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MATHEMATICAL MODELING OF A MAGNETIC GEAR FOR AN AUTONOMOUS WIND TURBINE

Purpose. Development of a two-dimensional field mathematical model of a magnetic gearbox operating as part of a low-power wind turbine for the purpose of evaluating its parameters and characteristics and optimizing geometric parameters from the point of view of electromagnetic torque pulsations.

Methodology. To carry out the research, the methods of the general theory of electromechanical energy converters, numerical methods of mathematical modeling based on the finite element method, numerical solution of nonlinear differential equations, and methods of spectral analysis to estimate pulsations of the electromagnetic torque were used in the work.

Findings. The paper developed a two-dimensional numerical field mathematical model of a magnetic gearbox for an autonomous wind turbine. The model was developed to evaluate the parameters and characteristics of the magnetic gear, as well as to evaluate the influence of the design parameters on the magnitude of the electromagnetic torque and the magnitude of the pulsations of the electromagnetic torque. The effect of the configuration of permanent magnets, the parameters of the ferromagnetic inserts of the magnetic flux modulator and the size of the air gap was investigated in the paper. The obtained results show that there is an optimal configuration of permanent magnets and ferromagnetic elements of the magnetic flux modulator in which the maximum electromagnetic torque and minimum pulsations are achieved. Changing the parameters of the magnetic system affects the dynamics of the magnetic gear, its reliability and efficiency, therefore configuration optimization is an important task in the design, development and implementation of such systems.

Originality. A two-dimensional field mathematical model of the magnetic gear has been developed, which makes it possible to estimate the change in its parameters and characteristics when the geometric dimensions change. This allows investigating the influence of various parameters of the magnetic system, such as the height of the permanent magnets and the width of the ferromagnetic inserts, on the electromagnetic torque. This makes it possible to obtain the optimal configuration of the system to achieve the optimal value of the torque and minimal pulsations and to determine the regularity of the change of the electromagnetic torque and other parameters of the gearbox under different operating modes in the future.

Practical value. The simulation results indicate the prospects of industrial implementation of magnetic gaers as part of a wind power plant, and the obtained research results indicate the possibility of optimizing the design of magnetic gears in order to increase their reliability and efficiency.

Keywords: *magnetic gear, permanent magnets, wind energy, wind-power engineering, electromagnetic torque, torque pulsations*

Introduction. The specific weight and dimensions of electromechanical energy converters (EMCs) largely depend on the rated rotor speed; the higher the speed, the smaller the dimensions. The ability to select the rated speed from a wide range when designing an EMF allows obtaining optimal weight, size, and cost parameters of the electrical installation as a whole [1]. However, the rated speed is often determined not so much by the desire to create an optimal EMF as by the requirements of the mechanical energy consumer, when it is an electric motor or its source in the case of an electric generator. Applications of electric machines, such as automotive, wind power, shipbuilding, oil production, and others, are characterized by low rotational speeds, which are usually only a few tens of revolutions per minute [2, 3]. In such cases, the direct connection of the electric machine shaft to the load becomes too costly from an economic point of view, and in some cases even impossible [4]. For example, in wind energy installations, there is a tendency to increase the installed capacity of a single object, which leads to the refusal of direct drive of the wind turbine generator due to the increase in the size and weight of the generator to levels that complicate the transportation and installation of such installations [5, 6]. Reducing the weight and dimensions of electric machines in such cases is possible only by significantly increasing their rated speed, which leads to the need to use gears. The effectiveness of this approach is due to the fact that the nominal mechanical torque of a gear transmission is more than twice as high as that of a modern synchronous electric machine excited by permanent magnets [2, 7]. This ensures the best weight and dimensions of the high-speed electric machine complex – a reduction gearbox compared to the direct drive system. Mechanical meshing in gear transmissions causes a number of disadvantages, such as low reliability, the need for lubrication and regular maintenance, fire hazard, high noise level, and limited overload capacity. The development of new interacting devices that do not have these disadvantages and at the same time retain the advantages of gears is an important task in the field of electromechanics. One of these devices is a magnetic gearbox, in which torque is transmitted by the interaction of magnetic fields rather than through mechanical engagement [8, 9]. This makes it possible to achieve a non-contact conversion of speed and torque, which, on the other hand, allows magnetic transmissions to get rid of certain disadvantages that are characteristic of their mechanical counterparts and at the same time maintain comparable overall characteristics [10, 11].

In power plants with an installed capacity of several megawatts, such as wind power, the use of magnetic gears instead of reduction gearboxes can be aimed at achieving technical advantages and overcoming the technological difficulties existing in the industry in the production of high-quality large-diameter gears for multi-megawatt class gearboxes [12, 13]. The complex technology of gear production increases the risk of using these devices [14]. At the same time, the production of magnetic gears as electromechanical devices requires the development of advanced technologies in machining and can be carried out on the existing base for the production of electric machines.

Traditional wind turbines with and without a multiplier operate at different points of the mechanical characteristic of the wind turbine rotor when the load and wind speed change [15, 16]. Wind turbines with a multiplier use classical permanent magnet generators with radial main magnetic flux, while systems without a multiplier use electric generators with axial magnetic flux, which have a number of advantages.

In previous studies, the authors investigated wind power plants with a permanent magnet generator of a non-multiplier type [15, 17]. According to the results of these studies, the high efficiency of using magnetization by additional capacitance of the generator armature winding and the use of magnetization by an additional winding of the magnetoelectric generator was revealed. The use of additional capacitance allows increasing the generator output active power by about 7–16 %. And the effect of increasing the generator's active power by magnetizing with an additional winding is approximately 32–35 %.

However, despite the undeniable advantages provided by the use of gears in technical devices, they have a number of disadvantages, such as high noise level, low reliability, the need for lubrication, the need for regular technical inspections, unstable to sudden gusty winds, and low overload capacity [18, 19]. In addition, at wind speeds exceeding 12–14 m/s, special braking devices are required to protect the mechanical gearbox from failure [20, 21].

