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CONSTRUCTION OF THE MATHEMATICAL MODEL OF MAGNETIC TRANSMISSION FOR AN AUTONOMOUS WIND POWER PLANT

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The object of research is electromagnetic and mechanical processes in magnetic transmission for an autonomous wind power plant of small power.

The use of magnetic transmission as part of an autonomous wind power plant makes it possible to improve the reliability and efficiency of such a system.

In the current work, a study of magnetic transmission as part of an autonomous wind power plant was carried out to investigate the parameters and characteristics of magnetic transmission.

This paper reports the construction of a numerical simulation mathematical model of a magnetic reducer operating as part of an autonomous wind power plant with a permanent magnet generator. The model takes into account discrete structure of internal and external rotors and modulator; changes in model parameters when input parameters change. It also takes into account losses, change of load angle and electromagnetic moment; the effect of changing the generator load.

The built model of the magnetic reducer system differs in that the change in the generator load leads to a shift of the operating point on the mechanical characteristics of the rotor of the wind power plant (WPP). The model also works in the opposite direction: changes in wind parameters affect power, voltage, current, and electromagnetic moment.

With the help of the model built, the parameters and characteristics of not only the magnetic reducer but also other components of the system were investigated. The efficiency at the output of the electric generator was determined, which is ≈75 % at a load of 2.0 kW. The magnetic transmission moment at a wind speed of 7.8 m/s for the high-speed rotor is 0.91 N·m, and the low-speed rotor is 7.8 N·m, which corresponds to a transmission ratio of 8.6. This expands opportunities for exploratory research

Keywords: magnetic transmission, mathematical modeling, simulation modeling, permanent magnets, electromechanical system

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1. Introduction

Magnetic transmissions (multipliers) are a separate class of electromechanical energy converters with permanent magnets. Designing this class of converters became possible owing to the increase in power and the development of new types of highly coercive permanent magnets. Magnetic transmissions [1] are used in mechanisms and devices characterized by a low speed of rotation: wind energy, automobile construction, shipbuilding, oil production, chemical and food industry, etc. These mechanisms are characterized by a low rotation frequency. The frequency of rotation of the shaft of the working mechanism can be tens of revolutions per minute.

The use of magnetic transmissions for autonomous wind power plants appears promising, especially considering that over the last decades (from 2001 to 2023), the share of power from wind generation increased by almost 75 times. Traditional wind turbines use a mechanical reducer to transmit torque [2]. This device converts the low rotation speed of the wind generator blades into the high rotation speed of the generator shaft. However, manual transmissions have their drawbacks, including low reliability. They consist of rotating gears, between which all the torque is transmitted through the point contact of the teeth, which leads to significant friction. This requires regular lubrication and maintenance, which increases operating costs. As the temperature drops, the fluid lubricant becomes thicker in manual transmissions and the gear metal becomes more brittle, greatly limiting the efficiency of wind turbines, especially in cold climates. In addition, the production of large gears increases the cost of the reducer, operating costs, weight, and reduces its reliability. It is advisable to use wind turbines when the average annual wind speed exceeds 4–5 m/s. At lower wind speeds, it is advisable to use special systems for converting low-potential mechanical energy into electrical energy.

The use of a multiplierless design of wind turbines [3] with a direct connection of the generator shaft to the wind turbine rotor is costly from an economic point of view, as well as impractical or impossible from a technical point of view. Such a design leads to an excessive increase in the size of the generator, its cost, weight, and reduced reliability, as well as possible problems with transportation and installation of such a generator.

One of the options for solving this problem is to reduce the dimensions of electric machines, which leads to an increase in their rated speed. However, this requires the use of gears. The effectiveness of this approach is due to the fact that the rated mechanical moment of the gear transmission is much higher than in modern synchronous electric machines with permanent magnets. This gives the best overall performance for high-speed electric machines compared to a direct drive system.

Mechanical coupling in gears has its disadvantages, such as low reliability, need for lubrication and maintenance, fire hazard, high noise level, and limited overload capacity. The share of failures of wind turbines due to failure of the mechanical system is about 15–25 %, depending on the power of the system. Designing new devices that would eliminate these shortcomings while preserving the advantages of transmissions is an important task in the field of electromechanics. One such device that helps solve this technical problem is a magnetic transmission, in which the torque is transmitted not by mechanical engagement but by the interaction of magnetic fields [4]. This makes it possible to achieve non-contact conversion of speed and torque, while eliminating some of the disadvantages inherent in their mechanical counterparts, while maintaining overall dimensions [5].

To evaluate the efficiency of the rotor-magnetic reducer-electric generator system and take into account dynamic modes of operation, it is necessary to build a numerical simulation mathematical model with further analysis of various modes of operation of the system when the wind speed changes.

Therefore, an urgent scientific and technical task is the construction of a numerical simulation mathematical model of a magnetic reducer that works as part of an autonomous wind turbine with a classical permanent magnet generator and a radial magnetic flux.

2. Literature review and problem statement

Most works on numerical simulation modeling of magnetic transmissions consider mathematical modeling using numerical field mathematical models using the finite element method. In [6], the authors optimize the design of the coaxial magnetic reducer and the brand of magnet material at different temperatures and gear ratios. It is known that when the temperature changes, the properties of permanent magnets change and, therefore, the properties of magnetic transmission. The model built makes it possible to determine the characteristics when the temperature changes but does not fully take into account a change in the demagnetization curve of permanent magnets.

The authors of [7] conducted a study on reducing the torque of the gear transmission of the integer gear ratio of the axial flux of the magnetic reducer for wind power plants with the help of two new types of pole tips. However, the design of the magnetic conductor with an axial magnetic flux has significant disadvantages associated with axial uncompensated electromagnetic forces. This significantly limits their use. In addition, the work lacks an analysis of the physical processes occurring in the ferromagnetic core at different rotation frequencies.

A three-speed coaxial magnetic reducer for wind turbine applications: an introduction and a comprehensive analysis were investigated by the authors of [8]. The principle of construction of a three-speed magnetic transmission is presented, its parameters and characteristics are analyzed. However, in order to evaluate the behavior of the hysteresis loop at different rotational speeds, additional studies are needed.

