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NUMERICAL ANALYSIS OF A SIMPLIFIED MAGNETIC GEARBOX FOR ENERGY HARVESTING APPLICATIONS

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Abstract. The paper assesses the mechanical torque of a two-dimensional magnetic gearbox used in energy harvesting applications by increasing wind turbines' low mechanical power speed. The simplified device doesn’t consider the rotational speed transmission from the inner magnetic rotor to the outer magnetic rotor, which is considered mechanically blocked. The numerical simulation analysis considers a parametric study to address the influence of the dimensions of the outer magnets on mechanical torque by introducing a shape factor and by maintaining the same area of the outer rotor magnets. The results are obtained using the finite element method (FEM).

1. INTRODUCTION

Magnetic gears are widely known and studied as they exhibit several advantages over mechanical gears because of no mechanical contact, which translates into no friction, low maintenance, and low acoustic noise and vibration. These devices can be employed in wind energy or wave energy conversion applications since they aim to increase the low power density of harnessed energy. In the case of wind energy harvesting applications, magnetic gears are used to increase the low mechanical speed of the turbine. They are employed with synchronous generators, squirrel cage induction generators, or doubly fed induction generators [1,2]. For wave energy harvesting, the magnetic gear may enhance the wave motion and propagation by mounting it with the buoy [3].

However, the main disadvantage of the device is the low magnetic torque and transmission efficiency [4]. Other researchers have outlined the effects of eddy current losses on the gear's overall efficiency and different solutions to reduce the value of these losses [5]. Since the aim of energy harvesting applications is to amplify the electric power density to increase the mechanical rotational speed further, the low-speed inner rotor will determine the motion of the higher-speed outer rotor, acting as a magnetic speed multiplier.

This paper focuses on the torque assessment for different design typologies of a simplified magnetic gearbox multiplier which doesn’t consider the magnetic motion transmission of the inner rotor to the outer magnetic rotor. No torque transmission is analyzed since the outer rotor is considered blocked. The device considers different dimensions of the outer ring’s magnets. Still, since the increase of the outer diameter of the device results in higher torque densities [6,7], the area of the entire gearbox is kept constant in this study.

By dividing the area of the model by the height of the outer ring magnets, the area will remain constant. A parametric study is employed by varying the height of the exterior magnets. The effects of eddy current losses are not accounted for in this paper and will be a concern in future research.

2. THE PHYSICAL MODEL

The magnetic gearbox model, with all the constitutive parts, is presented in Fig. 1. The outer and inner ring magnets are represented in different colors to outline the magnetic poles. Furthermore, the outer magnet corners were slightly rounded to prevent a powerful magnetic

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field around them. Blue arrows also represent the magnetic boundary conditions. To completely close the magnetic field, an enclosing external air domain is considered at which surface a magnetic insulation boundary condition is applied.