The use of magnetic gearboxes is promising [22, 23]. They make it possible to abandon the mechanical gearbox in favor of a magnetic gearbox and use a classic high-speed and more compact, cheap, affordable, and easy-to-maintain electric generator on the output shaft of the wind turbine [24, 25].

Summarizing the results of the literature search, it can be concluded that the main purpose of scientific research in this area is to study the parameters and characteristics of magnetic gears used as multipliers/gearboxes or as part of autonomous power plants, such as wind power systems.

Therefore, it is an urgent scientific and practical task to evaluate the parameters and characteristics of a magnetic gearbox at variable wind speeds. This will make it possible to abandon the mechanical gearbox in favor of a magnetic one with a subsequent increase in the operational reliability and efficiency of such a system.

The purpose of this work is to develop a two-dimensional field mathematical model of a magnetic gearbox operating as part of a low-power wind turbine in order to evaluate its parameters and characteristics and optimize geometric parameters in terms of electromagnetic torque fluctuations.

Basic material. A magnetic gear is an EMF that uses the interaction of magnetic fields of permanent magnets to transmit torque between two shafts with different rotational speeds. The interaction of the magnetic fluxes of the permanent magnets of the driving and driven rotors of the magnetic gear occurs in a special structural element – the modulator. The modulator consists of alternately arranged ferromagnetic elements (such as teeth) and non-magnetic inserts.

The design of the magnetic gear studied in this paper is shown in Fig. 1.

In Fig. 1 the following are indicated: *1* – outer rotor; *2* – permanent magnets of the outer rotor; *3* – filling of ferromagnetic elements with a non-magnetically conductive composite; *4* – modulator grooves intended for the location of ferromagnetic elements of the modulator; *5* – inner rotor; *6* – permanent magnets of the inner rotor.

The magnetic gearbox increases the rotational speed from the wind wheel to the electric generator, which increases the efficiency of converting mechanical wind energy into electrical energy.

According to the speed ratio for coaxial planetary magnetic transmission, the gear ratio is defined as [26].

$$i = \frac{p_m + p_i}{p_e}, \tag{1}$$

where p_m is the number of pole pairs on the stator; p_i is the number of pole pairs on the high-speed rotor

$$i = \frac{N_c}{p_i}. \tag{2}$$

The gear ratio is positive, which indicates the directional rotation of the magnetic transmission rotors.

The prototype used was a magnetic transmission variant with 26 pairs of poles on the stator, three pairs of poles on the high-speed rotor, and 29 segments of the low-speed rotor. Thus, according to (1, 2), the gear ratio was 8.67. The main design parameters of the prototype magnetic gear used to develop the mathematical model are shown in Table 1. The permanent magnets are made of sectoral magnets with homogeneous magnetization in the radial direction of the neodymium-iron-boron alloy N38UH with a residual magnetic induction of 1.26 T at 20 °C.

The stator magnetic circuit yoke is made of cold-rolled isotropic electrical steel grade 2,411, and the high-speed rotor magnetic circuit yoke is made of electrical steel grade 21,850. The segments of the low-speed rotor are made of Somaloy-based composite magnetically soft material. The shaft of the high-speed rotor is made of structural steel grade 45.

The main stages of developing a field mathematical model of a magnetic gear are as follows:

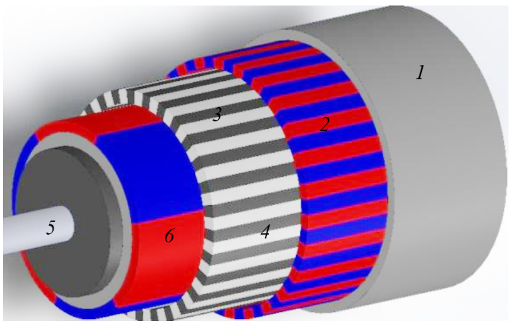

Fig. 1. Design of the studied magnetic gear

Table 1

Main parameters of the magnetic system

No	Parameter	Value
1	Number of pole pairs of the high-speed rotor	3
2	Number of pairs of low-speed rotor poles	26
3	Number of steel segments of the modulator	29
4	Axial length, mm	80
5	Residual magnetic induction of the PM, T	1.26 (N38UH)
6	Gear ratio	8.67
7	Stator magnetic circuit material	Steel 2411
8	Material of the magnetic circuit of the low-speed rotor	Samoloy
9	High-speed rotor magnetic circuit material	Steel 21850
10	Electrical conductivity of permanent magnets, MSm/m	0.56
11	Electrical conductivity of Somaloy, MSm/m	0.14
12	Height of permanent magnets, b_{mag}, mm	22
13	Width of ferromagnetic inserts of the magnetic flux modulator, mm	12
14	Rotation speed of the internal (high-speed) rotor, rpm	1,735
15	Rotation speed of the outer (low-speed) rotor, rpm	200
16	Air gap size, mm	4

1. Development of a geometric model of the magnetic gearbox under study according to the data from Table 1 and its subsequent import into the COMSOL Multiphysics numerical modeling environment.

2. Formation of a system of nonlinear differential equations characterizing the materials of the computational domain of the studied magnetic gear.

3. Determination of the physical properties of the computational domain of the object under study, formulation of the physical problem and boundary conditions.

4. Formation of a finite element mesh of the design area and, if necessary, optimization of its parameters.

5. Conducting a series of numerical calculations.

6. Processing and analysis of the results.

The software package used in this work implements the finite element method and is designed to simulate various physical and engineering processes. The modeling of the static characteristics of magnetic transmissions is performed in a two-dimensional approximation, taking into account the following simplifications and assumptions:

1. The axial length of the magnetic gear is taken into account empirically, i. e., longitudinal end effects are not taken into account.

2. The phenomenon of magnetic hysteresis is not taken into account, and the properties of electrical steel are determined using the basic magnetization curve.

3. Since it is a difficult technical task to take into account the full magnetization and demagnetization curve of permanent magnets, their properties were determined only by the residual magnetic induction and coercive force.

