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AN ANALYSIS OF MAGNETIC GEAR PERFORMANCE

ANALIZA PRACY PRZEKŁADNI MAGNETYCZNEJ

A b s t r a c t

Continuous development of technology determines the search for new solutions in the field of electric machine design with improved electromechanical properties. In recent years, there has been an increased interest in passive and active magnetic gears. This paper presents the design, operation and performance analysis of the modified magnetic gear. The new prototype magnetic gear allows obtaining a ratio of 4:1 or 5:1. For the analyzed construction, two and three-dimensional numerical models are developed for which the series of the magnetic field calculations are carried out . The characteristics of the magnetic torque vs. angle position of the inner rotor with respect to the intermediate ring (modulation ring) and the outer rotor are determined and compared. The examples of flux density distributions for the analyzed converter construction are presented. The calculation results are verified with measurements on the prototype.

Keywords: *magnetic gear*, *finite element method*

S t r e s z c z e n i e

Ciągły rozwój techniki determinuje poszukiwanie nowych rozwiązań konstrukcyjnych maszyn elektrycznych o poprawionych parametrach elektromechanicznych. W ostatnim czasie można zauważyć wzrost zainteresowania pasywnymi oraz aktywnymi przekładniami magnetycznymi. W niniejszej pracy przedstawiono budowę, zasadę działania oraz analizę pracy zmodyfikowanej przekładni magnetycznej. Zbudowano prototyp przetwornika momentu umożliwiającego uzyskanie przełożenia 4:1 lub 5:1. Dla analizowanej konstrukcji opracowano dwu- oraz trójwymiarowe modele numeryczne, dla których wykonano szereg obliczeń polowych. Wyznaczono oraz porównano charakterystyki momentu magnetycznego w funkcji kąta położenia wirnika wewnętrznego względem pierścienia pośredniczącego (modulującego) oraz wirnika zewnętrznego. Przedstawiono przykładowe rozkłady indukcji magnetycznej dla analizowanej konstrukcji przekładni. Wyniki obliczeń zostały zweryfikowane z pomiarami na prototypie przetwornika.

Słowa kluczowe: *przekładnia magnetyczna*, *metoda elementów skończonych*

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1. Introduction

Magnetic gears offer plenty of potential benefits, including: physical isolation between the driver and the receiver, reduction of noise and vibration levels, protection against overload and contactless torque transmission [1–4]. They do not require periodic inspections or maintenance checks, which significantly helps reduce operating costs. Conventional magnetic gear, illustrated in Fig. 1a), has a simple construction. It consists of a low and high-speed rotor, on which permanent magnets are mounted. It should be noted that the rotor contact interface is reduced significantly, this causes heavy losses in the magnetic circuit. Therefore, the gear efficiency decreases, as well as, the transmitted torque density is not sufficient for practical application, and it does not exceed 10 kNm/m^3 for this type of designs [1, 3].

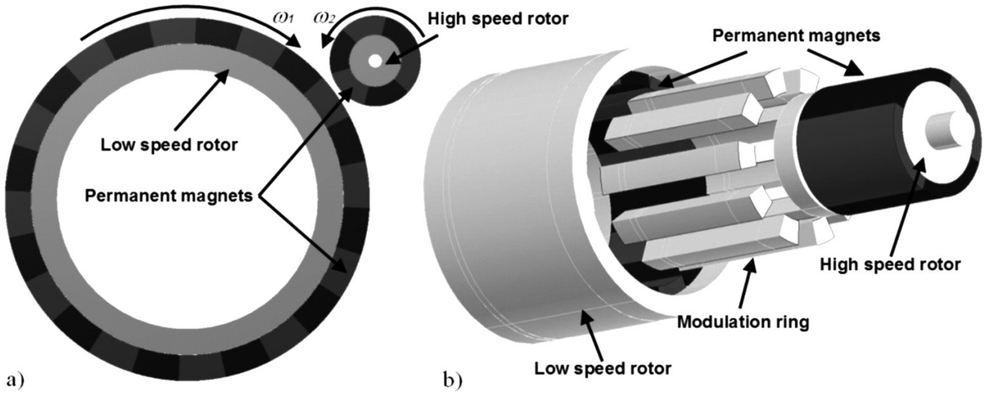

Fig. 1. Example of magnetic gear a) base construction [4], b) modified construction

This paper presents a modified magnetic gear, which can compete against certain mechanical constructions. A schematic diagram of magnetic gear is shown in Fig. 1b). The machine consists of external and internal rotors with permanent magnets mounted on the entire circumference and the intermediate ring formed of ferromagnetic poles. Additionally, by using the high-energy permanent magnets, it is possible to obtain a density of the transferred torque level of 150 kNm/m^3 [1, 4].