Other studies of magnetic transmissions are being conducted for high-speed drive systems. In [9], the authors report their research into a new magnetic reducer with flux switching for the drive system of a high-speed motor. In the work, appropriate mathematical models were built for the study of processes in magnetic transmissions at high frequency of operation. Experimental studies were conducted to confirm the adequacy of the results. In the cited work, there are no models and methods of research of dynamic modes of operation of magnetic gears.

Numerous powerful studies consider the analysis of topologies of magnetic transmissions for various fields of application. In paper [11], the authors study magnetic transmission technologies used in mechanical energy transmission. In the work, the use of magnetic transmissions of powerful complexes was analyzed using numerical modeling methods. It is shown that the influence of the magnetic core configuration on losses in steel can be much greater for this application. The work does not evaluate the calculation error and compare the effectiveness of each type of magnetic transmission.

The authors of [10] consider a dynamic model of a coaxial magnetic reducer implemented in MATLAB. The model is based on linearized systems of differential equations. However, this model is designed with the assumption that the drive motor is a source of ideal mechanical torque, which limits its use to static modes only. With a constant change in the speed of rotation of the drive shaft of the magnetic reducer, which is characteristic of wind generators, and the variable nature of the wind speed, the use of the constructed model is ineffective.

In [11], the authors consider a two-stage magnetic transmission with precession of the axis of rotation. It is obvious that the authors combine the results of numerical field mathematical modeling with the tools of the MATLAB-Simulink software package. However, the fluctuations of the electromagnetic moment, which naturally occur during the operation of the magnetic reducer, are taken into account in the developed model by an additional module. This is a certain limitation since the amplitude and frequency of these oscillations will change when the speed and load of the drive rotor of the reducer change.

Designing magnetic transmissions is an urgent scientific and practical task. In [12], the authors consider the design and characteristics of an axial magnetic transmission using a rectangular magnet. The rectangular shape of permanent magnets makes it possible to significantly reduce the cost of manufacturing a magnetic transmission. To calculate the efficiency, the loss curves in the magnetic material at different frequencies and for different values of the peak flux densities are used. This data is important for the analysis, design, and evaluation of the effectiveness of this technical solution. There is no analysis in the work of the processes in the active zone in which uncompensated forces, pulsations occur, and their influence on the magnetic transmission characteristics.

In [11], the authors analyzed the dynamics of two-stage magnet-precessional transmission. The authors investigated the dynamic properties of magnetic transmission under a gear mode using field methods. The load in this case is a high-speed electric generator with permanent magnets. This solution makes it possible to reduce the dimensions of the generator and the dimensions of the system as a whole. However, numerical field methods are completely insensitive to the source of mechanical energy and load.

Work [13] considers the modeling of a six-speed magnetic transmission as part of a car transmission. Magnetic transmission is simulated by solving a system of differential equations in MATLAB. As a result, the model built makes it possible to control the transmission power from the drive motor to the axles and wheels of the car.

However, this model is built on significant assumptions and simplifications, and the simulation model itself is based on mechanical modules.

The above simulation models of magnetic transmission do not take into account:

1) electromagnetic oscillations of the torque of the inner and outer rotors due to the discrete structure of the magnetic transmission;

2) change in the model parameters (pulsations, losses in the magnetic circuit and permanent magnets, changes in the load angle and transmitted electromagnetic moment) with a variable change in the input moment;

3) the effect of changing the load of the electric generator connected to the high-speed (output) shaft of the magnetic transmission;

4) the presence of a full-fledged source of mechanical energy in the form of a wind generator rotor and changes in wind speed.

Given this, it is necessary to conduct a study of magnetic transmission under the dynamic mode of operation as part of an autonomous wind power plant of small power.

3. The aim and objectives of the study

The purpose of our work is to construct a numerical simulation model of magnetic transmission as part of an autonomous low-power wind power plant. This will make it possible to study the dynamic and operational parameters and characteristics of the magnetic transmission and to evaluate the efficiency of its operation.

To achieve the goal, the following tasks were set:

– to build a numerical simulation model of magnetic transmission in MATLAB/Simulink software;

– to construct a functional diagram of the system for converting mechanical wind energy into electrical energy with magnetic transmission in MATLAB/Simulink;

– to analyze the static and dynamic modes of operation of the magnetic transmission.

4. The study materials and methods

The object of research is electromagnetic and mechanical processes in magnetic transmission for an autonomous wind power plant of small power.

The research hypothesis assumed that the use of magnetic transmission in combination with an autonomous low-power wind power plant makes it possible to increase the reliability and efficiency of such a system.

The following assumptions were accepted: the material of the magnetic transmission core is isotropic; temperature properties of materials are constant.

The following simplifications were adopted: physical objects are replaced by a system of nonlinear differential equations; the demagnetization curve of permanent magnets is assumed to be linearized.

Research materials: magnetic transmission, autonomous wind generator.

Research methods: methods of numerical simulation modeling, methods for solving nonlinear differential equations, methods for calculating the electromagnetic field.

A structure with 26 pairs of poles on a low-speed rotor, 3 pairs of poles on a high-speed rotor, and 29 segments of a magnetic modulator was used as a prototype of magnetic transmission [14, 15]. The gear ratio of this gearbox is 8.67. The main structural parameters of the magnetic transmission prototype used for the construction of a simulation mathematical model are given in Table 1.

Table 1

Main parameters of the magnetic transmission under study

No.	Parameter	Value
1	The number of pole pairs of the high-speed rotor	3
2	The number of pairs of poles of a low-speed rotor	26
3	The number of steel segments of the modulator	29
4	Axial length, mm	80
5	Residual magnetic induction of permanent magnets (PM), Tl	1.26 (N38UH)
6	Gear ratio	8.67
7	Stator magnetic core material	2,411
8	The material of the magnetic conductor of the low-speed rotor	Samoloy
9	The material of the magnetic circuit of the high-speed rotor	Steel 21850
10	Electrical conductivity of permanent magnets, MSm/m	0.56
11	Electrical conductivity of Samoloy, MSm/m	0.14
12	Height of permanent magnets, mm	22
13	The width of the ferromagnetic inserts of the magnetic flux modulator, mm	12
14	Rotational speed of the internal (high-speed) rotor, rev/min	1,735
15	The speed of rotation of the external (low-speed) rotor, rev/min	200
16	The size of the air gap, mm	4

The design of the magnetic transmission uses sector permanent magnets with uniform magnetization in the radial direction, made of N38UH type NdFeBr alloy with a residual magnetic induction of 1.26 Tl [16, 17].

