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ENERGY CONVERSION EFFICIENCY IN THE ELECTROMECHANICAL SYSTEM WITH MAGNETIC GEAR OF PASSENGER ELECTRIC TRANSPORT ROLLING STOCK

The object of research is electromechanical processes in the traction electric drive of the rolling stock of passenger electric transport under the action of strong and short-term moments of disturbance during acceleration, movement at a steady speed and deceleration.

The problem under consideration was to determine the influence of the parameters of the magnetic reducer on reducing the effect of external disturbances on the electromechanical system of the rolling stock of the metro. The analysis was carried out on the basis of a comparison of a typical traction electric drive with a mechanical reducer and the proposed electric drive with a magnetic reducer. This reducer transmits the moving moment to the wheel pairs without mechanical contact, but at the same time causes an elastic-viscous connection between its input and output shafts.

A comparison of the behavior of the electromechanical system using a typical mechanical reducer and the proposed magnetic reducer is presented. The influence on the efficiency of energy conversion of the parameters of the magnetic reducer, in particular the magnetic stiffness and the damping coefficient, is investigated. During the research, differences were found in the dependences of the amplitude of moments, the period of natural oscillations, and the time of damping of the transient process for two types of gearboxes. With a stiffness of the magnetic gearbox of 5000 Nm/rad, the amplitude of the moment decreased by 59% compared to the mechanical gearbox. The period of natural oscillations decreased by 62%, and the damping of the transient process increased by 59%. The research results showed that the rational choice of the parameters of the magnetic gearbox allows to increase the dynamic stability of the electric drive to short-term disturbances. At the same time, shock loads on the motor shaft and the amplitude of torque fluctuations are reduced. This is especially relevant for traction systems of transport operating in conditions of uneven resistance to movement.

The practical value of the research results lies in the possibility of improving the efficiency of energy conversion and the quality indicators of control of the traction electric drive of the rolling stock of passenger electric transport. This research will be useful for scientists and companies specializing in the field of rolling stock of passenger electric transport.

Keywords: *efficiency, magnetic transmission, reducer, damping, stiffness, electric transport, traction electric drive, torque.*

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1. Introduction

Increasing the efficiency of energy conversion in the electromechanical system of the rolling stock of passenger electric transport is an important scientific task. The second important one is to improve the quality of control of the traction electric drive, which is especially important in conditions of strong and short-term moments of disturbance caused by track irregularities. Solving this problem will improve passenger comfort during movement, reduce the shock load on the motor shaft and, accordingly, increase the service life and reduce the cost of maintenance.

One of the ways to solve this problem is to use magnetic gearboxes in the traction electric drive instead of mechanical gearboxes, which are receiving more and more attention in various industries. A study of the effectiveness of using magnetic transmission in the drive of a wind turbine based on a brushless motor is given in [1]. Compared to classic mechanical gearboxes, which use gears to transmit torque, magnetic gearboxes do not have a rigid connection between the input and output shafts. The main topologies are presented in [2].

The most common are magnetic gearboxes based on the magnetic flux modulation method [3]. The magnetic transmission consists of three concentric elements. The high-speed rotor, which is connected to the drive electric motor, is a steel pole piece. Permanent magnets are installed on the outer surface of this rotor, with the help of which the required number of p_H pairs of magnetic poles is created. The low-speed rotor has a similar design with permanent magnets on the inner surface with p_L pairs of magnetic poles. Between them is a fixed modulator with n_S ferromagnetic pole pieces, which modulates the magnetomotive force of the high-speed rotor. In the low-speed rotor, a high transmitting magnetic moment is created due to the interaction with the modulated magnetic flux. This design provides a high torque density at the level of 100–120 kNm/m^3, which is almost equal to the value of mechanical transmission.

The torque transmission in the magnetic gearbox is carried out due to magnetic interaction. Due to this, these transmissions have less vibration and noise, can dampen the effect of strong and short-term moments of disturbance and prevent mechanical overloads.

As a result, magnetic gearboxes have a longer service life and lower maintenance costs. In addition, the magnetic gearbox allows to smooth out peak values of torques and, accordingly, motor currents. This, in turn, leads to an increase in the service life of the entire electromechanical system and an increase in the efficiency of converting electrical energy into mechanical energy of the rolling stock of passenger electric transport.

Since a high-speed motor with a reduction gearbox is used to optimize weight-dimensional indicators in electric transport, it is possible to combine them into one system – a pseudo-direct drive [4], consisting of a brushless motor and a magnetic transmission.

In [5], a study of the magnetic fields of the reducer depending on the load was conducted by modeling, which allows a deeper understanding of the influence of operating modes on electromagnetic processes in the electromechanical system. In [6], a control system for a pseudo-direct electric drive was developed. The authors of [7] proposed a control system using only one position sensor located on one of the rotors and an observer to determine the degree of damping. Since the magnetic reducer can be represented as a two-mass system, its behavior and position control using a PI controller were considered in [8]. A comparative analysis of other types of controllers for motion control is given in [9].

The results of the conducted research create a basis for improving the electromechanical system of the rolling stock of passenger electric transport. At the same time, the influence of strong and short-term overloads on the dynamic and static stability indicators of a traction electric drive with a magnetic reducer when moving on sections of the track with uneven resistance remains insufficiently studied. In particular, the dependence of the transient process parameters (amplitude, period and damping factor) on the characteristics of the magnetic reducer, such as magnetic stiffness and damping degree, needs to be clarified.

The object of research is electromechanical processes in the traction electric drive of the rolling stock of passenger electric transport under the action of moment disturbances for different operating modes.

The aim of research is to determine the influence of the parameters of the magnetic reducer on the efficiency of energy conversion in the electromechanical system of the rolling stock of passenger electric transport. To achieve this, it is planned to study the energy conversion processes under the action of strong and short-term moments of disturbance during acceleration, steady motion and deceleration. The analysis is performed on the basis of the characteristic performance indicators of a typical traction electric drive with a mechanical reducer in comparison with the proposed system with a magnetic reducer, which will allow improving the control quality indicators and increasing passenger comfort. To achieve the aim, it is necessary to solve the following tasks:

1. Obtain the time dependences of torques, speeds and angles of rotation of the shafts for a typical traction electric drive with a mechanical gearbox and for the proposed system with a magnetic gearbox, taking into account the action of short-term disturbance moments.
2. Perform a spectral analysis of torque oscillations in order to determine the change in the frequency characteristics of the system and assess the influence of the elastic-viscous coupling between the shafts on its dynamic stability.
3. Conduct a study of the influence of the parameters of the magnetic gearbox – stiffness and damping coefficients – on the dynamic characteristics of the electromechanical system, the amplitude and frequency of torque oscillations.
4. Evaluate the effectiveness of using a magnetic gearbox as part of a traction electric drive, which is determined by a decrease in the amplitude of torque oscillations, an increase in the damping coefficient of the transient process, an increase in the smoothness of operation and an increase in the system's operating resource.

