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Application of a genetic algorithm for design optimisation of a passive magnetic gear

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This paper analyzes an influence of selected design parameters of a passive magnetic gear on the transmitted torque density. This constitutes the basis for determination of a number of design parameters and their ranges in the optimisation process. Calculations are carried out using the two–dimensional finite element method implemented in the Matlab environment. As a result of the optimisation process, the design parameters of the magnetic gear with a much higher value of the transmitted torque are obtained.

KEYWORDS: magnetic gear, finite element method, evolutionary algorithm

1. Introduction

Nowadays, increasingly higher requirements are set for currently constructed electromechanical and magnetic transducers. Only high–performance machines characterised by the high transmitted torque density, stable operation and resistance to external factors can effectively compete in the market. Also, the price and availability of materials necessary for the construction of a given transducer are an additional factor that is of great importance.

The rapid development of new materials in the field have an availability contributed to the replacement of conventional transducers with new high–performance constructions. A mechanical gear is one of such transducers. It is commonly known that mechanical gears are characterised by a very high density of the transmitted torque, but they also have some flaws that are visible during their operation. Such problems are caused by the physical contact between cooperating parts of the gear causing vibrations, noise and heating [1–14]. It is possible to eliminate these flaws by using a design that offers a physical isolation between moving parts in which the torque is transmitted through the magnetic field. The magnetic gear, which is the subject of the study in this paper, also offers other advantages such as noise and vibration level reduction, natural overload protection, high performance and low operating costs [1–14].

In case of conventional designs of magnetic gears, the active surface taking part in the torque transmission is small, which is reflected in a very low value of the transmitted torque density. The surface of interaction of moving parts must be maximum so that the magnetic gear could compete with the mechanical one. The design meeting the above–mentioned requirements is presented in Fig. 1. The machine consists of three basic elements, i.e. (high–speed) inner rotor and (low–speed) outer rotor, on which high–energy permanent magnets are mounted, and intermediate ring formed of ferromagnetic poles. The torque transmission capacity for such a structure reaches the value of 100 kN·m/m^3 [1, 10] and depends on parameters of permanent magnets, ferromagnetic materials and shape and dimensions of the magnetic circuit. The detailed analysis of the performance and operation of such a gear has been presented in papers [10, 11].

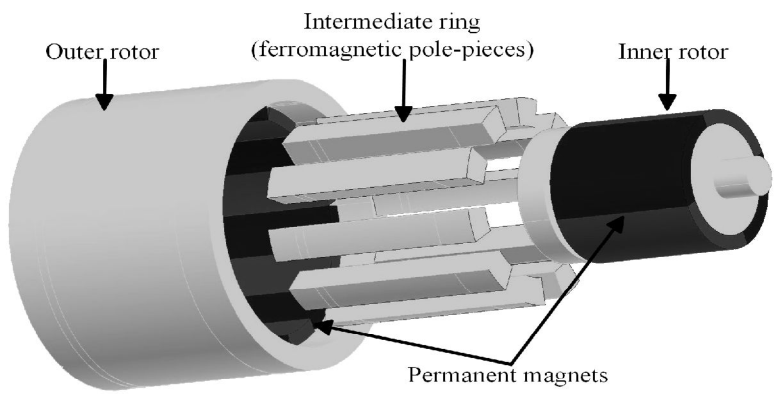

Fig. 1. Modified design of a magnetic gear

To fulfil the above–mentioned requirements, it is necessary to use special tools for the calculation and analysis of the electromagnetic field and one of a number of currently available optimisation methods in the design process. Currently available methods allowing for the performance of the optimisation task can be divided into three groups: deterministic, stochastic and hybrid methods.

Deterministic methods are based on precisely defined mathematical equations and require the calculation of the gradient and Hessian of the objective function which is the criterion for the task. The selection of the starting point is crucial for this class of methods as a wrong choice leads to malfunction of the device. These methods also require the continuity of the optimisation problem due to the need to determine derivatives, which significantly limits the range of possible applications.