2. Operating principle

The operating principle of the analysed magnetic gear is described in detail by the authors of previous work [4]. In order to enable the magnetic torque transmission at various speeds, one of the aforementioned components of the machine must be locked with respect to the others. During the design stage, it must be determined which element will be driven and which one will be locked. This has a significant impact on the value of the final drive ratio, while every possible configuration gives another gear ratio. Relationships that allow choosing the number of internal and external rotor magnets and the number of ferromagnetic pole pieces for a given gear drive, have been derived on the basis of distribution analysis of the modulated magnetic field produced by permanent magnets in the air gap [1–4]. The next stage of the designing process is to determine the number of pole pairs within one of the permanent magnet rotors and to indicate pole pieces of the intermediate ring. On this basis, by using the formula (1), we can calculate the number of pole pairs within the second rotor.

$$p_{rz} = p_s - p_{rw} \tag{1}$$

where:
p_{rz}, p_{rw} – number of pole pairs in the outer rotor and inner rotor,
p_s – number of pole pairs in the modulation ring.

Considering the operating state during which the modulating ring is locked and the internal rotor is being driven, the magnetic gear ratio (i_r), is given by:

$$i_r = \frac{p_s - p_{rw}}{p_{rw}} = \frac{p_{rz}}{p_{rw}} \tag{2}$$

Under such conditions, the external rotor will rotate in the opposite direction to the internal rotor. On the other hand, during the operating state (in which the external rotor is locked), the intermediary ring will be rotating in the direction of the internal rotor, and the gear ratio is determined by the formula:

$$i_r = \frac{p_s}{p_{rw}} \tag{3}$$

3. Physical model

The prototype of the magnetic gear on the test stand illustrates Fig. 2. Basic parameters are listed in Table 1.

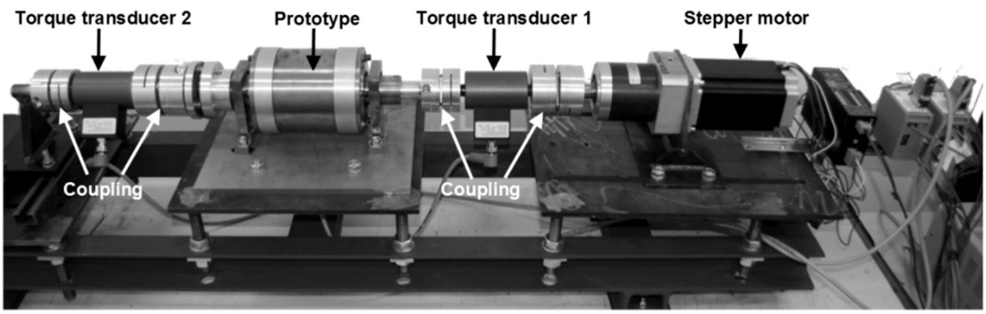

Fig. 2. Test bench for torque measurement

Table 1

Basic parameters of the designed gear

Inner rotor outer diameter	50 mm
Modulation ring inner diameter	54 mm
Modulation ring outer diameter	74 mm
Outer rotor inner diameter	78 mm
Outer rotor outer diameter	104 mm
Permanent magnets height	5 mm
Gear active length	50 mm

The external rotor has fixed neodymium magnets producing a magnetic field of eight pole-pairs; while the internal rotor of two pole-pairs. The number of ferromagnetic pole pieces in the modulation ring is ten. For easy measurement, it was assumed that the intermediary ring will be locked. For intermediary ring being locked, the gear ratio, according to the formula (2), is 4:1, while for the external rotor being locked, the gear ratio, based on the equation (3), is 5:1.