2. Materials and Methods

In the work, a study of the efficiency of energy conversion in the electromechanical system of the metro rolling stock was conducted by modeling in the MATLAB Simulink software environment. The study was performed for a traction electric drive with an asynchronous motor, where the options with a mechanical and magnetic gearbox are compared. The nominal power of the motor is P_{nom} = 150 kW, the nominal angular frequency is ω_{nom} = 188.49 rad/s and the nominal torque is T_{nom} = 795.77 Nm.

The magnetic transmission model was represented by a two-mass calculation scheme with an elastic-viscous connection between the input and output shafts [10, 11].

The transmission ratio of the magnetic gearbox is determined by the dependence

$$G_r = \frac{p_L}{p_H}, \tag{1}$$

where p_L – the number of pairs of magnetic poles of the low-speed output shaft; p_H – the number of pairs of magnetic poles of the high-speed input shaft of the gearbox. The highest torque transmission capability of the gearbox is achieved by observing the equality

$$p_L = n_s - p_H, \tag{2}$$

where n_s – the number of ferromagnetic pole pieces of the modulator.

The angular displacement between the input and output shafts is determined by the dependence

$$d\theta = \theta_H - G_r \cdot \theta_L, \tag{3}$$

where θ_H – the angle of the high-speed input shaft of the gearbox; θ_L – the angle of the low-speed output shaft.

The equation of the magnetic moment of the gearbox

$$T_{mag} = k_m d\theta + b_m d\dot{\theta}, \tag{4}$$

where k_m – the magnetic stiffness; b_m – the magnetic damping.

When $k_m \to \infty$, $b_m = 0$, the magnetic transmission becomes absolutely rigid as an ideal mechanical gearbox.

After substituting (3) into (4), the magnetic moment will be

$$T_{mag} = k_m\left(\theta_{Hn} - G_r \cdot \theta_L\right) + b_m\left(\omega_H - G_r \cdot \omega_L\right). \tag{5}$$

Taking into account (5), the equation of motion of the electromechanical system takes the form:

$$\left.\begin{aligned} \frac{d\omega_H}{dt} &= \frac{T_e - \left(k_m\left(\theta_H - G_r \cdot \theta_L\right) + b_m\left(\omega_H - G_r \cdot \omega_L\right)\right)}{J_H}, \\ \frac{d\omega_L}{dt} &= \frac{\left(k_m\left(\theta_H - G_r \cdot \theta_L\right) + b_m\left(\omega_H - G_r \cdot \omega_L\right)\right) - T_L}{J_L}, \end{aligned}\right\} \tag{6}$$

where ω_H - the speed of the electric motor; ω_L – the speed of the output shaft; T_L – the load moment; T_e – the torque of the electric motor; J_H – total moment of inertia of the electric motor and the high-speed gearbox shaft; J_L – total moment of inertia of the low-speed gearbox shaft and the load.

Fig. 1 shows the dependence of the efficiency of the electric drive with a magnetic gearbox on the output speed and torque. As can be seen, the highest efficiency is obtained at high speeds and high loads.

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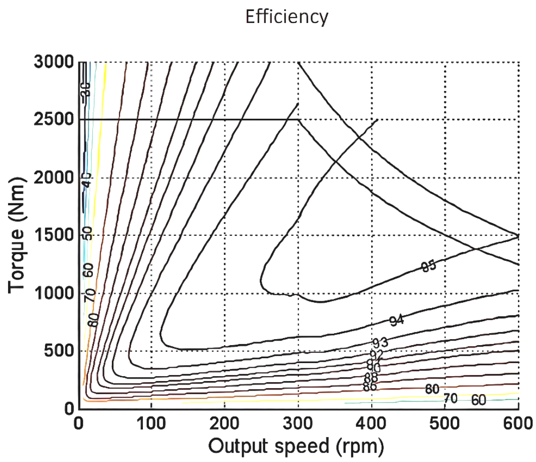


Fig. 1. Dependence of efficiency of a drive with a magnetic gearbox on speed and torque [12]

Asynchronous electric motor is the most common traction electric machine due to its simplicity of design and relative cheapness. Despite the complex control algorithms with the development of semiconductor converter and microprocessor technology, their use in electric transport is relevant. Fig. 2 shows a map of the dependence of the efficiency of an asynchronous motor on speed and torque on the shaft. As can be seen, the most efficient asynchronous motor operates at high speeds and at low loads. In vehicles, the load increases with increasing speed, so the efficiency of the asynchronous motor will decrease, but it still has some of the best energy characteristics [13].

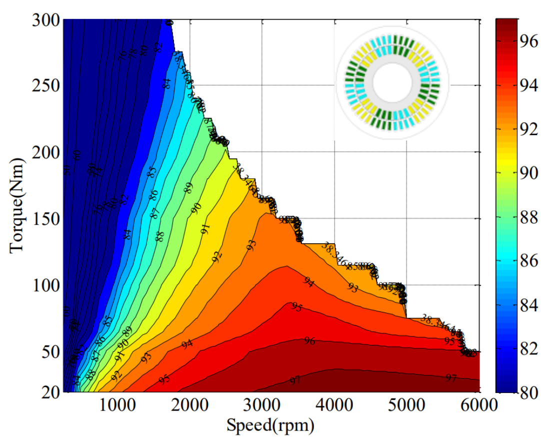


Fig. 2. Dependences of the efficiency of an asynchronous motor on the speed and torque on the shaft [13]

The mathematical equations of the model of an asynchronous motor in the natural coordinate system are the clearest. In it, the variables and parameters have a physical meaning and real value, so it is possible to take into account the asymmetry of both the supply voltage and the parameters of the electrical windings. The equivalent circuit of a three-phase asynchronous motor is shown in Fig. 3. The well-known system of differential equations according to Ohm's law for the stator and rotor phases has the form:

$$\begin{cases} u_A = i_A R_A + d\psi_A/dt; \\ u_B = i_B R_B + d\psi_B/dt; \\ u_C = i_C R_C + d\psi_C/dt, \end{cases} \begin{cases} u_a = i_a R_a + d\psi_a/dt; \\ u_b = i_b R_b + d\psi_b/dt; \\ u_c = i_c R_c + d\psi_c/dt, \end{cases} \quad (7)$$

where u_A – the instantaneous voltage at the terminals of phase A; i_A – the instantaneous current of phase A; ψ_A – the total flux linkage of phase A; R_A – the active resistance of the phase A winding.