Stochastic methods based on the principle of random selection are not limited by the continuity and differentiability requirements. They determine the value of the objective function for selected points of the calculation area. However, in spite of the simplicity, the random nature of the optimisation process requires a larger number of calculations to solve the problem. Currently available multiprocessor systems and extended network systems allow for the division of tasks and distribution of the calculations.

Hybrid methods combining the above–mentioned deterministic and stochastic methods significantly reduce those disadvantages related to the optimisation issue. In case of such a combination, a selected stochastic method is used to find the area in which the solution sought is located whereas the analytic method is used to find the optimum. The hybrid approach often gives better results than these two techniques used separately.

The authors advocate to use an evolutionary algorithm, which is a generalisation of the genetic algorithm and which operates similarly to the natural selection mechanism among living organisms, in the calculations. Better adapted individuals are selected through genetic operations, i.e. crossover and mutation. By defining an appropriate objective function, this algorithm maximises or minimises the quality factor value with high probability of success and avoidance of local extremes. The expected result of the process is to obtain geometric dimensions of the construction characterised by improved motion characteristics.

2. Selection of decision variables for the optimisation procedure

When proceeding to the preparation of numerical models, a number of initial assumptions are identified. At this stage, it is assumed that the gear ratio will be 4:1, the (high–speed) inner rotor will be driven, the intermediate ring will be blocked and the load will be coupled with the outer rotor (Fig. 1). According to the relationship (1) describing the gear ratio for the above–mentioned assumptions, there are several combinations of the number of pole pairs of magnets and poles of the intermediate ring.

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

where: i_r – magnetic gear ratio, p_{rw}, p_s, p_{rz} – number of pole pairs of the inner rotor, poles of the intermediate ring and pole pairs of the outer rotor, respectively.

The choice of a given combination depends on the transmitted magnetic torque density, the ripple ratio (ε) and the content of the cogging torque in the usable torque (τ). These relationships are described by equations (2) and (3).

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

where: ε – ripple ratio, T_{max}, T_{min}, T_{avin} – the maximum, minimum and average values of the magnetic torque on the inner rotor, respectively,

$$\tau = \frac{T_z}{T_{\max}} \cdot 100\% \qquad (3)$$

where: τ – ratio of the content of the cogging torque in the usable torque, T_z – cogging torque amplitude.

The results of calculations are presented in Table 1. Calculations carried out indicated the model with the combination $p_{rw} = 2$, $p_s = 10$, $p_{rz} = 8$, characterised by a relatively high torque density T_d, at relatively low torque ripples, as the most advantageous one. The authors use only this model in further analysis.

Table. 1. Impact of the change in the number of pole pairs

p_{rw} p_s p_{rz}	*1* *5* *4*	*2* *10* *8*	*3* *15* *12*	*4* *20* *16*
τ [%]	0,1	7,3	5,9	4,4
ε [%]	0,1	8,0	6,3	4,5
T_d [kN·m/m^3]	22,5	36,7	32,6	24,5

Permanent magnets are the basic elements of all magnetic gears. With a high diversity of currently available magnets in mind, the authors decided to use neodymium magnets N35 in simulations. Energy accumulated in these elements, determining the performance parameters of the gear, is proportional to their volume. Taking the above into account, a series of simulations, described in detail in the paper [12] was carried out, on the basis of which the same thickness of magnets for both rotors amounting to 5 mm was assumed.

A similar procedure was used in case of the intermediate ring, also known as the modulating ring. Calculations showed relatively little impact of its thickness on the value of the transmitted torque density and much higher impact on ratios ε and τ. The modulating ring 10 mm thick was used in the initial geometry of the transducer on the basis of simulations carried out.