4. Within the computational domain, the magnetic induction vector was assumed to be tangent to any point.

The distribution of the electromagnetic field in the computational domain of the studied gearbox is described by equations and boundary conditions with respect to the vector magnetic potential and known sources of the magnetic field

$$\nabla^2 A = \mu\nabla \cdot M;$$

$$n \cdot (A_1 - A_2) = 0;$$

$$n \cdot ([\mu_0^{-1}\nabla \cdot A - M] - [\mu_0^{-1}\nabla \cdot A - M]);$$

$$n \cdot A_{in} = 0,$$

where A is the vector magnetic potential, Vb/m; M is the magnetization vector, A/m; A_{in} is the vector magnetic potential at the outer boundary of the computational domain, Vb/m; A_1, A_2 are the vector magnetic potentials at the boundary of adjacent domains 1 and 2, Vb/m; n is the normal vector.

To calculate the electromagnetic torque, the Maxwell's magnetic tension tensor is used, which has proven to be a reliable method for determining this kind of force. The magnitude of the force acting on the inner and outer rotor of the magnetic gear was determined by the following equation

$$f = \mu((nH)H - 0.5nH^2),$$

where H is the magnetic field strength, A/m.

$$H = \mu^{-1}\nabla \cdot A - M.$$

The total electromagnetic torque is the result of integrating the electromagnetic forces acting on the inner and outer rotors of the magnetic gear, calculated as follows

$$T = \int_{S_g} (r - r) \cdot f dS, \tag{3}$$

where S_g is the area of integration, which is the area of the circle bounding the outer and inner rotors of the gearbox; f is the distribution of electromagnetic force on the surface of the studied magnetic gearbox rotor.

The total number of finite element mesh elements in the computational domain of the developed two-dimensional model is 296,840 triangular elements, 880 vertex elements, and 62,661 edge elements. A general view of a fragment of the finite element mesh of the developed model of the magnetic gear is shown in Fig. 2.

The distribution of magnetic induction B and vector magnetic potential A in the computational domain of the studied magnetic gear is shown in Fig. 3.

Fig. 3 shows that the magnetic system is not saturated, while the average value of magnetic induction in the structural elements of the gearbox does not exceed the permissible values for the selected materials and steel grade. Namely: in the yoke of the high-speed rotor, the average magnetic induction value is 0.91 T; in the yoke of the low-speed rotor, the average magnetic induction value is 0.47 T; in the ferromagnetic cores of the magnetic flux modulator, the average magnetic induction value is 0.94 T, the average induction value in the air gap bordering the high-speed rotor and the modulator is 0.75 T, the average induction value in the air gap bordering the low-speed rotor and the modulator is 0.63 T.

The time dependence of the electromagnetic torque of the inner and outer rotors of a magnetic reducer at a constant speed of rotation of the inner and outer rotors is shown in Fig. 4.

Fig. 4 shows that the average value of the electromagnetic torque of the outer (high-speed) rotor is ≈7.4 N · m, while the

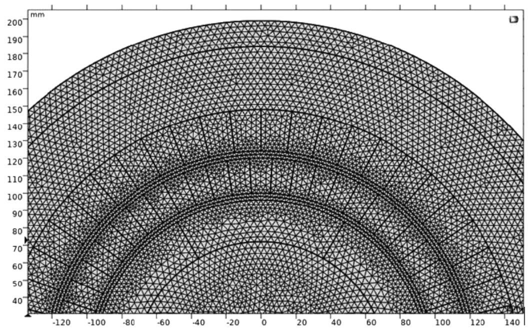

Fig. 2. Finite element mesh of a fragment of the computational domain of the investigated magnetic gear

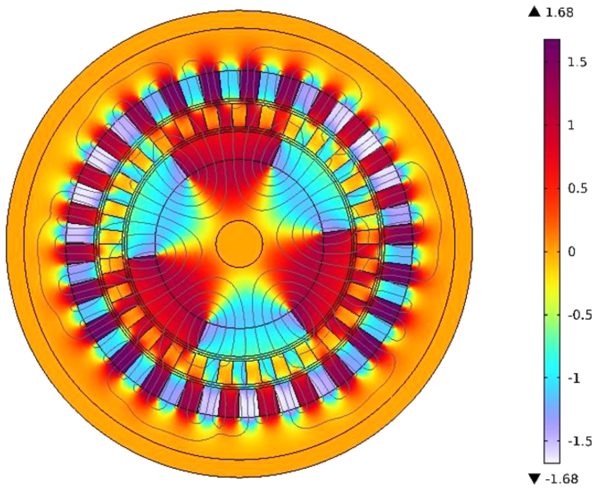

Fig. 3. Distribution of magnetic induction and vector magnetic potential of the studied magnetic gear

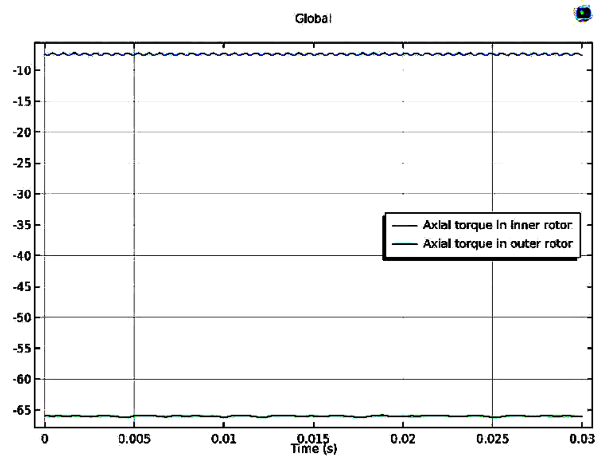

Fig. 4. Time dependence of the electromagnetic torque of the inner and outer rotors

value of the electromagnetic torque for the outer rotor is ≈66 N · m. The ratio of the torques of the outer and inner rotors is 8.67, which correlates with the reduction ratio of the studied gearbox (Table 1).