4. Numerical models

To carry out verification of the computations results, two and three-dimensional field models were developed (see Fig. 3). Calculations were carried out using the finite element method. In both models, eddy currents and magnetic hysteresis effects were neglected. The base point in the analysis is the angular position of the rotors where the magnetic moment is zero.

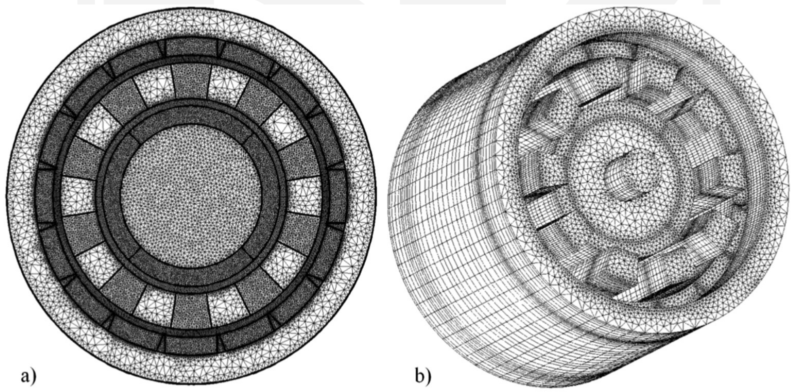

Fig. 3. Finite element mesh for a) two-dimensional model b) three-dimensional model (version B)

Due to the fact that the gear outer diameter is twice as large as the active length, 3D numerical models were developed to validate computation results from the two-dimensional model. In the first model (version A), it was assumed that the cross-section of the gear is the same along its whole length. The second model includes the actual dimensions of ferromagnetic elements, which can significantly affect the operation of the converter.

The difference between these two models lies in the length of intermediate ring pole pieces, which in model B is much greater than the length of permanent magnets. Of course, adaptation of those differences increase computational costs because it is impossible to impose symmetry and periodicity boundary conditions.

5. Simulation results and measurement verification

A series of computer simulations was carried out by using the developed numerical models. Calculations results of the magnetic torque have been verified on the prototype. For this purpose, a test-stand was built, which consists of: a prototype of the magnetic gear; two torque transducers equipped with encoders and terminals allowing for capturing the measurement data; a stepper motor with a planetary gearbox; the stepper motor controller; a system designed by the authors for stepper motor control and data acquisition. Figures 4–6 show characteristics of the magnetic torque acting on particular elements of the converter as a function of the rotation angle of the internal rotor. Based on the calculation results, the highest torque value (T_{max}) of which the gear can be loaded is obtained for the 45-degree angular displacement of the internal rotor with respect to the external rotor or intermediary ring. When the maximum value of the torque is exceeded, the magnetic gear stops. Table 2 lists the obtained computation results for the developed models and specifies their percentage change in terms of the measured magnetic torque (ΔT_{max}).

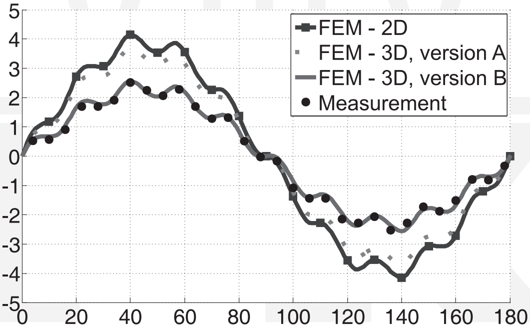

Fig. 4. Magnetic torque acting on the inner rotor vs. its angular displacement when the outer rotor and intermediary ring are locked

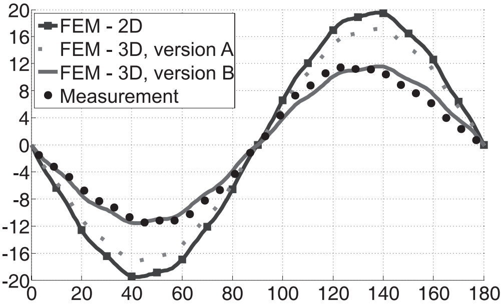

Fig. 5. Magnetic torque acting on the intermediary ring vs. angular displacement of the inner rotor when the outer rotor and intermediary ring are locked