The designation of variables and parameters for phases B and C is similar.

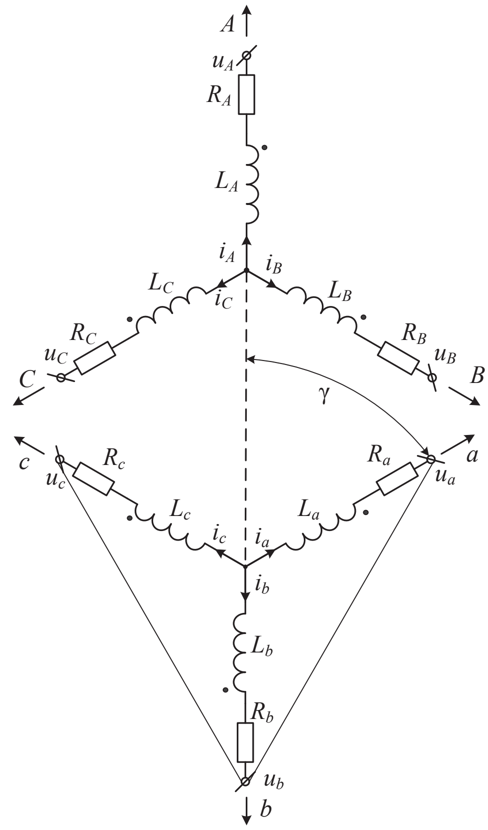


Fig. 3. Equivalent circuit of a three-phase induction motor

The stator and rotor flux linkages of the motor are expressed as follows:

$$\begin{aligned} \psi_A &= L_A i_A + M_{AB} i_B + M_{AC} i_C + M_{Aa} i_a \cos\gamma + \\ &+ M_{Ab} i_b \cos(\gamma + 2p/3) + M_{Ac} i_c \cos(\gamma - 2p/3); \\ \psi_B &= M_{BA} i_A + L_B i_B + M_{BC} i_C + \\ &+ M_{Ba} i_a \cos(\gamma - 2p/3) + \\ &+ M_{Bb} i_b \cos\gamma + M_{Bc} i_c \cos(\gamma + 2p/3); \\ \psi_C &= M_{CA} i_A + M_{CB} i_B + L_C i_C + \\ &+ M_{Ca} i_a \cos(\gamma + 2p/3) + \\ &+ M_{Cb} i_b \cos(\gamma - 2p/3) + M_{Cc} i_c \cos\gamma, \end{aligned} \quad (8)$$

$$\begin{aligned} \psi_a &= M_{aA} i_A \cos\gamma + M_{aB} i_B \cos(\gamma - 2p/3) + \\ &+ M_{aC} i_C \cos(\gamma + 2p/3) + L_a i_a + M_{ab} i_b + M_{ac} i_c; \\ \psi_b &= M_{bA} i_A \cos(\gamma + 2p/3) + M_{bB} i_B \cos\gamma + \\ &+ M_{bC} i_C \cos(\gamma - 2p/3) + M_{ba} i_a + L_b i_b + M_{bc} i_c; \\ \psi_c &= M_{cA} i_A \cos(\gamma - 2p/3) + \\ &+ M_{cB} i_B \cos(\gamma + 2p/3) + \\ &+ M_{cC} i_C \cos\gamma + M_{ca} i_a + M_{cb} i_b + L_c i_c, \end{aligned} \quad (9)$$

where γ – the angle between the axes of the stator windings A and a of the rotor; L_A – the inductance of the phase A winding; M_{AA} – the maximum value of the mutual inductance between the stator and rotor windings; M_{AB} – the mutual inductance between the phases A and B windings.

The system of equations (7)–(9) allows for the study of electromagnetic processes in an induction motor, but for the synthesis of control algorithms it is cumbersome due to the presence of periodic coefficients. After Park transformations, a well-known mathematical model of an induction motor in the d–q synchronous coordinate system is obtained, which is oriented along the rotor flux linkage vector:

$$\begin{cases} \dfrac{di_{1d}}{dt} = -\dfrac{R_1}{\sigma} i_{1d} - \alpha\beta L_m i_{1d} + \omega_0 i_{1q} + \alpha\beta |\psi_2| + \dfrac{u_{1d}}{\sigma}; \\ \dfrac{di_{1q}}{dt} = -\dfrac{R_1}{\sigma} i_{1q} - \alpha\beta L_m i_{1q} - \omega_0 i_{1d} - \beta\omega_H p_n |\psi_2| + \dfrac{u_{1q}}{\sigma}; \\ \dfrac{d|\psi_2|}{dt} = -\alpha|\psi_2| + \alpha L_m i_{1d}; \\ \dfrac{d\omega_H}{dt} = \dfrac{T_e}{J} - \dfrac{T_L}{J}; \\ T_e = \dfrac{3}{2} p_n \dfrac{L_m}{L_2} |\psi_2| i_{1q}, \end{cases} \tag{10}$$

where $\alpha = R_2/L_2$, $\sigma = L_1 - L_m^2/L_2$, $\beta = L_m/\sigma L_2$ – model parameters; R_1, R_2 – active electrical resistance of the stator and rotor windings; L_1, L_2, L_m – inductance of the stator, rotor and magnetization circuit windings; ω_H, ω_0 – angular velocity of the rotor and magnetic field; J – moment of inertia of the motor; T_e, T_L – motor torque and resistance torque; u_{1d}, u_{1q} – components of the stator voltage vector; i_{1d}, i_{1q} – components of the stator current vector; $|\psi_2|$ – modulus of the rotor flux linkage vector; p_n – number of magnetic pole pairs.