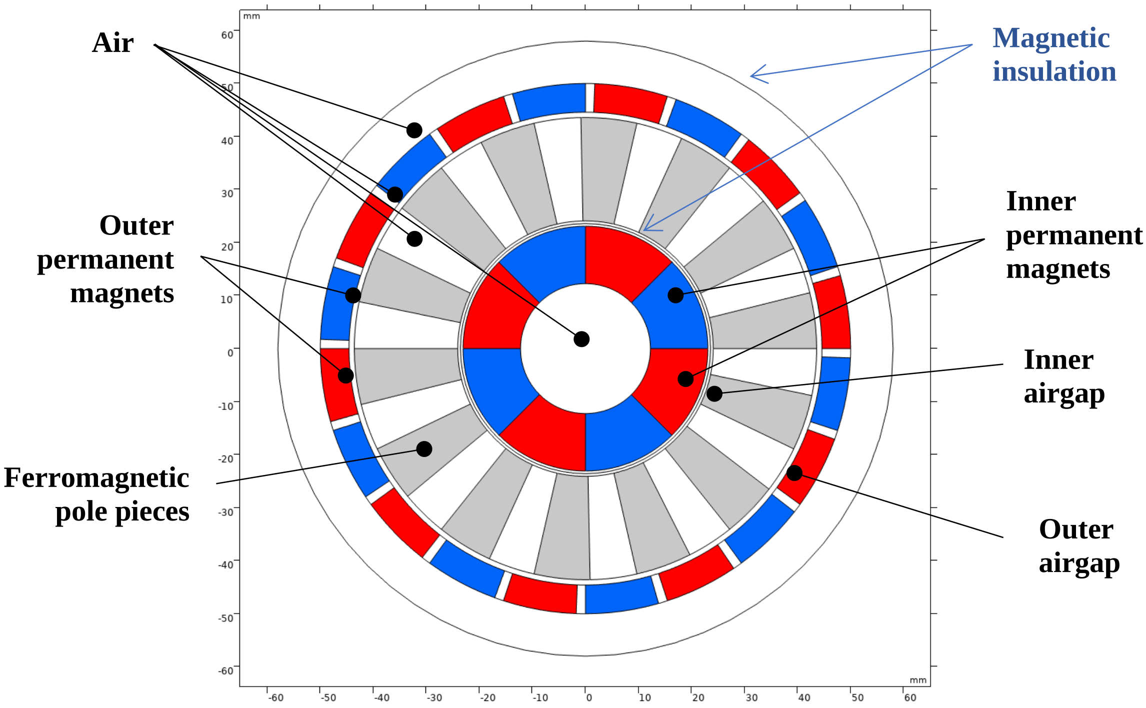


Fig. 1 – The main components of the magnetic gearbox. Dimensions are in millimeters.

The main dimensions and constitutive geometrical relations are presented in Table 1. The overall thickness of the device is 20 mm.

Table 1

Parameters of the magnetic gearbox under study

Symbol	Quantity	Relation/value
R	Radius of the device	50 mm
A_g	Area of gearbox	$\pi \cdot R^2$
A_{out}	Area of the outer rotor's magnets	$Height_{outt} \cdot Length_{out}$
f	Shape factor	$\frac{Height_{out}}{Length_{out}}$
$Height_{out}$	Height of outer magnets	mm
$Length_{out}$	Length of outer magnets	mm
N_f	Number of pairs of the ferromagnetic pole pieces	7
N_{out}	Number of pole pairs of outer rotor	10
N_{in}	Number of pole pairs of inner rotor	4
δ_{out}	Outer airgap thickness	1 mm
δ_{in}	Inner airgap thickness	1 mm

The height value of the magnets of the outer rotor, $Height_{out}$ will vary. Because the area of the outer rotor's magnets, A_{out}, will remain constant, an adimensional shape factor f is introduced by dividing the height by the length of the outer rotor's magnets, $f = \frac{Height_{out}}{Length_{out}}$ The area of the entire gearbox, A_g, and the inner rotor's magnets will remain constant during the study. The motion of the inner rotor is considered in this paper, as the outer rotor is mechanically blocked. Quasi-stationary working condition is assumed.

The constitutive physical relations are presented below. The magnetic circuit law describes the physical model:

$$\mathbf{\nabla} \times \mathbf{H} = \mathbf{J}, \tag{1}$$

H [A/m] is the magnetic field strength, and J [A/m^2] is the conduction electrical current density. The magnetic flux law is expressed as:

$$\mathbf{\nabla} \cdot \mathbf{B} = \mathbf{0}, \tag{2}$$

where B [T] is the magnetic flux density. The formulation of the magnetic flux density is given by the magnetic vector potential **A** [T·m] and the gauge condition:

$$\mathbf{B} = \nabla \times \mathbf{A}\,, \tag{3}$$

$$\nabla \cdot \mathbf{A} = 0\,, \tag{4}$$

The electric conduction law gives the value of the electric current density:

$$\mathbf{J} = \boldsymbol{\sigma}\mathbf{E}, \tag{5}$$

where J [A/m^2] is the conduction electric current density, σ [S/m] is the electrical conductivity, and E [V/m] is the electric field strength.

The equation gives the mechanical rotor's movement with time derivatives of the electric field:

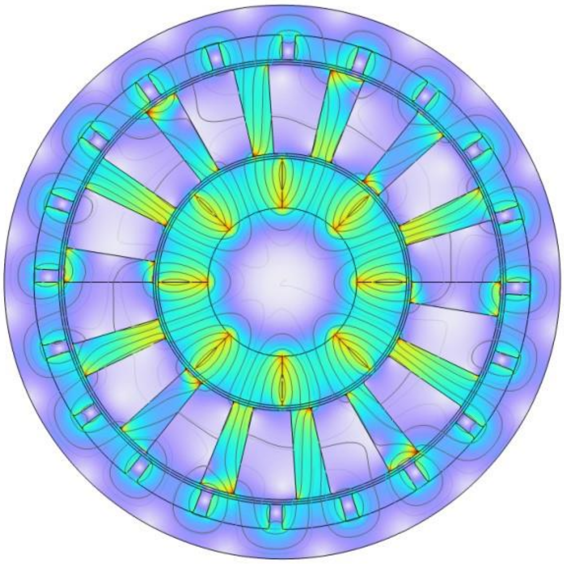
$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial \mathbf{t}}, \tag{6}$$

The constitutive material laws are added to these equations for the permanent magnets $\boldsymbol{B} = \boldsymbol{\mu}_\mathbf{0}\boldsymbol{\mu}_\mathbf{r}\mathbf{H} + \mathbf{B}_\mathbf{r}$, the air domains $\mathbf{B} = \boldsymbol{\mu}_\mathbf{0}\boldsymbol{\mu}_\mathbf{r}\mathbf{H}$**,** and the nonlinear relation of the ferromagnetic material $\boldsymbol{B} = \mathbf{f}(|\mathbf{H}|)\frac{\mathbf{H}}{|\mathbf{H}|}$. Here, B_r [T] is the remanent magnetic flux density of the permanent magnets with a value of 1.2 T, μ_0 and μ_r are the magnetic permeability of free space and the relative magnetic permeability, respectively.