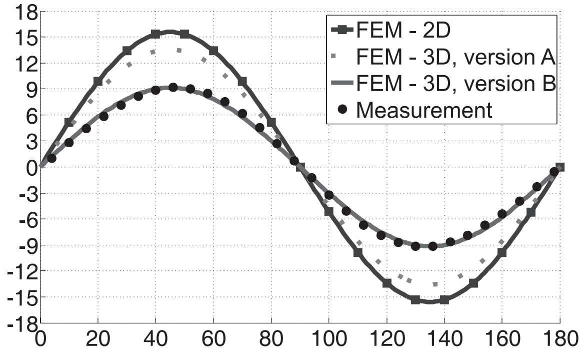

Fig. 6. Magnetic torque acting on outer rotor vs. angular displacement of the inner rotor when the outer rotor and intermediary ring are locked

Table 2

Magnetic torque peak values comparison

	Inner rotor		Intermediary ring		Outer rotor	
	T_{max} [Nm]	ΔT_{max} [%]	T_{max} [Nm]	ΔT_{max} [%]	T_{max} [Nm]	ΔT_{max} [%]
FEM 2D	4.21	+64.5	19.46	+69.9	15.56	+68.8
FEM 3D (version A)	3.72	+45.3	16.80	+46.6	13.63	+47.5
FEM 3D (version B)	2.59	+1.6	11.25	-1.8	9.20	-0.4
Measurement	2.56	-	11.46	-	9.24	-

Figures 7–9 show the change of the magnetic torque acting on particular elements of the gear when the intermediate ring is locked and the external rotor is loaded by the maximum torque value.

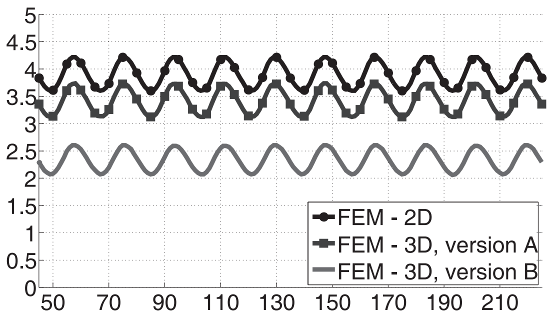

Fig. 7. Magnetic torque acting on the inner rotor vs. its angular displacement when the outer rotor is unlocked

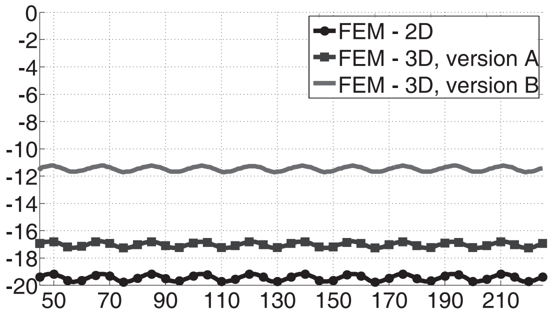

Fig. 8. Magnetic torque acting on the intermediary ring vs. angular displacement of the inner rotor when the outer rotor is unlocked

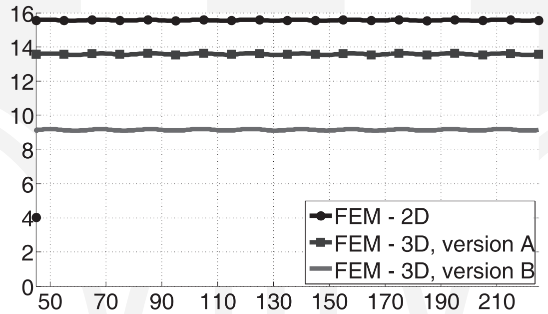

Fig. 9. Magnetic torque acting on the outer ring vs. angular displacement of the inner rotor when the outer rotor is unlocked

The change of the external rotor rotation angle with respect to the internal rotor was computed according to the formula:

$$\alpha_z = -\frac{p_{rw}}{p_{rz}}\alpha_w \tag{4}$$

where:
α_w, α_z – displacement angle of the inner and outer rotors, respectively.

Tables 3–5 provide a comparison of the most relevant parameters for all models. Furthermore, for calculation purposes, a parameter describing the electromagnetic torque ripples (ε) was introduced, which is described by the formula shown below:

$$\varepsilon = \frac{T_{\max} - T_{\min}}{2T_{av}} \cdot 100\% \tag{5}$$

where:
$T_{\min}$ – the lowest value of torque,
T_{av} – the average value of torque.

