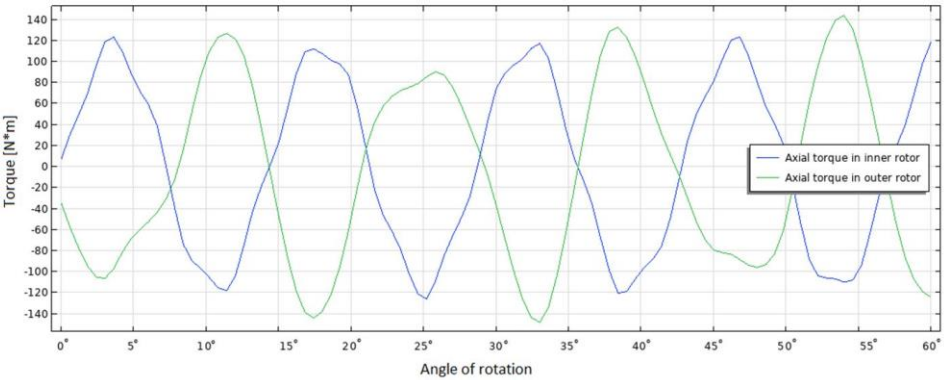

Fig. 12 – The resulted outer torque of the finite element analysis of the constructive solution proposed for the magnetic flux modulator.

The comparison of these two solutions displays a loss of approx. 29% of the output torque of flux modulator with ferromagnetic bridges. In the case of the modulator with non-magnetic bridges and with a section length exceeding that of the rotors, the losses are below 11%, which is a considerable improvement.

2.3.2. Solutions for assembling magnetic parts on ferromagnetic cores

The assembly method of the magnetic parts on the ferromagnetic cores is an aspect little addressed in scientific research in the field. Theoretical models with permanent magnets attached to the surface (SPM - surface mounted magnets) are most often used to obtain simulation results, but do not present a constructive solution applicable in real situations.

In this chapter, two solutions are proposed that represent rotors with permanent magnets fixed or framed on ferromagnetic cores, which are described in Fig. 13.

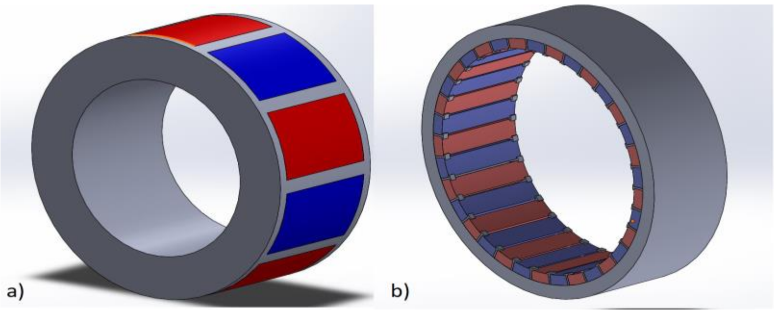

Fig. 13 – Proposed solutions for mounting the permanent magnets on the rotors:
a) the inner rotor with permanent magnets embedded in the ferromagnet core;
b) the external magnetic rotor with permanent magnets fixed by
non-magnetic clamping segments on the ferromagnetic core.

The simulation results for these types of assemblies, show promising values, the value of the transmitted torque calculation for the solution with buried magnets is shown in Fig. 14.

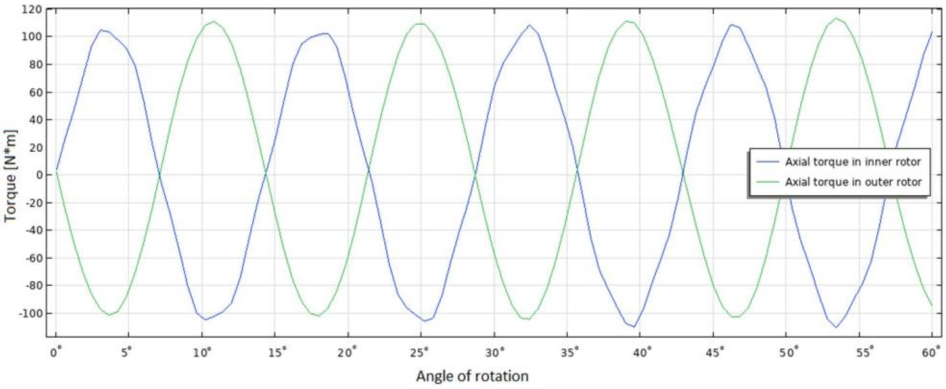

Fig. 14 – Torque values for the magnetic gear with permanent magnets embedded in the ferromagnet core.