To control a traction induction motor based on model (10), a typical system of vector control of the torque of an electric motor [14] is used.

3. Results and Discussion

The research results of the efficiency of energy conversion in the electromechanical system of the passenger electric drive rolling stock were obtained for a typical tachogram of movement. It includes three stages: acceleration with constant acceleration, movement at a steady speed and braking with constant deceleration. At each stage, the effect of strong but short-term mechanical disturbance moments is taken into account. The entire cycle lasts 40 s. The acceleration of the traction electric drive is performed to the nominal speed ω_{nom} = 188.49 rad/s, which corresponds to the speed of movement V = 52.92 km/h for time t = 15 s. The short-term disturbance moment is applied to the system at times t = 10, 20 and 30 s and is 25% of the nominal. The basic stiffness coefficient of the magnetic transmission is k_m = 10000 Nm/rad, and the damping coefficient of the magnetic transmission is b_m = 250 Nms/rad.

Fig. 4 shows in relative units the dependence of the angular frequency $\omega^* = \omega^* = \omega/\omega_{nom}$ (ω_{nom} = 188.49 rad/s) and the torque $T^* = T/T_{nom}$ (T_{nom} = 795.77 Nm) of the traction electric motor at all stages of working out the given tachogram for the system with a mechanical gearbox (Fig. 4, *a*) and a magnetic gearbox (Fig. 4, *b*).

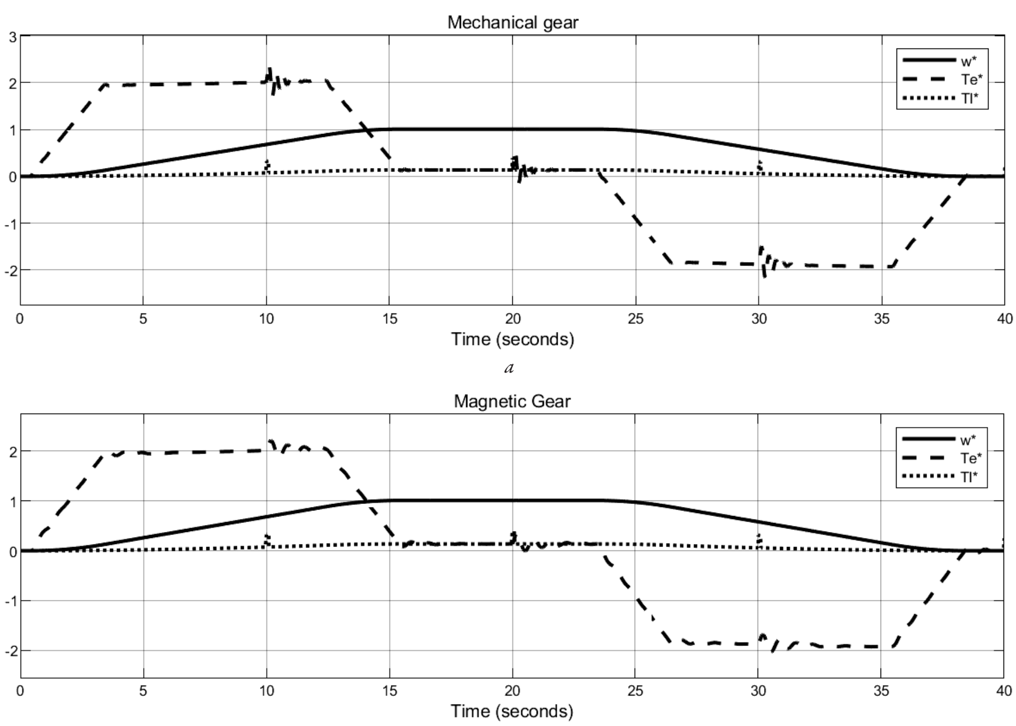
Fig. 5 shows a comparison of the graphs of the electric motor torques during disturbances for an electromechanical system with a mechanical and magnetic gearbox. As can be seen, the maximum amplitude of torque fluctuations is half as small when using a magnetic gearbox, but the period of natural oscillations and, accordingly, the damping time of the transient process is three times greater, 660 ms versus 220 ms with a mechanical gearbox.

For an electromechanical system with a magnetic gearbox, due to the presence of an elastic-viscous connection between the input and output shafts, under the action of short-term disturbances of the load torque, the angle difference between the shafts increases to a value of 0.15 rad (Fig. 6, *a*), and the speed difference reaches a value of 0.13 rad/s (Fig. 6, *b*).

Fig. 7 shows the characteristics of the electric motor torque oscillation spectrum for a system with a mechanical gearbox and a magnetic gearbox under the action of a short-term load torque disturbance.

The influence of the stiffness coefficient of the magnetic transmission on the movement parameters of the electromechanical system for its two other values k_m = 5000 and 50,000 Nm/rad, which differ by ten times, was studied.

Fig. 8–10 present graphs of torques, angle differences and shaft speeds of the magnetic gearbox, as well as the spectrum of torque oscillations at low stiffness of the magnetic transmission equal to 5000 Nm/rad.



a

b

Fig. 4. Dependences of angular velocity and torque of a traction electric motor: *a* – mechanical gearbox; *b* – magnetic gearbox