The data given in Table 1 are used to build a numerical simulation mathematical model and are given in more detail in [18].

5. Results of investigating magnetic transmission

5. 1. Numerical mathematical model of magnetic transmission

The operation of the magnetic transmission is considered under a multiplier mode, that is, the drive torque is applied to the low-speed rotor, and the load torque is applied to the high-speed rotor. However, all of the following considerations apply to gear mode as well.

Thus, in a general form, the equations describing the movement of low- and high-speed rotors are written according to Newton's second law:

$$\begin{cases} J_e \dfrac{d\omega_e}{dt} = T_t - T_e - T_{le}; \\ J_i \dfrac{d\omega_i}{dt} = T_i - T_{li} - T_l, \end{cases} \tag{1}$$

where J_e, J_i are moments of inertia of low- and high-speed rotors, kg·m^2; ω_e, ω_i – angular velocities of low- and high-speed rotors, rad/s; T_t – torque of the drive motor (wind turbine rotor), N·m; T_i is the electromagnetic moment of the high-speed rotor, N·m; T_e – electromagnetic moment of the low-speed rotor, N·m; T_{le} is the loss moment of the low-speed rotor, N·m; T_{li} is the loss moment of the high-speed rotor, N·m; T_l is the load moment of the generator with permanent magnets, N·m.

If we assume that the load moment is determined by the parameters of the wind turbine, then in the system of equations (1) the unknown variables are ω_e, ω_i, T_i, T_e, T_{le}, T_{li}. Thus, four additional equations must be added to solve (1). The first two additional equations to system (1) reflect the dependence of the loss moments on the speed of rotation of the rotors:

$$\begin{cases} T_{le} = k_{2e} \cdot \omega_e + k_{1e}; \\ T_{li} = k_{2i} \cdot \omega_i + k_{1i}, \end{cases} \tag{2}$$

where k_{2e}, k_{2i} are power loss coefficients caused by eddy current losses in the magnetic core of low- and high-speed rotors; k_{1e}, k_{1i} are power loss coefficients caused by hysteresis losses in the magnetic core of low- and high-speed rotors.

The ratio of the electromagnetic moments acting on the low- and high-speed rotors of the magnetic system remains constant and equal to the transmission ratio, from which the third additional equation to system (1) follows:

$$\frac{T_e}{T_i} = -i. \tag{3}$$

In the air gaps of the magnetic reducer, the magnetic field has a complex nature of distribution and has a large number of harmonic components, among which the working harmonic, which participates in power transmission, stands out. The rotation angle of the magnetic field excited by the rotor-modulator system for a low-speed rotor in the internal non-magnetic gap can be written as follows:

$$\varphi_e = p_e \cdot i \int \omega_e(t)\,\mathrm{d}t. \tag{4}$$

Expression (4) is valid for any harmonic rotating in the non-magnetic gap of the magnetic reducer. Obviously, for the transmission of the main torque, the first or main harmonic of the magnetic flux is of interest.

The angle of rotation of the field of the high-speed rotor in the internal non-magnetic air gap:

$$\varphi_i = p_i \cdot i \int \omega_i(t)\,\mathrm{d}t. \tag{5}$$

Knowing the dependence of the rotation angles on time for both rotors of the magnetic reducer (4), (5), it is possible to determine the load angle (the angle between the magnetic fields) at each time point:

$$\theta = \varphi_e - \varphi_i = p_i \cdot \left(i \int \omega_e(t)\,\mathrm{d}t - \int \omega_i(t)\,\mathrm{d}t \right). \tag{6}$$

Since the magnetic reducer operates under a multiplier mode, the moment acting on the low-speed rotor will be braking. The dependence of the moment on the load angle is represented by the following expression:

$$T_e = -T_{e\max} \sin\theta, \tag{7}$$

where $T_{e\max}$ is the maximum electromagnetic moment of the low-speed rotor.

Together, (6), (7) form an additional fourth equation for system (1). Thus, the complete system of equations describing the dynamics of the magnetic transmission takes the following form:

$$\begin{cases} J_e \dfrac{d\omega_e}{dt} = T_t - T_e - k_{2e} \cdot \omega_e - k_{1e}; \\ J_i \dfrac{d\omega_i}{dt} = T_i - k_{2i} \cdot \omega_i - k_{1i} - T_l; \\ T_e = -T_{e\max} \sin\theta; \\ \theta = p_i \cdot \left(i \int \omega_e(t)\,\mathrm{d}t - \int \omega_i(t)\,\mathrm{d}t \right). \end{cases} \tag{8}$$

The solution of the nonlinear system of equations (8) is carried out in the MATLAB-Simulink software environment. The equivalent circuit of the magnetic transmission is built according to the principle that the mechanical and electromagnetic moments in the system are phase variables of the flow type, and the rotation frequency is of the potential type. The structure of the constructed magnetic transmission model is shown in Fig. 1.

The main components of the model built: moments of inertia of the rotors J_i, J_e are represented by the corresponding modules; hysteresis losses and eddy currents in steel elements of the magnetic transmission design k_{2e}, k_{2i}, k_{1e}, k_{1i} are represented by modules that contain simulation of losses in the magnetic core. The load is further simulated by connecting to the output, high-speed shaft, a generator with permanent magnets. The connection of the mechanical subsystems of the low- and high-speed rotors of the magnetic transmission is implemented by adding the ratio between the electromagnetic moments T_i, T_e acting on each of the rotors (module 2, Fig. 1).