The width of air gaps has definitely the greatest impact on the value of the torque transmitted by the magnetic gear. It is very difficult to maintain a relatively narrow air gap that is the same over its entire circumference at the stage of the construction of prototypes of transducers with permanent magnets. The results of calculations, collected in Table 2, show a significant increase in the transmitted torque value resulting from the decrease in the gap width. When analysing values of other ratios, taking technological aspects and their experience into account, the authors assumed air gaps which are 1 mm wide in further considerations.

The above–presented analysis leads to the preparation of the prototype model of the magnetic gear (Fig. 2), further considered as the initial (base) model in the optimisation process.

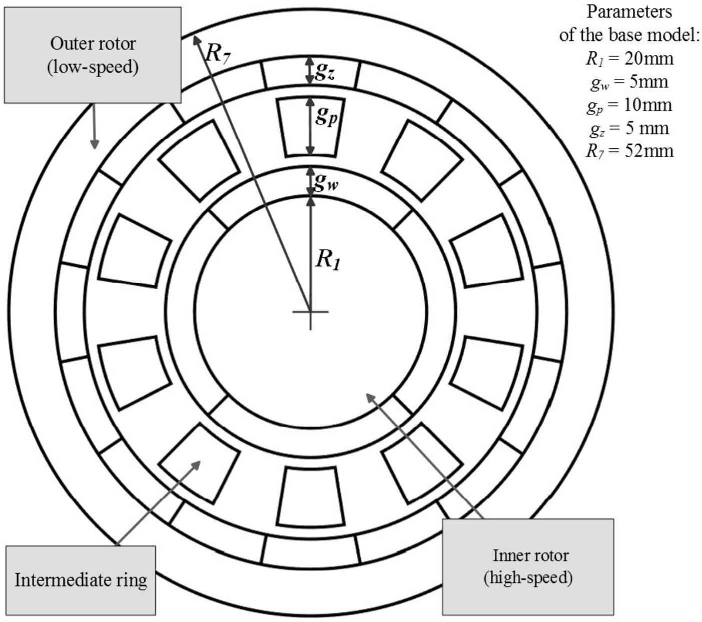

Fig. 2. Cross–section of the magnetic gear in which the most important parameters are marked

Table. 2. Impact of the air gap width

***g* [mm]**	0,5	1,0	1,5	2,0
τ [%]	14,0	11,3	9,2	7,3
ε [%]	17,7	13,8	10,4	8,0
T_d [kN·m/m^3]	61,9	51,7	43,5	36,7

Due to a very large search space, when choosing decision variables the authors limited themselves to 4 design parameters: g_w, g_p, g_z and R_1. The minimum range of parameter variability is limited to 0.1 mm. The constant value of the outer radius R_7 is assumed in the optimisation task.

3. Optimisation procedure using the evolutionary algorithm and database

Carrying out the optimisation procedure with the use of the evolutionary algorithm involves a great number of calculations. The evolutionary algorithm used in cyclic operations of crossover, mutation and selection creates populations of individuals with the size specified by the user. Each individual has to be analysed in order to assess its adaptation level.