Electromagnetic torque fluctuations are one of the operational disadvantages that occur during the operation of a magnetic reducer, as they lead to an increase in noise and vibration levels, and negatively affect the service life of the bearings, reduce operational reliability, and when operating on an electric generator are a source of distortion of the shape of the output EMF curve. The source of electromagnetic torque pulsations is the interaction of permanent magnets of the rotor with ferromagnetic elements of the magnetic modulator

$$k_p = \frac{2 \cdot p_1 \cdot n}{N_s},$$

where p_1 is the number of pairs of poles of the high-speed rotor of the magnetic reducer; n is the number of ferromagnetic elements of the magnetic flux modulator; N_s is the least common multiple between the number of poles of the high-speed rotor and the number of ferromagnetic elements of the magnetic flux modulator.

Investigating the influence of the configuration and design parameters of a magnetic reducer on the magnitude of electromagnetic torque fluctuations is an urgent scientific and practical task. The following parameters affect the magnitude of pulsations: the configuration and number of permanent magnets on the rotor, the configuration and number of ferromagnetic modulators, and the size of the air gap.

Results of studying the electromagnetic torque when changing the configuration of permanent magnets and a ferromagnetic modulator. The estimate of the electromagnetic torque value is determined by expression (3), the magnitude of the torque fluctuations is determined by expanding $M_{em}(t)$ into a Fourier series and analyzing the corresponding harmonic. It is obvious that the main torque fluctuations are directly proportional to the rotational speed of the inner rotor and the number of elements of the ferromagnetic modulator. The decomposition of the torque curve for the inner rotor is as shown in Fig. 5.

The zero frequency corresponds to the average value of the electromagnetic torque for a high-speed rotor and is ≈7.4 N · m, the harmonic value at a frequency of 1,675 Hz is 0.113 N · m and is directly proportional to the product of the inner rotor rotation speed and the number of magnetic flux modulator elements.

In this study, the height of the permanent magnets was changed with the configuration of the steel elements of the magnetic modulator unchanged and with the width of the magnetic inserts of the ferromagnetic modulator changed in the range of 50, 100 and 200 % of the base value (Table 1) in order to study the electromagnetic torque fluctuations and its average value.

The results of calculating the electromagnetic torque for the inner rotor of a magnetic reducer are shown in Table 2.

Fig. 6 shows the dependence of the electromagnetic torque on the height of the permanent magnets and when the width of the ferromagnetic inserts of the magnetic modulator is changed.

The curves in Fig. 6 correspond to a change in the width of the ferromagnetic inserts of the magnetic modulator relative to the base width (shown in Table 1) by 50, 100 and 200 %.

According to the results obtained from Fig. 6, it can be concluded that with a decrease in the height of permanent magnets, the value of electromagnetic torque decreases, which is explained by a decrease in the energy of permanent magnets, and hence the electromagnetic force. At the same time, with an increase in the height of the permanent magnet, the expected value of the electromagnetic torque should increase; however, the relative magnetic permeability of the permanent magnet material is μ_{mag} ≈1.05 and an increase in the height of the permanent magnets leads to an increase in the equivalent air gap, an increase in the magnetic flux of the magnetic circuit, and a decrease in the level of magnetic induction. Therefore, Fig. 6 shows that with an increase in the height of permanent magnets, the electromagnetic torque increases by ≈10–15 %.

When the width of the ferromagnetic inserts was reduced, their number remained unchanged. This also leads to a de-

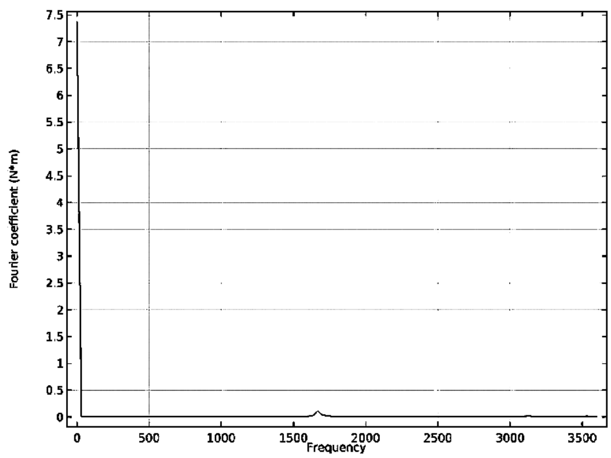

Fig. 5. Decomposition of the electromagnetic torque curve into a spectrum

Table 2

Results of the torque calculation on the inner rotor from the width value ferromagnetic insert when changing the thickness of magnets

50 %	0.75	1.24	2.7	4.5	5.1	5.75
100 %	1.3	3.54	5.7	7.4	7.92	8.5
200 %	1.11	2.93	4.8	6.142	6.78	8.04
b_{mag}, mm	5	10	15	22	30	40

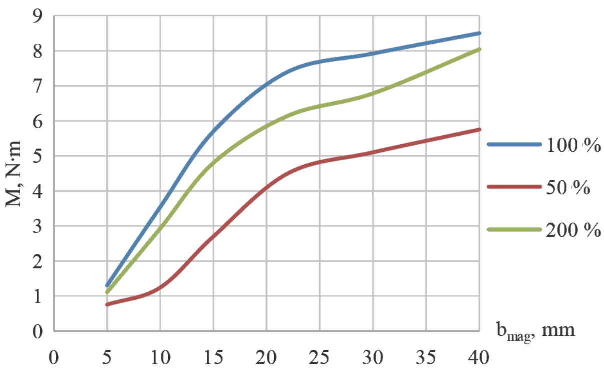

Fig. 6. Dependence of the inner rotor torque on the width of the ferromagnetic insert when changing the height of the magnets

crease in the electromagnetic torque, which is explained by their saturation and, accordingly, an increase in the size of the equivalent air gap. When the width of the ferromagnetic inserts increases, the distance between them decreases (since the radius remains unchanged), part of the magnetic flux begins to be tongue and groove between adjacent ferromagnetic inserts, and this also leads to a decrease in the electromagnetic torque.