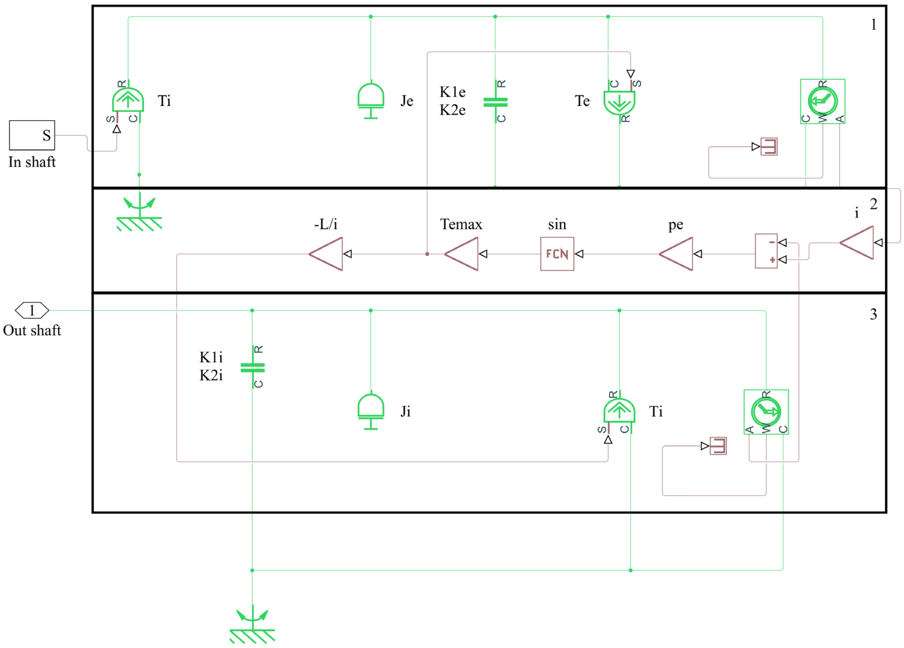


Fig. 1. Magnetic transmission model in MATLAB/Simulink: 1 — low-speed magnetic transmission rotor; 2 — magnetic connection between the rotors of the magnetic reducer, i.e., the magnetic flux modulator; 3 — high-speed rotor

5. 2. Functional diagram of the system for converting wind mechanical energy into electrical energy with magnetic transmission in MATLAB/Simulink

The construction of a simulation model of the system, which includes the rotor of the wind turbine – magnetic transmission – electric generator, was carried out using the tools from the MATLAB/Simulink software package. Mathematical models of the wind turbine rotor, load, measuring devices, etc. are available in the package. To build a simulation model, a model of a synchronous machine with permanent magnets is used. The electric generator module makes it possible to simulate both generator and engine operation modes. The electrical and mechanical components of the generator are described by algebraic and differential equations. When building a mathematical model of a machine with permanent magnets, the following assumptions were adopted: the air gap is uniform, the stator winding is evenly distributed. The general system of equations includes a description of the operation of a synchronous machine with permanent magnets in the d–q coordinate system:

$$\begin{cases} \dfrac{d}{dt} i_d = \dfrac{1}{L_d} V_d - \dfrac{R_1}{L_d} i_d + \dfrac{L_q}{L_d} p \cdot \omega_r \cdot i_q; \\ \dfrac{d}{dt} i_q = \dfrac{1}{L_q} V_q - \dfrac{R_1}{L_q} i_q - \dfrac{L_d}{L_q} p \cdot \omega_r \cdot i_d - \dfrac{\Phi \cdot p \cdot \omega_r}{L_q}; \\ T_{em} = 1.5 p \left[\Phi i_q + \left(L_d - L_q \right) i_d i_q \right], \end{cases} \quad (9)$$

where L_q, L_d are the inductances of the armature winding along the axes d, q; R_1 – active resistance of the stator winding; i_q, i_d – current components of the generator armature winding along the d, q axes; V_q, V_d – voltage components of the armature winding along the axes d, q; ω_r is the angular velocity of the rotor; Φ is the amplitude of the magnetic flux created by the permanent magnets on the rotor, which induces electromotive force (EMF) in the generator armature winding; p is the number of generator pole pairs; T_{em} is the electromagnetic moment of the generator.

The position of the rotor affects the magnitude of the inductances L_q and L_d. These values are determined by the phase inductance. For example, the inductance between phases a and b can be described by the following expression:

$$L_{ab} = L_d + L_q + \\ + \left(L_q - L_d \right) \cos\left(2\theta_e + \frac{\pi}{3} \right), \quad (10)$$

where θ_e is the electrical angle of the generator rotor position.

The rotor of the wind turbine is the source of mechanical torque for the low-speed shaft of the magnetic reducer. The stiffness of the wind turbine drive is assumed to be infinite, and the friction coefficient and inertia of the turbine are agreed and implemented with the corresponding coefficients attached to the turbine. The output power on the wind turbine rotor shaft is given by the following equation [18]:

$$P_t = c_p \left(\lambda, \beta \right) \frac{\rho A}{2} v_w^3, \quad (11)$$

where P_m is the output mechanical power of the wind turbine rotor (W); c_p is the efficiency factor of the wind turbine; ρ is the air density (kg/m^3); A is the area of the wind turbine rotor; v_w is the wind speed (m/s); λ is the coefficient of the ratio of the turbine rotation speed to the wind speed; β is the angle of inclination of the blade.

The input parameters of the wind turbine in the environment defined in the MATLAB-Simulink simulation model are:

– rated output mechanical power on the rotor shaft of the wind turbine;

– rated power of the electric generator (WEE). This parameter is used to calculate the output rated torque;

– the rated wind speed (m/s) is used in the v.o. system. the value of the expected (average) wind speed for a given region or the speed at which the rated power of the wind turbine develops is set;

– maximum power at basic wind speed;

– basic wind speed;

– the angle of attack of the wind turbine blades.

Based on the simulation model of magnetic transmission, a numerical mathematical model of a magnetic reducer as part of an autonomous low-power wind turbine operating on an electric generator with permanent magnets has been constructed. The appearance of the model built in the MATLAB/Simulink software package is shown in Fig. 2.