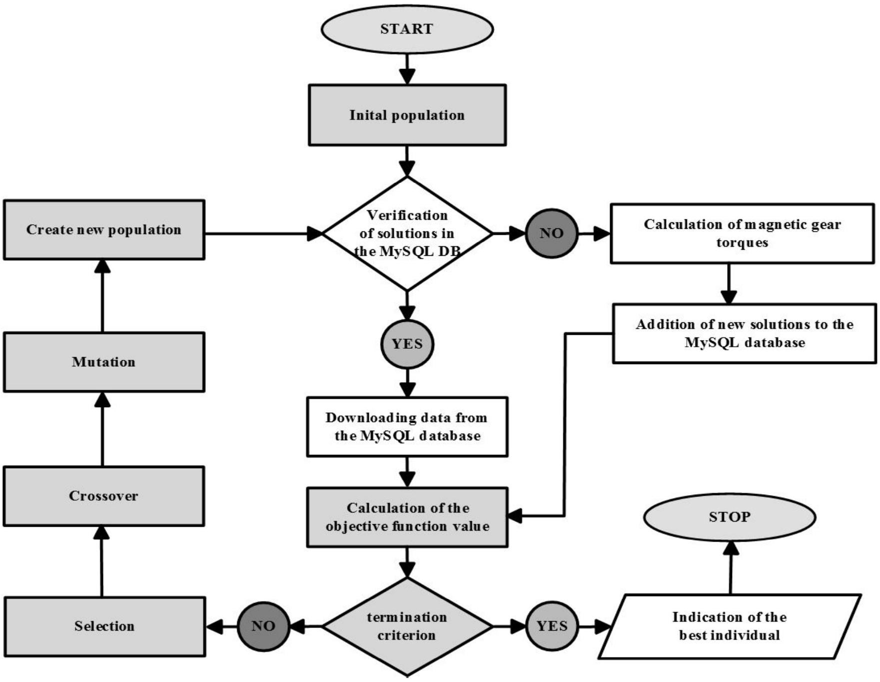

Fig. 3. Diagram of the optimisation procedure

In case of the magnetic gear, field calculations should be carried out for the generated model and input parameters should be determined for the objective function. To reduce the time dedicated to calculations, the authors use a database containing the key information about the already generated individuals in the optimisation procedure. During the optimisation procedure, the operation algorithm, presented in Fig. 3, searches the database in order to find the already known solutions. Such an approach significantly reduces the calculation time.

4. Calculation results

Using the algorithm presented in the previous section, the optimisation procedure is defined as a search for the highest value of the transmitted torque density. The objective function, presented in equation (4), refers at each stage to the base model in which the value of the transmitted torque density is T_{db} = 51.7 kN·m/m^3. Moreover, the authors included the factor responsible for the minimisation of magnetic torque ripples in the objective function. The same value of weighting factors is assumed for all components of the function, the selection of which is a separate issue requiring a great number of calculations. The authors also decided not to evaluate the efficiency of the algorithm used in the optimisation procedure. Crucial parameters of the evolutionary algorithm (initial population, number of generations, crossover and mutation probability) are selected on the basis of separate test calculations.

$$\max_{\underline{x} \subset X} \left\{ \xi(\underline{x}) = w\left(\frac{T_d(\underline{x})}{T_{db}(\underline{x})}\right)^2 + (1-w)(1-\varepsilon(\underline{x}))^2 \right\}$$

$$X \subset R^4 \qquad (4)$$

$$\text{where } x^T = [r_1, g_w, g_p, g_z]$$

The analysis of the variability of the objective function for the third generation is presented below in Fig. 4. The authors carried out a larger number of calculations, but they only present the best solution in this paper.

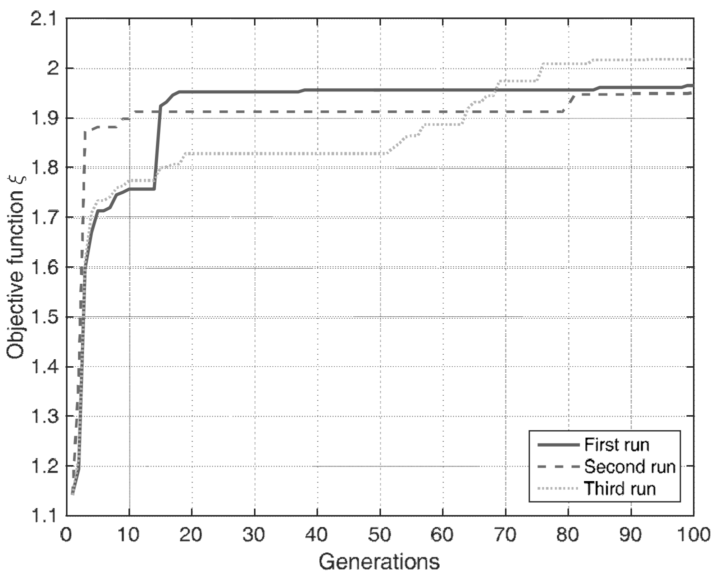

Fig. 4. Objective function depending on the number of generations for 3 inductions