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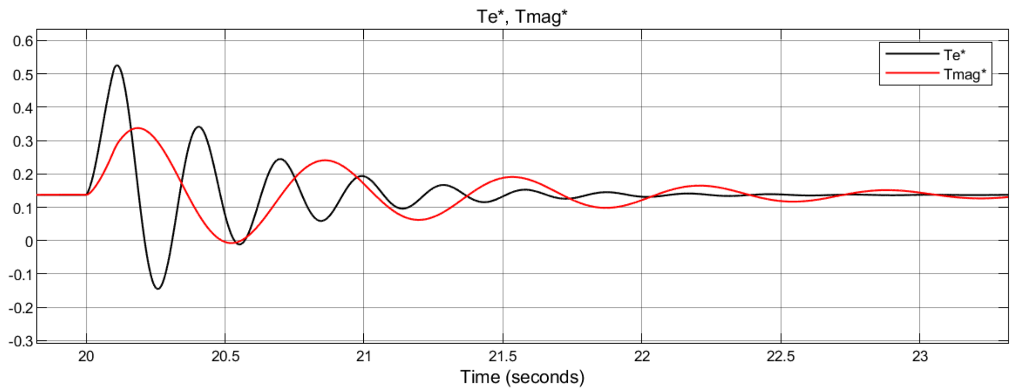
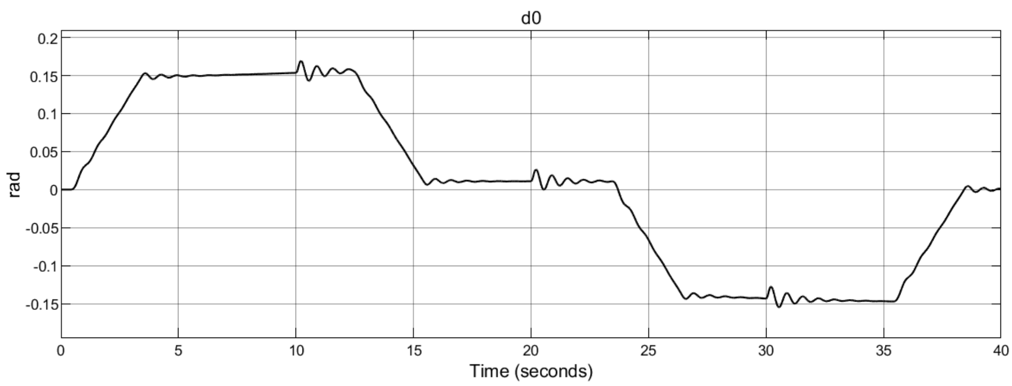


Fig. 5. Electric motor torque graphs for a system with a mechanical gearbox T_e^* and a magnetic gearbox T_{mag}^*



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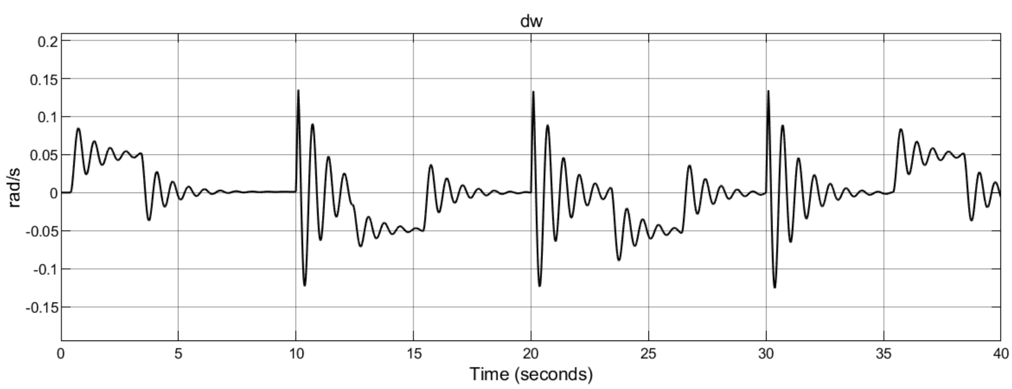
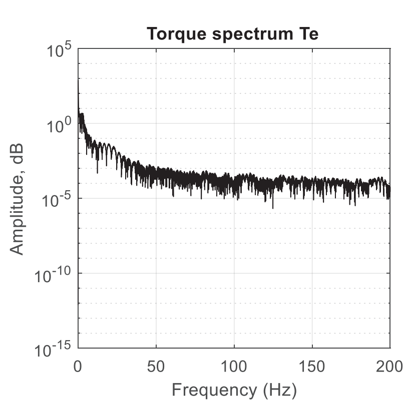


b

Fig. 6. The effect of a short-term load torque disturbance on:
a – angle difference; *b* – speed difference of the shafts of the magnetic gearbox



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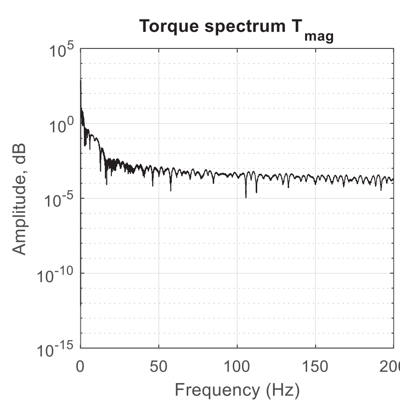


b

Fig. 7. The spectrum of oscillations of the electric motor torque:
a – with a mechanical gearbox T_e^*; *b* – with a magnetic gearbox T_{mag}^*

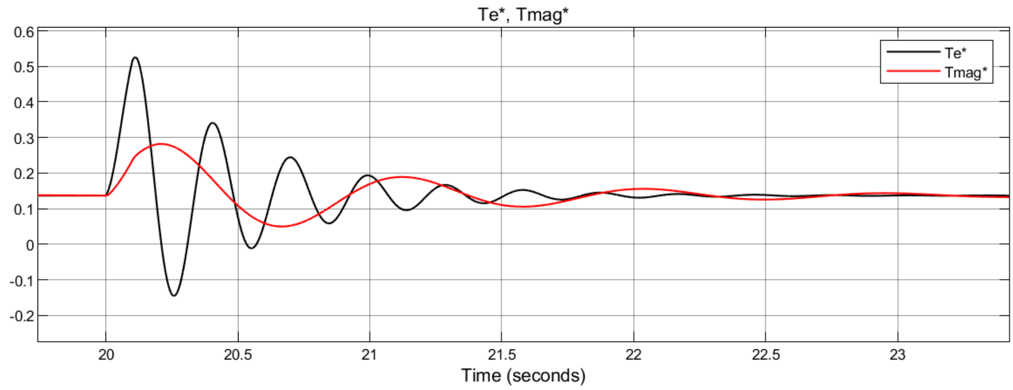
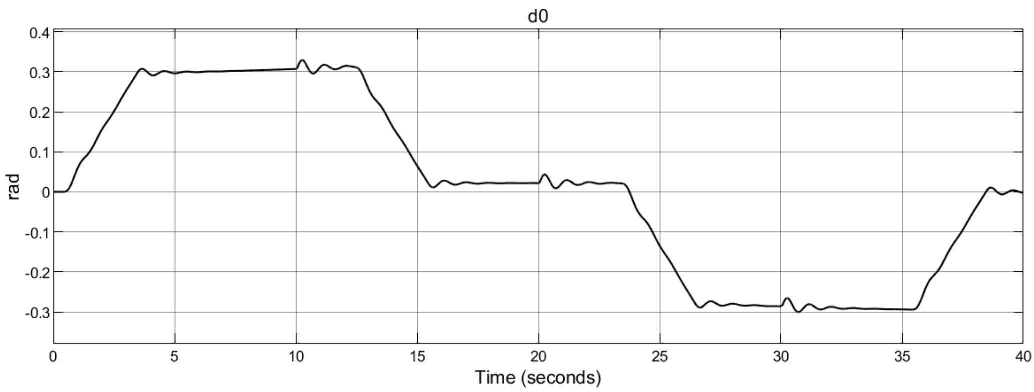