That is, each of the elements of the simulation model in the environment is represented by a separate module, which, in turn, is described by a system of nonlinear (linearized) differential equations. For example, the block diagram of the rotor of the wind turbine in the MATLAB-Simulink system has 3 logical inputs and one output, the output value of the wind turbine model is the value of the mechanical moment directly applied to the magnetic transmission shaft.

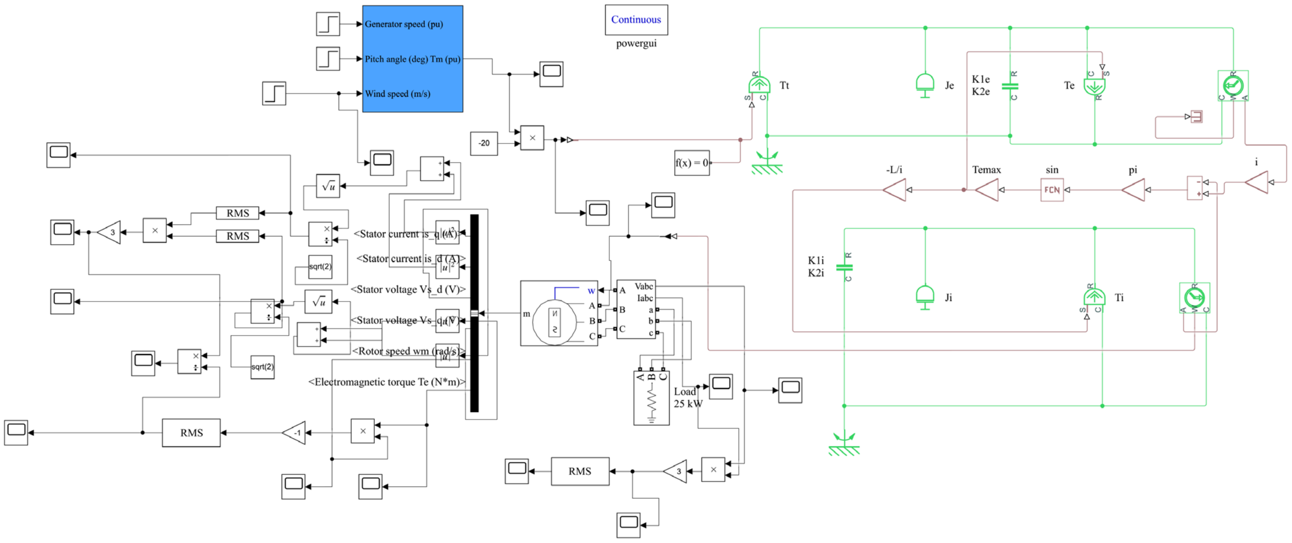


Fig. 2. Simulation model of a wind power plant with a magnetic reducer:
1 – wind turbine rotor unit with specified NASA 40 blade parameters and a random number generator that simulates a change in wind speed in the range of 3–8 m/s. The unit works according to (11); 2 – module that implements nonlinear differential equations (8) of magnetic transmission; 3 – module of parameters of an electric generator with permanent magnets, which implements the system of differential equations (9) and (10); 4 – module in which the generator load is implemented in the form of a three-phase load; 5 – unit for measurement, control, recording, and processing of output parameters of the electric generator, load and mechanical parameters of the system

A feature of the model built is that when the generator load changes (module 4, Fig. 2), the electromagnetic moment of the generator changes (module 3, Fig. 2). This leads to a change in the operating point on the mechanical characteristics of the wind turbine rotor, which is an important feature of the model built. Conversely, when the wind parameters change, the output parameters of the generator change: its output power P_1, voltage U_1, current I_1 and electromagnetic moment of the generator T_{em}.

5. 3. Results of simulating the static and dynamic modes of magnetic transmission operation

During magnetic transmission operation, there are various changes in both the drive torque and the load. This leads to a change in the load angle θ and causes an oscillating process of the rotors.

To simulate the processes that occur when the drive torque changes sharply (for example, during sudden gusts of wind), in the mathematical model of the magnetic transmission, a time-varying torque is applied to the low-speed shaft function shown in Fig. 3.

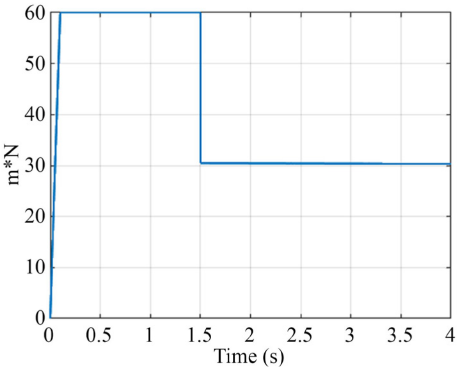


Fig. 3. Dependence of drive torque on time

At 1.5 seconds, the drive torque is reset by 50 %, which causes pulsations in the speed of rotation and the electromagnetic moment of rotors (Fig. 4).

The frequencies of oscillations occurring in both rotors are the same, while their amplitude on the high-speed rotor is much smaller than on the low-speed one (Fig. 5).