Therefore, it can be concluded that there is an optimal width of ferromagnetic inserts and an optimal height of permanent magnets at a constant air gap and overall geometric dimensions. This reduces electromagnetic noise and vibrations, increases bearing life, and reduces losses in the electrically conductive elements of the magnetic gearbox (ferromagnetic elements of the modulator, electrical steels).

Changing the configuration of permanent magnets and the width of the ferromagnetic elements of the magnetic modulator also affects the magnitude of the electromagnetic torque fluctuations. Fig. 7 shows the dependence of the electromagnetic torque for a high-speed rotor on time at a permanent magnet width b_{mag} = 22 mm and the number of ferromagnetic elements 29.

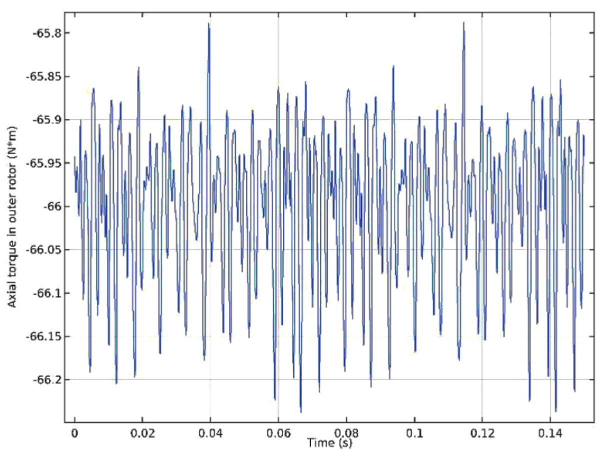

Fig. 7. Dependence of the internal rotor torque on time

The pulsations shown in Fig. 7 are caused by the discreteness of the magnetic modulator in interaction with the permanent magnets of the inner rotor. Table 3 shows the dependence of the electromagnetic torque ripple coefficient corresponding to the torque ripple frequency on the ferromagnetic inserts of the modulator and permanent magnets at a constant rotational speed of the magnetic gearbox rotors.

Fig. 8 shows the character of the change in the electromagnetic torque ripple coefficient depending on the height of permanent magnets and when the width of ferromagnetic inserts of the magnetic modulator changes.

The curves in Fig. 8 correspond to a change in the width of the ferromagnetic inserts of the magnetic modulator relative to the base width by 50, 100 and 200 %.

It is obvious that the smallest value of electromagnetic torque fluctuations is observed with an increase in the width of ferromagnetic modulators. This is due to the reduction of the internal boring of the magnetic modulator and, accordingly, the reduction of torque fluctuations. This is one of the effective methods to combat the radial end effects inherent in this class of EMFs. However, with an increase in the width of the ferromagnetic inserts, the magnitude of the electromagnetic torque decreases (Fig. 6) relative to the base width of the ferromagnetic elements of the magnetic modulator.

At the same time, with the increase in the height of permanent magnets, there is a tendency to reduce the electromagnetic torque fluctuations. This is due to an increase in the value of the equivalent air gap (due to an increase in the height of the permanent magnets) and a corresponding increase in the MPF for the "tooth" harmonics of the magnetic modulator. Further increase in the height of permanent magnets (over 35 mm) leads to an increase in torque ripples, since the induction in the air gap increases due to the increase in the volume and energy of permanent magnets.

When the width of the ferromagnetic inserts of the modulator is 50 % of the base width and the height of the permanent magnets is reduced, the magnitude of the electromagnetic torque fluctuations is obviously the largest and reaches ≈16 %

Table 3

Electromagnetic torque ripple coefficient

50 %	16.533	12.419	6.4814	4.3777	4.176	4.33
100 %	3.6153	1.8361	1.3859	1.5270	1.477	2.517
200 %	0.9909	0.5802	0.4375	0.390	0.398	0.398
b_{mag}, mm	5	10	15	22	30	40

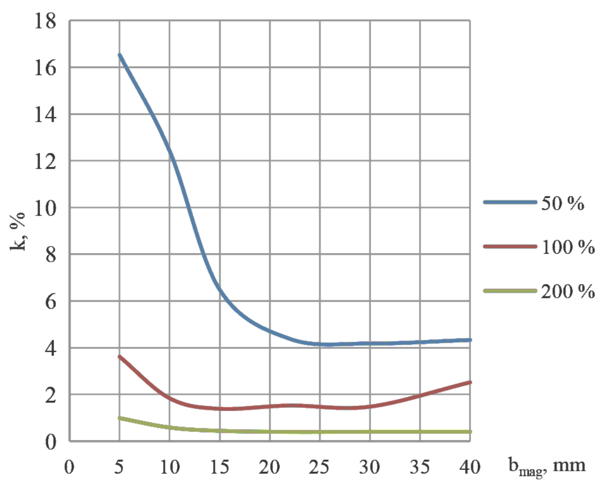

Fig. 8. Dependence of the electromagnetic torque ripple coefficient

of the average (effective) torque. As the height of the permanent magnets decreases, the size of the air gap decreases, the magnetic flux of the magnetic circuit decreases, and the influence of the ferromagnetic modulator's discreteness increases (Fig. 9).

The upper curve (Fig. 9) corresponds to the electromagnetic torque of the inner (high-speed) rotor, and the lower curve to the torque of the outer (low-speed) rotor at a minimum height of permanent magnets b_{mag} = 5 mm and a minimum width of the ferromagnetic insert of 6 mm.

In addition, as the height of permanent magnets decreases, the effective value of the electromagnetic torque decreases with the simultaneous appearance of harmonics in the torque spectrum, the effect of which begins to manifest itself at a significant decrease in the equivalent air gap. The decomposition of the moment distribution curve for the inner rotor (Fig. 9) is shown in Fig. 10.

Fig. 10 shows that with a decrease in the size of the air gap, other harmonics of the electromagnetic moment begin to appear, which do not appear with an increase in the air gap, including the equivalent one.