Fig. 8. Comparison of electric motor torques for a system with a mechanical gearbox T_e^* and a magnetic gearbox T_{mag}^* with low stiffness k_m = 5000 Nm/rad



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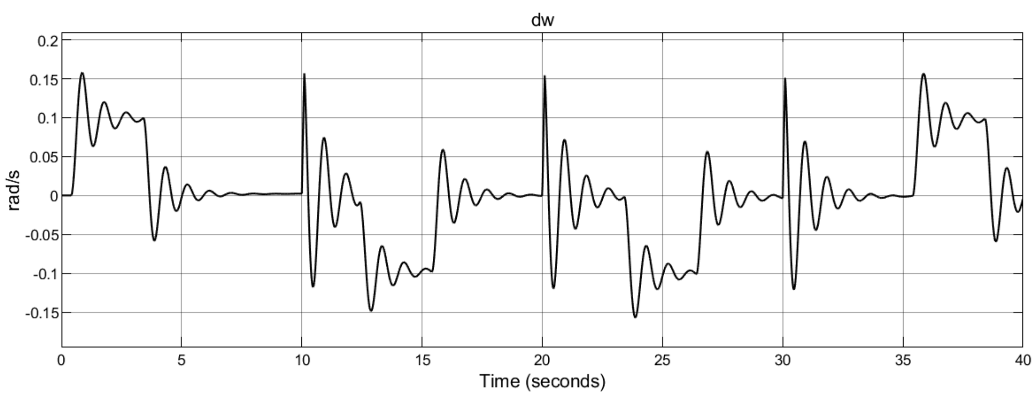
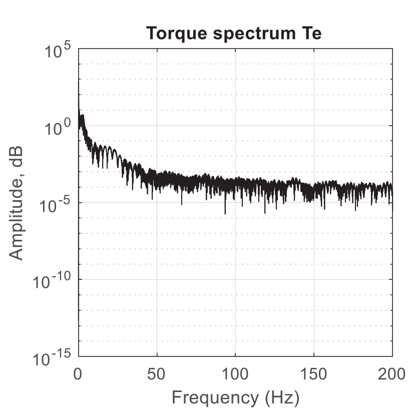


b

Fig. 9. The effect of a short-term disturbance at low transmission stiffness k_m = 5000 Nm/rad on:
a – angle difference; *b* – speed difference of the shafts of the magnetic gearbox



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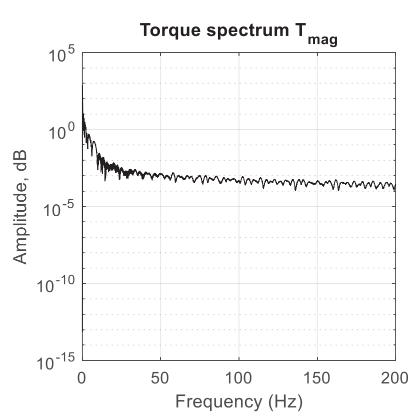

b

Fig. 10. Spectrum of oscillations of the electric motor torque:
a – with a mechanical gearbox T_e^*; *b* – with a magnetic gearbox T_{mag}^* with low transmission stiffness k_m = 5000 Nm/rad

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The research results show that a decrease in the stiffness coefficient of the magnetic transmission leads to a decrease in the amplitude of the oscillations of the electric motor torque, but increases the damping time of the transient process. In this case, the angle difference of the shafts of the magnetic gearbox increased to a value of 0.3 rad (Fig. 10, *a*), and the amplitude of oscillations of the difference in shaft speeds increased to 0.16 rad/s (Fig. 10, *b*).

Fig. 11–13 present graphs of torques, angle differences, and speeds of the magnetic gearbox shafts, as well as the spectrum of torque oscillations at high magnetic transmission stiffness equal to 50,000 Nm/rad.

The research results show that an increase in the stiffness coefficient of the magnetic transmission causes an increase in the amplitude of the electric motor torque oscillations, approaching the processes with a mechanical gearbox. The oscillation frequency also approaches the values with a mechanical gearbox, but the damping of the transient process occurs much more slowly. At the same time, the difference in the angles of the shafts of the magnetic gearbox decreased to a value of 0.037 rad (Fig. 12, *a*), and the amplitude of the oscillations of the difference in the speeds of the shafts decreased to 0.062 rad/s (Fig. 12, *b*).

The influence of the damping coefficient of the magnetic transmission on the movement indicators of the electromechanical system for its two other values b_m = 100 and 500 Nms/rad, which differ by five times, was also studied.

Fig. 14–16 present graphs of the moments, the difference in the angles and speeds of the shafts of the magnetic gearbox, as well as the spectrum of oscillations of the moments at a low damping coefficient of the magnetic transmission equal to 100 Nms/rad.

The research results show that a decrease in the damping coefficient of the magnetic transmission leads to a significant increase in the time of the transient process, but practically does not affect the magnitude of the amplitude of the oscillations.