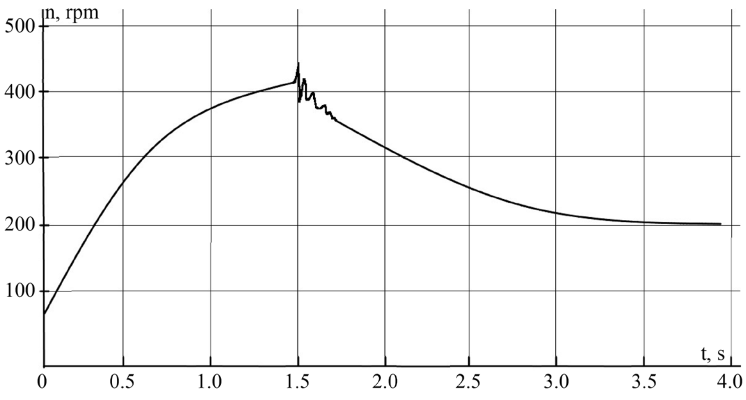


Fig. 4. Calculation dependences of rotational speed for a low-speed rotor

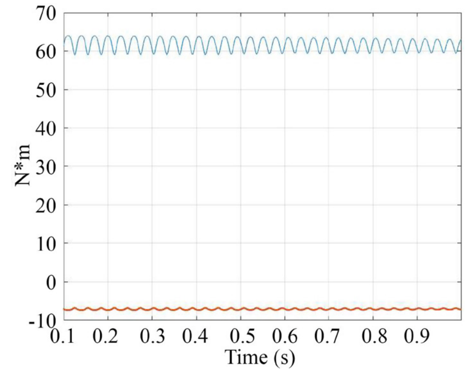
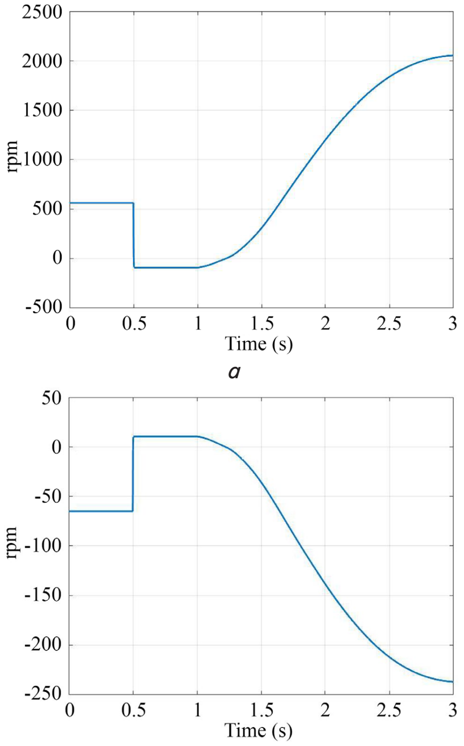


Fig. 5. Estimated speed pulsations for a period of time from 3.5 to 4 s: 1 – low-speed rotor, 0 – high-speed rotor

With variable wind speed, the corresponding parameters of the magnetic transmission and the output parameters of the electric generator also change. Fig. 6 shows a change in the speed of rotation of the low-speed and high-speed rotor of the magnetic transmission.



a

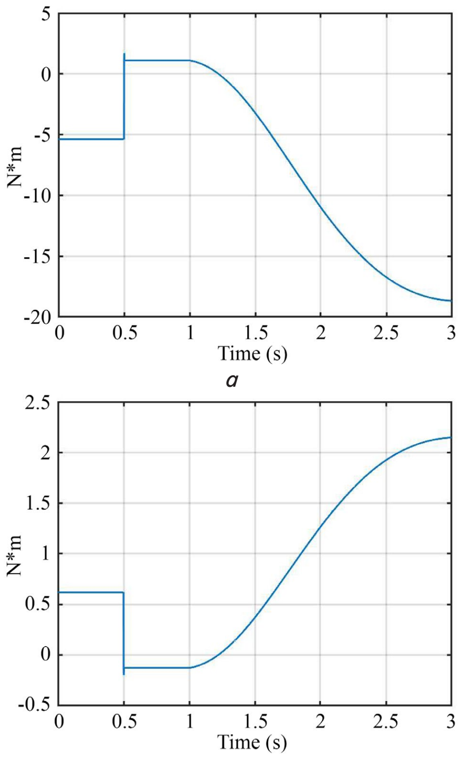
b

Fig. 6. Change in rotation speed with change in wind speed: *a* – high-speed rotor; *b* – low-speed rotor

When the wind speed and the load of the generator with permanent magnets change, the magnitude of the electromagnetic moment of the magnetic transmission changes proportionally, which is shown in Fig. 7.

When the wind speed changes, the output parameters of the synchronous generator with permanent magnets also change. The change in the instantaneous values of the phase voltage and current when the wind speed changes on the generator clamps is shown in Fig. 8.

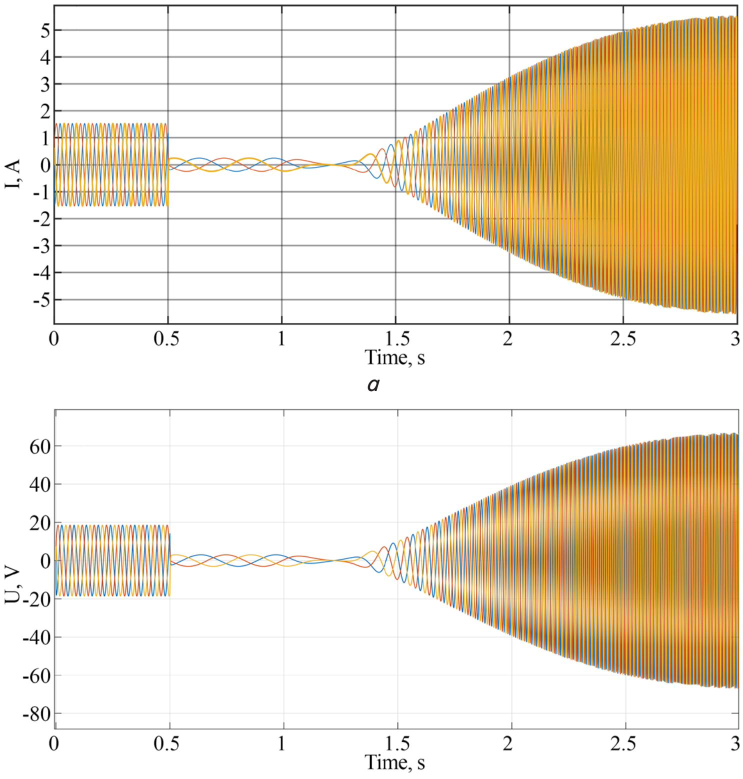
Fig. 9 shows a change in the instantaneous power value in the phases of the generator when the wind speed changes.



a

b

Fig. 7. Dependence of electromagnetic moment of magnetic transmission for: *a* – high-speed rotor; *b* – low-speed rotor



a

b

Fig. 8. Instantaneous values: *a* – current; *b* – voltage at the output of a generator with permanent magnets