From this it can be concluded that, depending on the configuration of the magnetic system of the magnetic reducer, there is an optimal configuration of permanent magnets and ferromagnetic inserts at which higher harmonics are minimized.

The results of the study of electromagnetic torque when the size of the air gap changes. Magnetic gearboxes are characterized by significant electromagnetic attraction forces and electromagnetic torque fluctuations. For this purpose, when designing magnetic reducers, a larger value of the air gap between the inner and outer rotor and the fixed magnetic modulator is chosen compared to classical electric machines. In the studied prototype of the magnetic reducer, the nominal value of the air gap δ = 4 mm was chosen. The paper investigates the dependence of the electromagnetic torque of the inner and outer rotors on the size of the air gap and analyzes the effect of the gap size on the pulsation coefficient. Fig. 11 shows the dependence of the obtained torque values on the size of the air gap.

Obviously, when the air gap decreases, the resistance to magnetic flux decreases, the magnetic flux of the magnetic circuit increases, which leads to an increase in electromagnetic torque. Reducing the air gap by a factor of 2 leads to an increase in torque of ≈55 %, while increasing the air gap by 2 mm leads to a decrease in torque by ≈3 %. The distribution of electromagnetic torque for the inner and outer rotors of the studied gearbox at δ = 3 mm is shown in Fig. 12.

Another criterion that changes when the air gap changes is the magnitude of torque fluctuations. The dependence of the rotating harmonic, a multiple of the number of steel elements of the magnetic modulator and the rotor speed, when the air gap changes is shown in Fig. 13.

Fig. 13 shows that the smaller the air gap, the greater the magnitude of electromagnetic torque fluctuations. However, a further increase in the size of the air gap (>5 mm) no longer leads to a significant reduction in torque fluctuations, but at the same time, the value of the useful electromagnetic torque decreases.

Conclusions. The study of magnetic gearboxes for their use in wind power systems is of great scientific and practical value due to the growing interest in renewable energy sources and autonomous power plants.

In this paper, a two-dimensional field mathematical model of a magnetic reducer is developed that allows estimating the electromagnetic torque and pulsation when parameters such

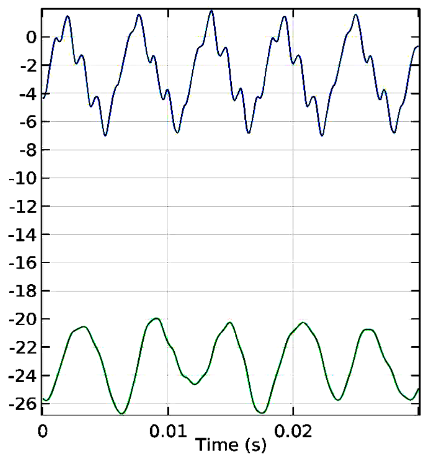

Fig. 9. Dependence of the inner and outer rotor torque on time at b_{mag} = 5 mm

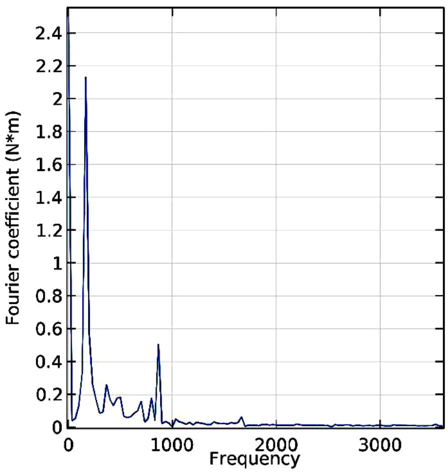

Fig. 10. Fourier expansion of the moment distribution curve for the inner rotor

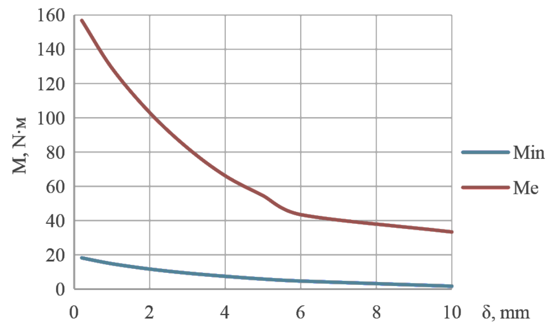

Fig. 11. Torque dependence on air gap

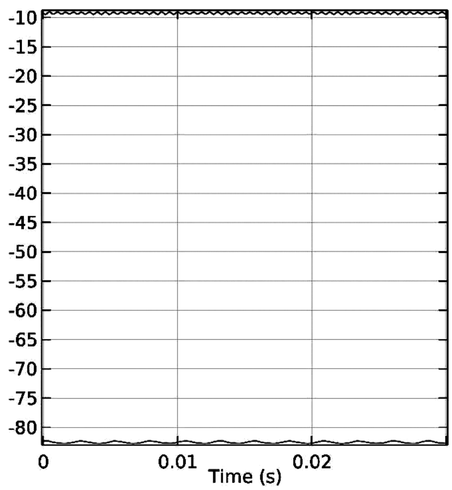

Fig. 12. Dependence of torque on air gap

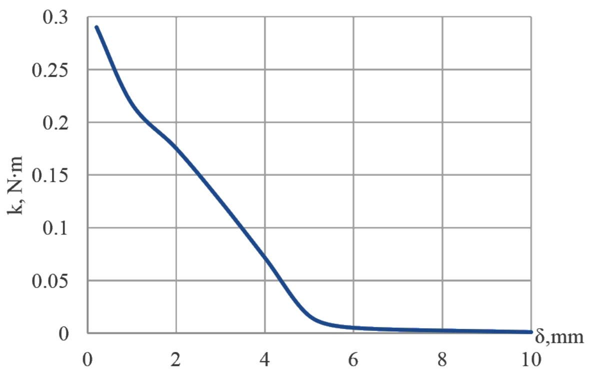

Fig. 13. Dependence of the electromagnetic torque fluctuation coefficient at $\delta = var$

as the height of permanent magnets, the width of ferromagnetic inserts of the magnetic flux modulator, and the size of the air gap are changed.