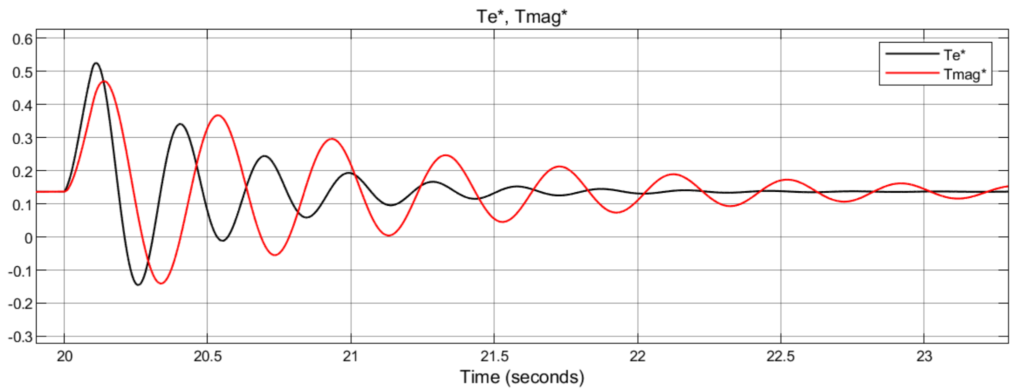
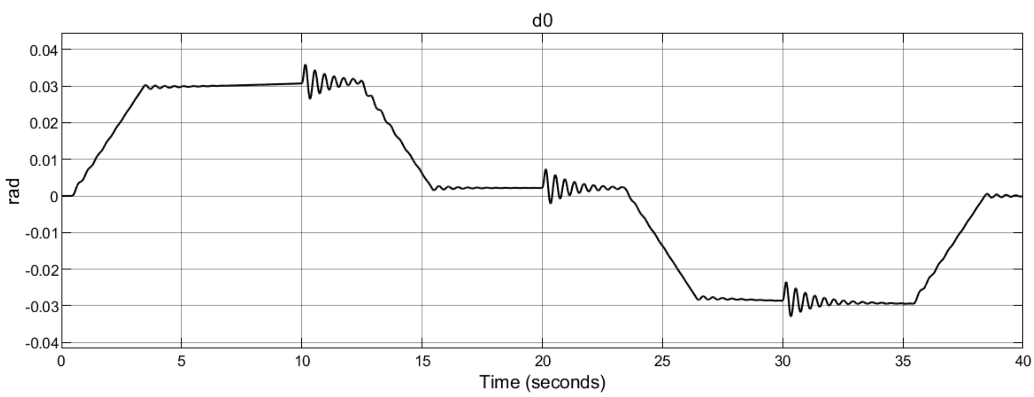
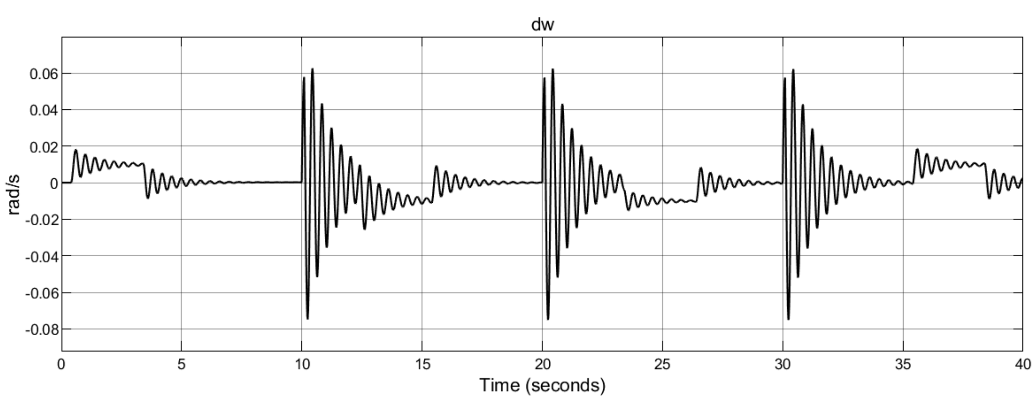


Fig. 11. Comparison of electric motor torques for a system with a mechanical gearbox T_e^* and a magnetic gearbox T_{mag}^* with high rigidity k_m = 50,000 Nm/rad



a



b

Fig. 12. The effect of a short-term disturbance at a high transmission rigidity k_m = 50,000 Nm/rad on: *a* – angle difference; *b* – speed difference of the shafts of the magnetic gearbox

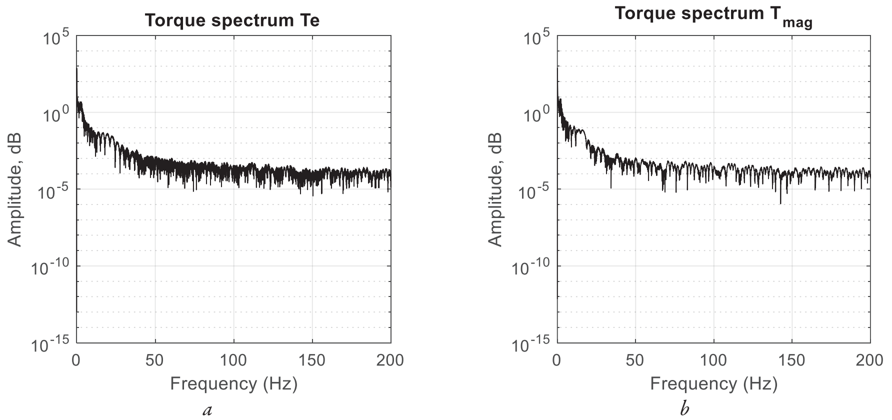


Fig. 13. Electric motor torque oscillation spectrum:
a – with a mechanical gearbox T_e^*; *b* – with a magnetic gearbox T_{mag}^* with high transmission rigidity k_m = 50,000 Nm/rad

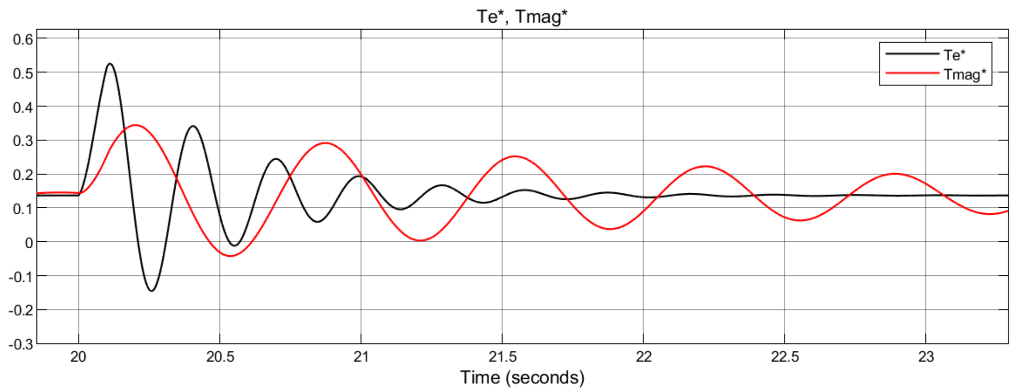


Fig. 14. Comparison of electric motor torques for a system with a mechanical gearbox T_e^* and a magnetic gearbox T_{mag}^* with low damping b_m = 100 Nms/rad