Table. 3. Comparison of parameters of the magnetic gear before and after the optimisation procedure

	ξ [–]	r_1 [mm]	g_w [mm]	g_p [mm]	g_z [%]	τ [%]	ε [%]	T_d [kN·m/m^3]
Base model	0,871	21	5	10	5	11,3	13,8	51,7
First run	1,965	22,4	11,9	5,4	5,3	15,8	19,3	93,6
Second run	1,951	22,4	11,9	5,1	5,5	16,2	19,7	93,3
Third run	2,018	20,3	12	6,0	6,7	13,5	16,4	94,4

Table 3 presents design and integral parameters obtained for the best individuals as a result of the optimisation procedure in three inductions. The torque density value typical to the best individual is close to 100 kN·m/m^3. Coefficients τ and ε remained at a level similar to that of the base model. The thickness of magnets on the inner rotor is doubled whereas the thickness of the intermediate ring is decreased in the solution obtained. The comparison of the calculated static magnetic torque of the base model and for the best individual obtained from the optimisation procedure (see Table 3 – hird run) is presented Fig. 5.

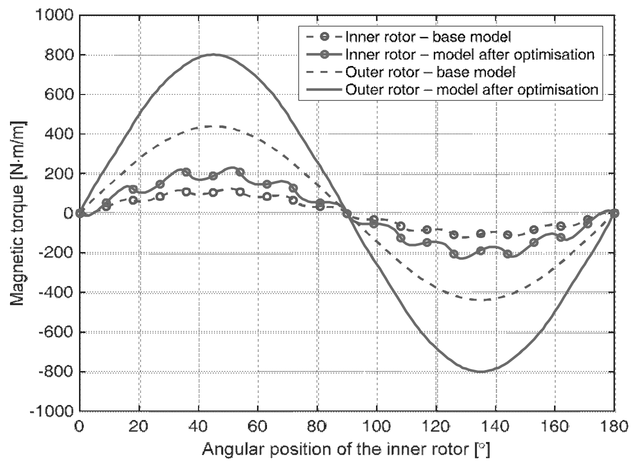

Fig. 5. Magnetic torque of the gear at idle speed

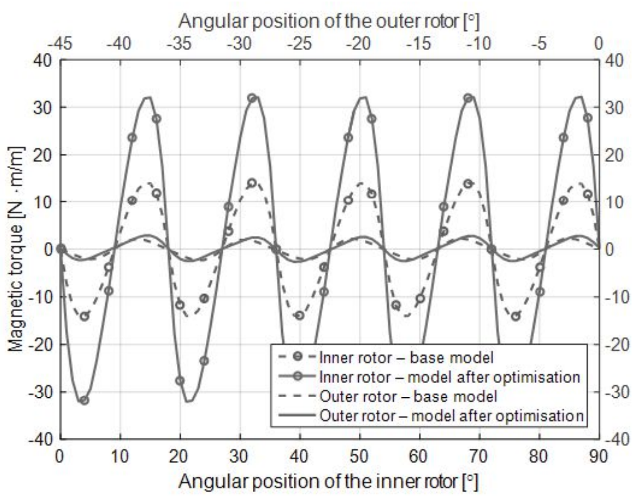

Fig. 6. Magnetic torque of the gear at idle speed

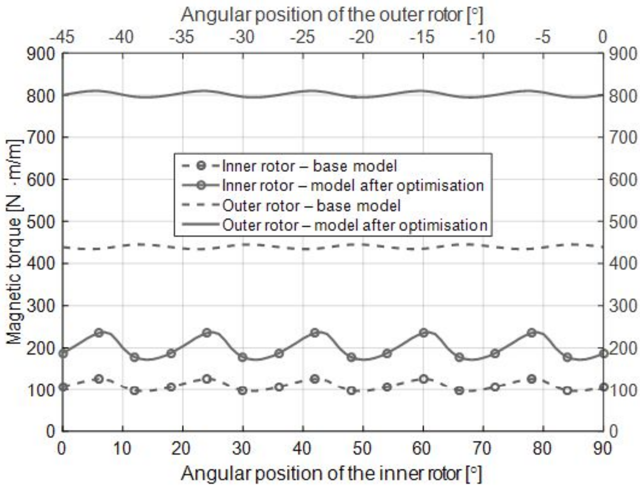

Fig. 7. Magnetic torque of the gear under the maximum load

Figures 6 and 7 present the characteristics of the torque acting on the moving parts of the magnetic gear in two variants of operation – at the idle speed (Fig. 6) and under maximum load (Fig. 7). When the maximum load value is exceeded, the torque transmission is interrupted, vibrations occur on the outer rotor and, consequently, the outer rotor is stopped.

Figure 8 shows the magnetic field lines distribution before and after optimization process.