The torque transmission capacity of the solution where the permanent magnets are “buried” in ferromagnetic core stands to about 115 N*m which represents a reduction of approx. 18% when comparing with benchmark design.

The second solution, where the permanent magnets are fixed by non-magnetic clamping segments on the ferromagnetic core, has shown even better simulation results, as shown in the Fig. 15:

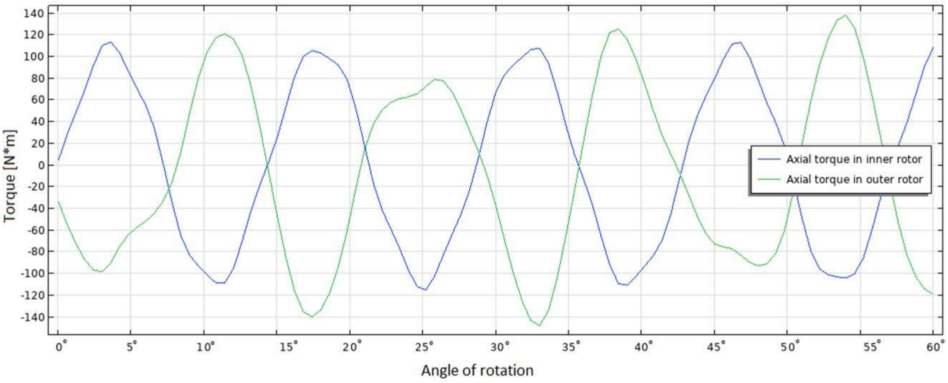

Fig. 15 – Torque values for the magnetic gear with permanent magnets fixed by clamping non-magnetic segments on the ferromagnetic core.

The torque transmission capacity of this solution stands around the value of 120 N*m, which represents a torque capacity reduction of about 14% and is in line with expected values.

The summary with the solutions analyzed in this article and with the corresponding torque capabilities are displayed in the Table 3.

Table 3

Overview of proposed solutions and comparison with the benchmark Magnetic Gear

Heading	Heading	Torque capacity in comparison with benchmark MG
Benchmark MG	140 [N*m]	-
MG with bridged modulator	100 [N*m]	-29%
MG with flux modulator with extended non-magnetic bridges	125 [N*m]	-11%
MG with permanent magnets embedded in the ferromagnet core.	115 [N*m]	-18%
MG with permanent magnets fixed by clamping segments on the ferromagnetic core	120 [N*m]	-14%

3. Conclusions

In this paper was presented the optimization of the key parameters of a coaxial, flux modulated magnetic gear. A benchmark magnetic gear was designed based on available scientific papers and on own simulation results.

The torque capacity of the benchmark design was obtained by simulations done with 3D FEA. A several solutions regarding assembly of flux modulator and magnetic pieces on outer and inner rotors were considered and their torque capacity calculated with FEA.

The results have shown that a reduction of torque that ranges between 14% and 29% was observed when comparing with the performance of benchmark design. This paper focused on calculation done when implementing just one solution at a time.

The future works will focus on performance and behaviour of magnetic gear when considering more complex assembly solutions.

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ANALIZA UNOR PARAMETRI DE PROIECTARE ŞI A UNOR SOLUŢII CONSTRUCTIVE PENTRU TRANSMISIILE MAGNETICE COAXIALE

(Rezumat)

Această lucrare prezintă optimizarea transmisiilor magnetice cu scopul obținerii cuplului optim și analiza parametrilor transmisiilor magnetice coaxiale la implementarea unor soluții constructive și de asamblare.

S-a realizat o investigație teoretică a mai multor soluții propuse pentru atașarea magneților permanenți pe suprafețele rotoarelor interioare și exterioare. Montarea pieselor magnetice pe rotoarele exterioare și interioare este luată în considerare, deoarece modelele teoretice ale angrenajelor magnetice nu prezintă capacitatea reală de cuplu oferită de versiunile construite.

Proiectarea, geometria și asamblarea modulatorului de flux magnetic sunt studiate pentru a determina unele soluții fezabile.

Impactul soluțiilor constructive propuse asupra capacității cuplului este apoi studiat și calculat cu ajutorul metodei elementelor finite (FEA), iar rezultatele sunt sumarizate și prezentate.