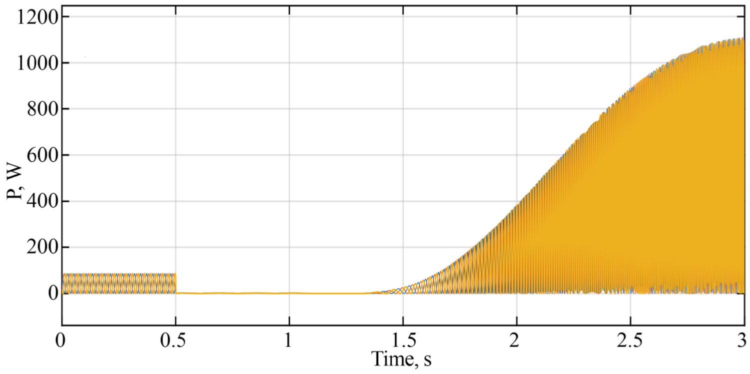


Fig. 9. Instantaneous power value of each generator phase

The model built has wide functionality for analyzing the output parameters of both the electric generator and the magnetic transmission operating as part of an autonomous wind power plant.

The time dependence of the drive torque under an emergency mode is shown in Fig. 10.

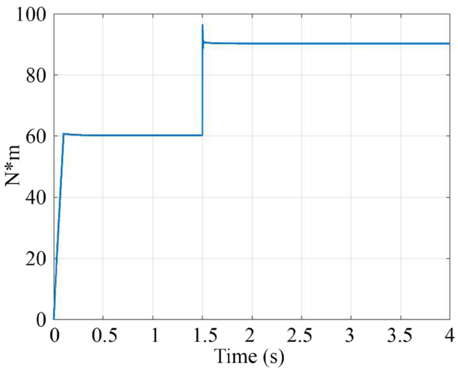
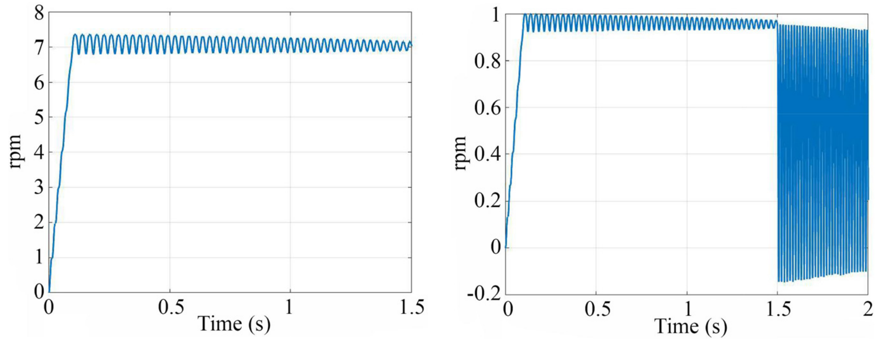


Fig. 10. Dependence of the drive torque on time under an emergency mode

To analyze the behavior of magnetic transmission under emergency modes, it is necessary to consider the speed pattern of the rotation of low-speed and high-speed rotors of the magnetic reducer, which is shown in Fig. 12.

The calculated dependence of the moment acting on the high-speed rotor in the region of «disruption» is shown in Fig. 12.

Loss of the magnetic transmission from synchronism is not considered a disadvantage when used as part of an autonomous wind power plant.



a

b

Fig. 11. Estimated dependence of rotation speed on time: *a* — for a low-speed rotor; *b* — for a high-speed rotor

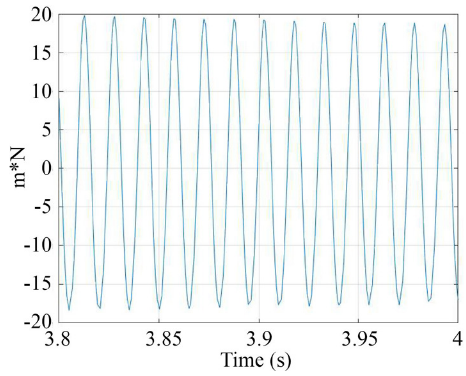


Fig. 12. Estimated dependence of the moment acting on a high-speed rotor in the «disruption» region

This effect makes it possible to preserve the mechanical part of the wind turbine and helps smooth out sharp mechanical fluctuations. Similar phenomena when using mechanical multipliers would lead to an emergency stop of the installation or its failure altogether.

6. Discussion of results of investigating magnetic transmission for an autonomous wind power plant

When the torque increases from zero to rated in 0.1 s (Fig. 4), it has a constant value that is maintained for 1.5 s. During this time, the rotor rotation frequency reaches the set value. Under the influence of the driving moment of the rotor of the wind turbine, both rotors begin to rotate in opposite directions, according to the principle of planetary coaxial magnetic transmission.

The frequency spectrum of oscillations also contains subharmonics associated with the nonlinearity of the angular characteristic of the electromagnetic moment, but their amplitude is small compared to the amplitude of the main harmonic (Fig. 5). The presence of electromagnetic torque fluctuations (Fig. 5) of the magnetic transmission and their consideration in the developed numerical simulation model is another characteristic feature of the constructed magnetic transmission system, which distinguishes it from known analogs.

The zone from 0–1 s in Fig. 6 corresponds to a wind speed of 4.4 m/s, and the rotation frequency of the wind turbine rotor and the low-speed rotor of the magnetic transmission is 21 rpm. At the same time, the rotation frequency of the high-speed rotor (output rotor) is 183 rpm, which corresponds to a transmission ratio of 8.7. This corresponds to the data in Table 1.

It is obvious that the moment of the high-speed rotor is smaller than the moment of the slow-speed rotor. For example, for a time interval of 2–4 s, at a wind speed of 7.8 m/s, the torque of the high-speed rotor is 0.91 N·m, and the torque of the slow-speed rotor is 7.8 N·m, which corresponds to a transmission ratio of 8.6 (Fig. 7). It is worth noting that the transmission coefficient in this case differs from the value obtained above since the model takes into account losses in the magnetic transmission line and mechanical losses. Since the low-speed rotor is a drive rotor, it produces a braking torque and has a «+» sign, while the high-speed rotor is subjected to generator torque, so it has a «–» sign.