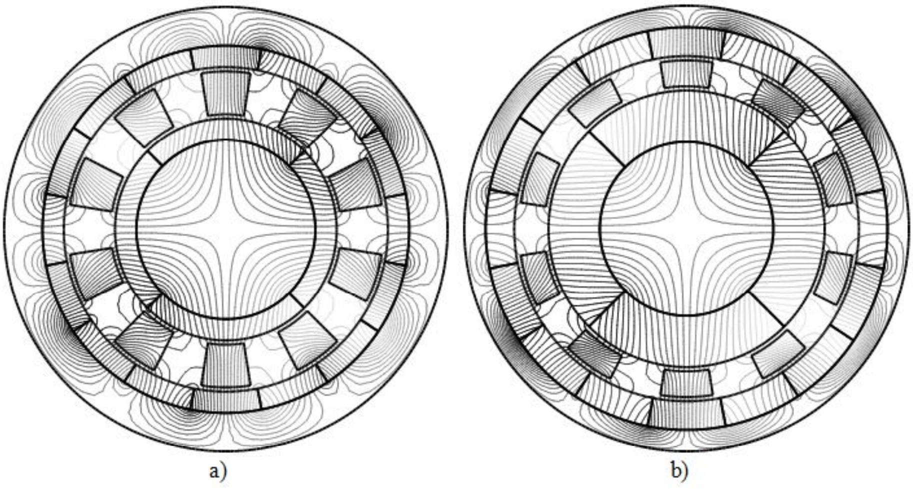

Fig. 8. Magnetic field lines a) before and b) after optimization process

5. Summary

The paper has presented the optimisation procedure for design parameters of the magnetic gear with the use of the evolutionary algorithm and the two–dimensional finite element method. The analysis allowed the authors to determine such design parameters that consequently give the best solution in terms of the objective function used. The optimisation carried out using the finite element method at a very large number of decision parameters and improperly defined parameters of the evolutionary algorithm may lead to very time–consuming calculations and the resulting solution does not have to be necessarily the best one. For this reason, before the optimisation, it is necessary to check the impact of design parameters of the transducer on mechanical parameters allowing for the reduction of the number of decision variables and their ranges of variability.

In case of optimisation tasks in which field models are used, it is useful to use a database. The storage of individuals and their solutions in the database is reflected in the reduction of the calculation time and the possibility of performing rapid tests related to the behaviour of different variants of the objective function. The analysis of the calculation results presented in Table 3 showed a relatively low sensitivity of the objective function to the value of the torque ripple ratio. The authors are planning to carry out calculations in future works using modified objective functions, which are useful in specific application areas.

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