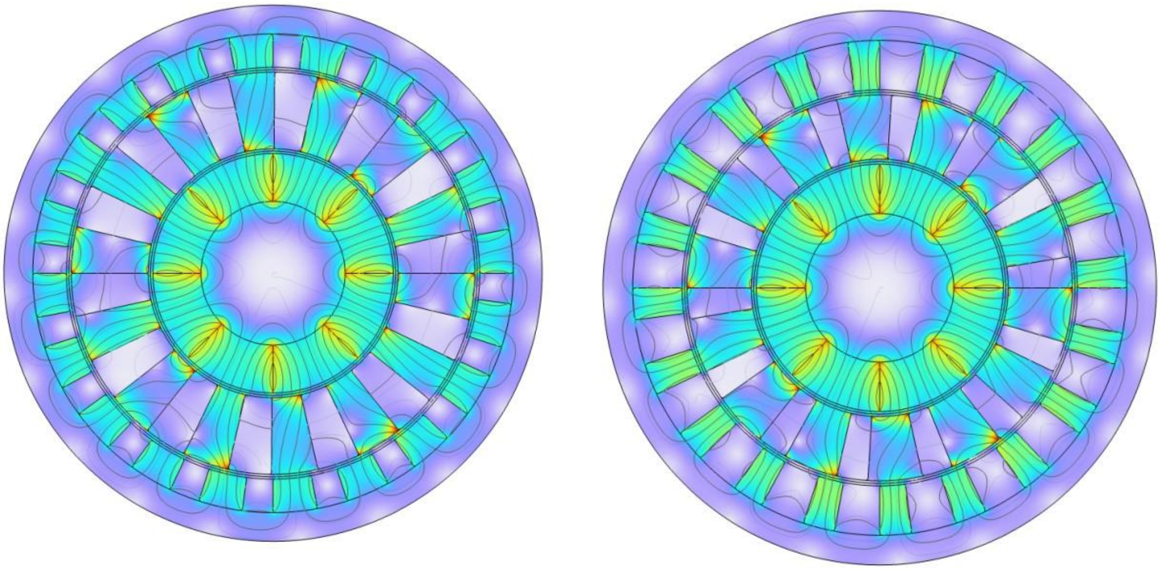
The magnetic boundary condition is magnetic insulation on the outer surface of the air-enclosing domain and on the boundary that divides in half the inner airgap, as half of the airgap will rotate and the other half will be assumed fixed. The study assumes stationary conditions. A parametric study is employed.

3. RESULTS AND DISCUSSION

The magnetic flux density distribution for three different configurations, corresponding to the shape factor $f = 0.38$ ($Height_{out}$ = 5 mm), $f = 0.75$ ($Height_{out}$ =7 mm), and $f = 1.5$ ($Height_{out}$ = 10 mm) are shown in Fig. 2. The lines of the *z* component of the magnetic vector potential are also represented. Quasi-stationary working condition is assumed.



a. $f = 0.38$ as $Height_{out} = 5$ mm, $B_{max} = 1.3$ T.



b. $f = 0.75$ as $Height_{out} = 7$ mm, $B_{max} = 1.8$ T. c. $f = 1.5$ as $Height_{out} = 10$ mm, $B_{max} = 1.9$ T.

Fig. 2 – The magnetic flux density and the lines of the magnetic vector potential.

The magnetic flux density value increases with the increase in the height of the exterior magnets, so with the increase of the shape factor f. Although the magnets were slightly rounded, a much stronger magnetic flux density is located around the unrounded corners of the ferromagnetic polar pieces. In reality, the exterior magnets will be parallelepipeds, with no rounded corner.

The parametric study considers a variation in the height of the magnets of the outer rotor. The mechanical torque is plotted in Fig. 3 for each of these dimensions.