At a wind speed of 4.4 m/s (at time point of 0–1 s), the amplitude value of the current in the armature phase of the synchronous generator is 0.82 A, and the amplitude value of the voltage at this point is 5.2 V (Fig. 8). When the wind speed changes, the voltage, current, and power at the output of the generator change accordingly, a change in frequency is observed, which corresponds to real physical processes and indicates the adequacy of the constructed simulation model.

Fig. 9 demonstrates that with a weak wind <3 m/s, the effective value of the output power is ≈0 W. In this case, most of the usable power developed by the wind turbine rotor is used to cover mechanical and electrical losses in the magnetic transmission and the electric generator.

The efficiency is obtained with an active load of the generator of 2.0 kW and is ≈75 %; when the active load is reduced (for example, at 1.0 kW), the calculated efficiency value is 81.3 %. This corresponds to the trends and the general theory of electromechanical energy converters.

During the operation of the magnetic transmission, there are modes of operation when the drive or load moment exceeds the maximum value of the electromagnetic moment. Such modes are typical for sudden gusts of wind (>12 m/s) or emergency modes of operation of the electric generator: sudden short circuit, overload, sudden load shedding, etc. This leads to the cessation of energy transfer between the rotors. This mode is similar to the desynchronization mode of a synchronous electric machine. To analyze this mode of operation, a torque from the load is applied to the low-speed shaft of the simulation model of the magnetic transmission. At a time of 1.5 s, the torque of the drive increases to 90 N m, which exceeds the maximum torque of the gear under study (Fig. 10).

When the drive exceeds the maximum torque value, the magnetic transmission goes out of synchronism, and its input (low-speed) rotor begins to accelerate sharply (Fig. 11, *a*), and the output (high-speed) rotor begins to brake (Fig. 11, *b*) and, finally, loses the constant component of the rotation speed, oscillating around zero.

The torque of the magnetic transmission also loses its constant component and oscillates around zero with an amplitude equal to the maximum torque on the corresponding rotor (Fig. 12), that is, it actually becomes reactive since it does not participate in energy transfer.

Existing wind farms are mainly built using multiplier or multiplierless systems. Multiplier systems, on the one hand, have proven successful in practice, and on the other hand, they require regular maintenance and have worse mass-dimensional indicators. Multiplierless installations have the simplest design, but the technical execution leads to a significant increase in price. The proposed system is free of these shortcomings, has higher reliability, does not require regular maintenance, and has a number of operational advantages under emergency conditions.

The use of a magnetic transmission, in contrast to [18, 19], makes it possible to abandon the mechanical gear transmission. This will reduce the overall weight of the system and increase its reliability. This becomes possible due to the simplicity of the design of magnetic gears and contactless energy transfer between the input and output shafts. The model built makes it possible to study the parameters and characteristics of not only magnetic transmission but also other components of the system: electric generator, wind generator, load, etc., which increases variability and opportunities for conducting scientific research of an exploratory nature.

Owing to our model of magnetic transmission as part of an autonomous wind power plant, the reliability of autonomous electric power complexes has been increased. An assessment of the dynamic modes of operation of the magnetic transmission in emergency modes of operation was also carried out.

The limitations of the proposed conversion system with magnetic transmission are related to the saturation of the steel ferromagnetic elements of the magnetic transmission when designing the latter with a high transmission ratio. The task of optimal design of such gears requires a balance between geometrical parameters, minimum torque ripples, its weight, and final cost.

The disadvantages of using magnetic gears are due to the limitations of using permanent magnets, as they are sensitive to mechanical influences and shocks, high temperatures, and demagnetization. There are also technological disadvantages associated with the complexity of manufacturing the elements of the magnetic modulator and ensuring its mechanical strength, as it is affected by significant amounts of transmission forces.

This research may be advanced from the point of view of developing magnetic transmissions with a variable transmission ratio, which could increase the flexibility of such systems. Also, on the basis of our results, a number of further studies related to experimental studies of magnetic transmissions for autonomous energy complexes would follow.

7. Conclusions

1. A numerical simulation model of magnetic transmission was built in MATLAB/Simulink software. The constructed simulation model of the magnetic transmission takes into account the pulsations of the electromagnetic moment due to the discrete structure of the magnetic transmission. Also, the model parameters change when the input torque changes: losses in the magnetic circuit and permanent magnets, changes in the load angle and transmitted electromagnetic torque.

2. A functional diagram of the system for converting mechanical wind energy into electrical energy with magnetic transmission was developed in MATLAB/Simulink using the example of an autonomous low-power wind power plant. The use of magnetic transmission for autonomous wind energy systems makes it possible to increase the reliability of such installations, reduce operating costs, and increase their

efficiency. Under emergency modes of operation, the use of magnetic transmission makes it possible to avoid the destruction or emergency shutdown of electrical equipment. A feature of the built model of the magnetic transmission system is that a change in the generator load leads to a change in the operating point on the mechanical characteristics of the wind turbine rotor. Conversely, when the wind parameters change, the output parameters of the generator change: power, voltage, current, and electromagnetic moment.

3. We have analyzed the static and dynamic parameters and characteristics of magnetic transmission with changing wind speed. With light wind <3 m/s, the effective value of the output power is ≈0 W, which covers active and mechanical losses. The efficiency at an active load of the generator of 2.0 kW is ≈75 %, with a decrease in the value of the active load, the calculated efficiency value is 81.3 %. At a wind speed of 7.8 m/s, the moment of the high-speed rotor is 0.91 N·m, and the low-speed one is 7.8 N·m, which corresponds to a gear ratio of 8.6. At a wind speed of 4.4 m/s, the amplitude value of the current in the phase of the armature winding of the synchronous generator is 0.82 A, the amplitude value of the voltage at the same moment of time is 5.2 V. At higher values, the wind speed, voltage, and current of the generator increase and are ≈2.8 A and 234 V. When the magnetic transmission operates within the rated transmission torque, its operation is stable in strong and gusty winds. When the maximum transmission torque is exceeded, the inner and outer rotors go out of sync.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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