The optimal configuration of permanent magnets and ferromagnetic elements of the modulator was obtained to achieve maximum efficiency and reduce electromagnetic torque fluctuations. When the height of permanent magnets is reduced by 2.2 times, the torque value decreases by ≈2 times, while the electromagnetic torque fluctuations increase by 30 %. Reducing the air gap by a factor of 2 leads to an increase in torque of ≈55 %, while increasing the air gap by 2 mm leads to a decrease in torque by ≈35 %.

The research results provide practical recommendations for the design of magnetic gearboxes to improve efficiency, reliability, and reduce electromagnetic torque fluctuations.

It was found that there is an optimal value of the air gap at which the electromagnetic torque fluctuations are reduced and the manifestation of higher harmonics of electromagnetic torque fluctuations is minimal.

The obtained results allow us to improve the design of magnetic gearboxes, ensure optimal parameters and improve their functional characteristics, which can positively affect the development of wind power systems.

References.

1. Golovko, V., Ostroverkhov, M., Kovalenko, M., Kovalenko, I., & Tsyplenkov, D. (2022). Mathematical simulation of autonomous wind electric installation with magnetoelectric generator. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 74-79. https://doi.org/10.33271/nvngu/2022-5/074.

2. Chumack, V., Bazenov, V., Tymoshchuk, O., Kovalenko, M., Tsyvinskyi, S., Kovalenko, I., & Tkachuk, I. (2021). Voltage stabilization of a controlled autonomous magnetoelectric generator with a magnetic shunt and permanent magnet excitation. *Eastern-European Journal of Enterprise Technologies, 6*(5(114), 56-62. https://doi.org/10.15587/1729-4061.2021.246601.

3. Ostroverkhov, M., Chumack, V., Kovalenko, M., & Kovalenko, I. (2022). Development of the control system for taking off the maximum power of an autonomous wind plant with a synchronous magnetoelectric generator. *Eastern-European Journal of Enterprise Technologies*, *4*(2(118), 67-78. https://doi.org/10.15587/1729-4061.2022.263432.

4. Beshta, O.O., Beshta, O.S., Beshta, D., Tkachenko, S., Khalaimov, T., & Skliar, D. (2023). Technologies for Increasing the Energy Efficiency of Electric Vehicles. *IEEE 5th International Conference on Modern Electrical and Energy System (MEES)*, 1-5. https://doi.org/10.1109/MEES61502.2023.10402470.

5. Jian, H., Yao, L., Li, W.-J., & Zhang, J. (2017). Design and realization of a novel magnetic nutation drive for industry robotic wrist reducer. *Industrial Robot: An International Journal*, *44*, 58-63. https://doi.org/10.1108/IR-04-2016-0130.

6. Yu, W., Wang, C., & Xu, T. (2019). The design method of a novel magnetic suction gear reducer. *IOP Conference Series: Materials Science and Engineering*, *504*, 012093. https://doi.org/10.1088/1757-899X/504/1/012093.

7. Hasanpour, S., Johnson, M., Gardner, M., & Toliyat, H. (2022). Cycloidal Reluctance Magnetic Gears for High Gear Ratio Applications. *IEEE Transactions on Magnetics*, *58*(6), 1-10, 8001210. https://doi.org/10.1109/TMAG.2022.3163419.

8. Gardner, M., Praslicka, B., Johnson, M., & Toliyat, H. (2021). Optimization of Coaxial Magnetic Gear Design and Magnet Material Grade at Different Temperatures and Gear Ratios. *IEEE Transactions on Energy Conversion*, *36*(3), 2493-2501. https://doi.org/10.1109/TEC.2021.3054806.

9. Dai, B., Nakamura, K., Suzuki, Y., Tachiya, Y., & Kuritani, K. (2022). Cogging Torque Reduction of Integer Gear Ratio Axial-Flux Magnetic Gear for Wind-Power Generation Application by Using Two New Types of Pole Pieces. *IEEE Transactions on Magnetics*, *58*(8), 1-5, 8002205. https://doi.org/10.1109/TMAG.2022.3159002.

10. Chumak, V., Ostrovierkhov, M., Kovalenko, M., Holovko, V., & Kovalenko, I. (2022). Correction of the output power of the generator of the multiplierless wind power plant at discrete and random values of the wind speed. *Bulletin of NTU "KhPI". Series: Problems of improvement of electric machines and devices. Theory and practice, 2*(8), 39-46. https://doi.org/10.20998/2079-3944.2022.2.07.

11. Chumak, V., Kovalenko, M., Tkachuk, I., & Kovalenko, I. (2022). Comparison of synchronous generators for an autonomous gasoline installation. *Bulletin of NTU "KhPI". Series: Problems of improvement of electric machines and devices. Theory and practice*, *2*(8), 32-38. https://doi.org/10.20998/2079-3944.2022.2.06.

12. Moghimi, A., Aliabadi, M., & Farahani, H. (2022). Triple-speed coaxial magnetic gear for wind turbine applications: introduction and comprehensive analysis. *COMPEL – The international journal for computation and mathematics in electrical and electronic engineering*, *41*(4). https://doi.org/10.1108/Compel-01-2022-0001.

13. Aiso, K., Akatsu, K., & Aoyama, Y. (2021). A Novel Flux-Switching Magnetic Gear for High-Speed Motor Drive System. *IEEE Transactions on Industrial Electronics*, *68*(6), 4727-4736. https://doi.org/10.1109/TIE.2020.2988230.

14. Ruiz-Ponce, G., Arjona, M., Hernandez, C., & Escarela-Perez, R. (2023). A Review of Magnetic Gear Technologies Used in Mechanical Power Transmission. *Energies*, *16*, 1721. https://doi.org/10.3390/en16041721.