Table 3

Torque values for the inner rotor

	FEM 2D	FEM 3D (version A)	FEM 3D (version B)
T_{max} [Nm]	4.21	3.72	2.60
T_{min} [Nm]	3.59	3.12	2.06
T_{av} [Nm]	3.89	3.41	2.33
ε [%]	7.98	8.87	11.56

Table 4

Torque values for the intermediary ring

	FEM 2D	FEM 3D (version A)	FEM 3D (version B)
T_{max} [Nm]	19.75	17.29	11.72
T_{min} [Nm]	19.18	16.81	11.25
T_{av} [Nm]	19.46	17.04	11.48
ε [%]	1.47	1.43	2.05

Table 5

Torque values for the outer rotor

	FEM 2D	FEM 3D (version A)	FEM 3D (version B)
T_{max} [Nm]	15.60	13.63	9.20
T_{min} [Nm]	15.53	13.52	9.10
T_{av} [Nm]	15.57	13.58	9.15
ε [%]	0.22	0.39	0.55

Figure 10 represents angular change of magnetic torque acting on the intermediary ring with no load on the gear. Exemplary flux density distributions at the same angular position for the three-dimensional models are illustrated in Fig. 11.

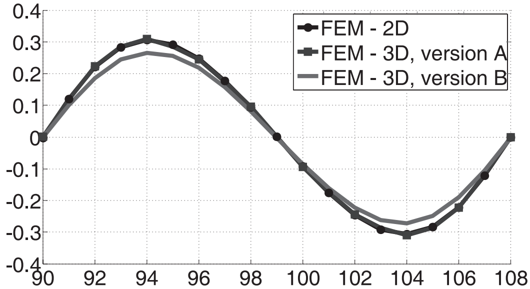

Fig. 10. Magnetic torque acting on the intermediary ring vs. angular displacement of the inner rotor when the outer rotor is unlocked

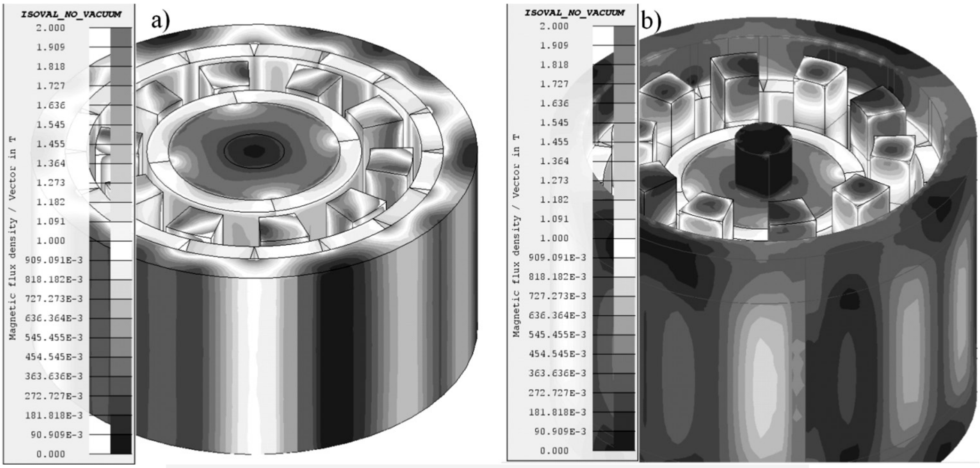

Fig. 11. Example of magnetic flux density distribution computed using 3D numerical model a) version A, b) version B

6. Summary

The paper describes the design and operation of the magnetic gear allowing for substantial increases in the torque transmission level. Significant impact of the length of the pole pieces in the modulation ring on the magnetic torque value was shown. Torque density in the 2D model equals 39.6 kNm/m^3 while in the 3D model in version A, it is 34.6 kNm/m^3 and in version B, it is 15.3 kNm/m^3. Such large discrepancies in torque density values are caused by an improper design of the converter. However, it should be noted that the constructed machine is the first prototype built in the Chair of Electrical Machines at the Technical University of Opole. Further research study will involve works on the design improvement and optimization of the magnetic circuit.

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