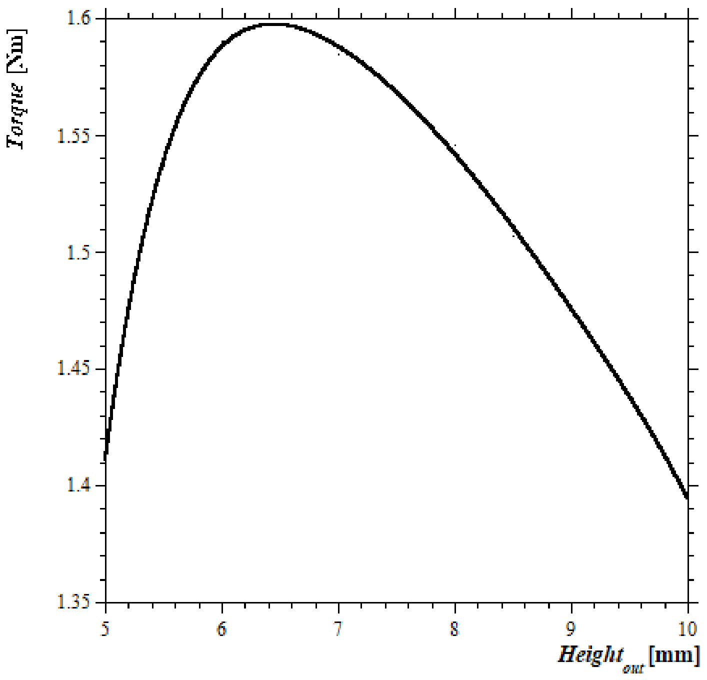


Fig. 3 – The torque for different configuration designs.

As we can see the highest torque is achieved at a specific value of the height of the outer rotor, at $Height_{out} \approx 6.5$ mm, $f = 0.65$, suggesting an optimal configuration design would yield higher mechanical torques.

For some particular dimensions of the magnet ($Height_{out} = 5$ mm, $Height_{out} = 7$ mm, and $Height_{out} = 10$ mm, respectively) the torque variation is illustrated in Fig. 4. The study is made under quasi-stationary functioning conditions as the mechanical rotation of the inner rotor is swept from 0 to 360 degrees with a step of 4 degrees.

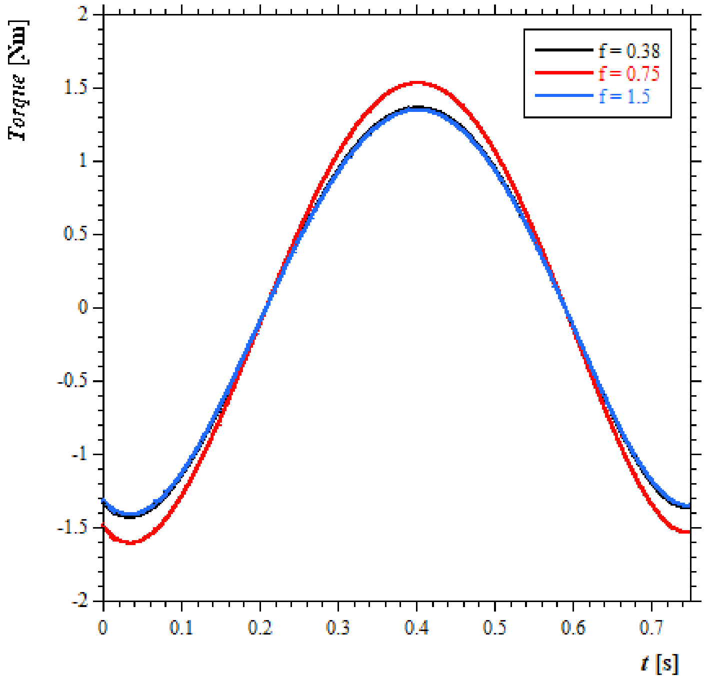


Fig. 4 – The torque for different configuration designs, different values of the shape factor *f*.

Figure 4 is plotted by interpolation and the uneven ripples are smoothed. The ripples are a result of the ferromagnetic and air domain intercalation, and some numerical artifacts. The results show that an optimal value of the shape factor (particular dimensions of the outer rotor's magnets) exists.

4. CONCLUSIONS

The paper is concerned with a quasi-stationary parametric study design. The height of the exterior magnets of the outer rotor is varied and a shape factor *f* is introduced by dividing the height by the length, the area is kept constant. The mechanical torque is determined for each geometrical configuration.

The magnetic flux density increases with the increase of the shape factor. Higher torque is achieved at a specific configuration of the outer magnet suggesting an optimal value of it. The analyzed model assumes quasi-stationary working conditions and no torque transmission from the inner to the outer rotor, as the latter is considered mechanically blocked. The outer rotor is considered a fixed domain alongside the ferromagnetic pole pieces, the mechanical rotational motion transmission will be analyzed in future work.

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