15. Wang, Y., Filippini, M., Bianchi, N., & Alotto, P. (2019). A Review on Magnetic Gears: Topologies, Computational Models, and Design Aspects. *IEEE Transactions on Industry Applications*, *55*(5), 4557-4566. https://doi.org/10.1109/TIA.2019.2916765.

16. Nielsen, S., Wong, H., Baninajar, H., Bird, J., & Rasmussen, P. (2022). Pole and Segment Combination in Concentric Magnetic Gears: Vibrations and Acoustic Signature. *IEEE Transactions on Energy Conversion*, *37*(3), 1644-1654. https://doi.org/10.1109/TEC.2022.3151654.

17. Ding, J., Yao, L., Xie, Z., Wang, Z., & Chen, G. (2022). A Novel 3-D Mathematical Modeling Method on the Magnetic Field in Nutation Magnetic Gear. *IEEE Transactions on Magnetics*, *58*(5), 1-10. https://doi.org/10.1109/TMAG.2022.3158973.

18. Syam, S., Kurniati, S., & Ramang, R. (2022). *Design and Characteristics of Axial Magnetic Gear Using Rectangular. Magnet*. https://doi.org/10.31219/osf.io/5c724.

19. Mizuana Yuma, Nakamura Kenji, Suzuki Yuma, Oishi Yuhei, Tachiya Yuichi & Kuritani Kingo (2020). Development of spoke-type IPM magnetic gear. *International Journal of Applied Electromagnetics and Mechanics, 64*, 771-778. https://doi.org/10.3233/JAE-209389.

20. Cansiz, A., & Akyerden, E. (2019). The use of high temperature superconductor bulk in a coaxial magnetic gear. *Cryogenics*. https://doi.org/98.10.1016/j.cryogenics.2019.01.008.

21. Tzouganakis, P., Gakos, V., Kalligeros, C., Papalexis, C., Tsolakis, A., & Spitas, V. (2022). Torque ripple investigation in coaxial magnetic gears. MATEC *Web of Conferences, 366*. https://doi.org/01004.10.1051/matecconf/202236601004.

22. Misron, N., Mohd Saini, L., Aris, I., Vaithilingam, C.A., & Tsuyoshi, H. (2020). Simplified Design of Magnetic Gear by Considering the Maximum Transmission Torque Line. *Applied Sciences*. https://doi.org/10.3390/app10238581.

23. Ishikawa, S., & Todaka, T. (2020). Transient-operation phenomena of a magnetic reducer analyzed with the time-stepping FEM. *23rd International Conference on Electrical Machines and Systems*, 1898-1901. https://doi.org/10.23919/ICEMS50442.2020.9291208.

24. Tzouganakis, P., Gakos, V., Kalligeros, C., Tsolakis, A., & Spitas, V. (2022). Fast and efficient simulation of the dynamical response of coaxial magnetic gears through direct analytical torque modelling. *Simulation Modelling Practice and Theory, 123*. https://doi.org/10.1016/j.simpat.2022.102699.

25. Kastawan, I., & Rusmana (2016). Pengujian pembangkitan tegangan generator axial-flux permanent magnet (AFPM) tiga-fasa ganda. *Jurnal Teknik Energi*, *6*, 503-509. https://doi.org/10.35313/energi.v6i2.1713.

26. Asfirane, S., Hlioui, S., Amara, Y., & Gabsi, M. (2019). Study of a Hybrid Excitation Synchronous Machine: Modeling and Experimental Validation. *Mathematical and Computational Applications, 24*(2), 34. https://doi.org/10.3390/mca24020034.

Математичне моделювання магнітного редуктора для автономної вітроустановки

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Мета. Розробка двовимірної польової математичної моделі магнітного редуктора, що працює у складі вітроустановки малої потужності, з метою оцінки його параметрів і характеристик та оптимізації геометричних параметрів з точки зору пульсацій електромагнітного моменту.

Методика. Для проведення дослідження в роботі використовувались методи загальної теорії електромеханічних перетворювачів енергії, чисельні методи математичного моделювання, в основі яких лежить метод скінченних елементів, чисельне розв'язання нелінійних диференційних рівнянь і методи спектрального аналізу для оцінки пульсацій електромагнітного моменту.

Результати. У роботі розроблена двовимірна чисельна польова математична модель магнітного редуктора для автономної вітроустановки. Модель розроблена для оцінки параметрів і характеристик магнітного редуктора, а також для оцінки впливу конструктивних параметрів на величину електромагнітного моменту й величину пульсацій електромагнітного моменту. У роботі досліджено вплив конфігурації постійних магнітів, параметрів феромагнітних вставок модулятора магнітного потоку й величини повітряного проміжку. Отримані результати показують, що існує оптимальна конфігурація постійних магнітів і феромагнітних елементів модулятора магнітного потоку, за яких досягається максимальний електромагнітний момент і мінімальні пульсації. Зміна параметрів магнітної системи впливає на динаміку магнітного редуктора, його надійність і ефективність, тому оптимізація конфігурації є важливою задачею при проєктуванні, розробці та впровадженні таких систем.

Наукова новизна. Розроблена двовимірна польова математична модель магнітного редуктора, що дозволяє оцінити зміну його параметрів і характеристик при зміні геометричних розмірів. Це дозволяє дослідити вплив різних параметрів магнітної системи, таких як висота постійних магнітів і ширина феромагнітних вставок, на електромагнітний момент. Це дає можливість отримати оптимальну конфігурацію системи для досягнення оптимального значення моменту й мінімальних пульсацій та визначити закономірність зміни електромагнітного моменту та інших параметрів редуктора за різних режимів роботи в подальшому.

Практична значимість. Результати моделювання свідчать про перспективність промислової реалізації магнітних редукторів у складі вітроелектричної установки, а отримані результати дослідження вказують на можливість оптимізації конструкції магнітних редукторів з метою підвищення їх надійності та ефективності.

Ключові слова: *магнітний редуктор, постійні магніти, вітроенергетика, електромагнітний момент, пульсації моменту*

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