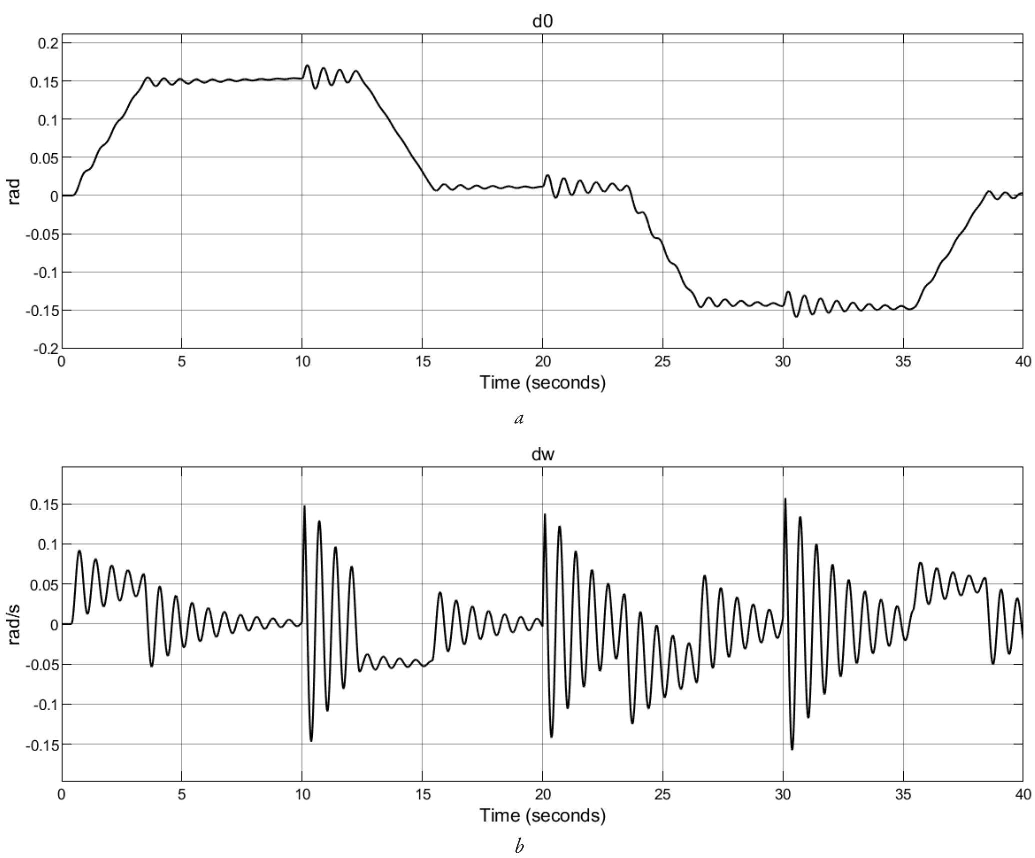


Fig. 15. The effect of a short-term disturbance at low damping b_m = 100 Nms/rad on:
a – angle difference; *b* – speed difference of the shafts of the magnetic gearbox

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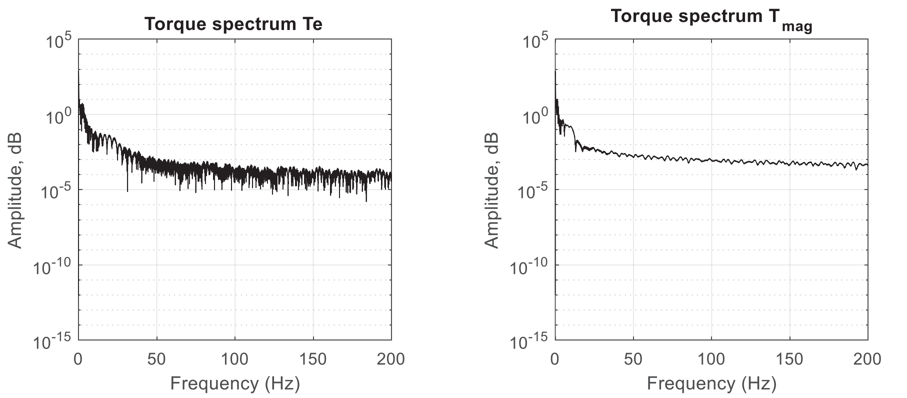


a *b*

Fig. 16. Spectrum of electric motor torque oscillations:
a – with a mechanical gearbox T_e^*; *b* – with a magnetic gearbox T_{mag}^* with low damping b_m = 100 Nms/rad

Fig. 17–19 present graphs of torques, angle differences and shaft speeds of the magnetic gearbox, as well as the spectrum of torque oscillations at a high damping coefficient of the magnetic transmission equal to 500 Nms/rad.

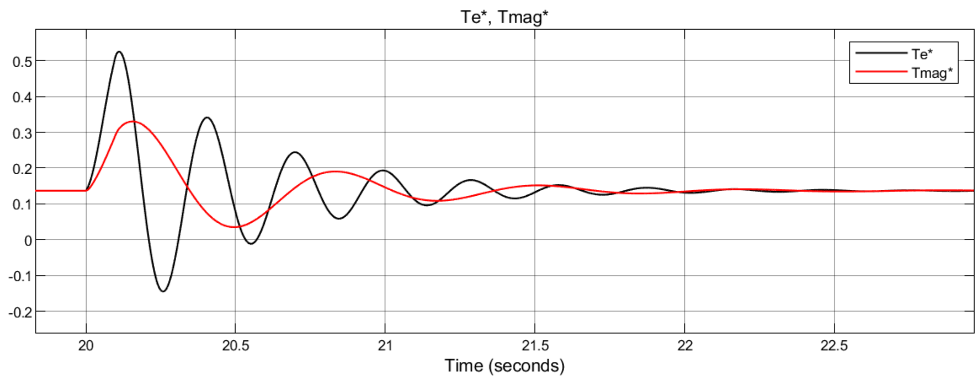
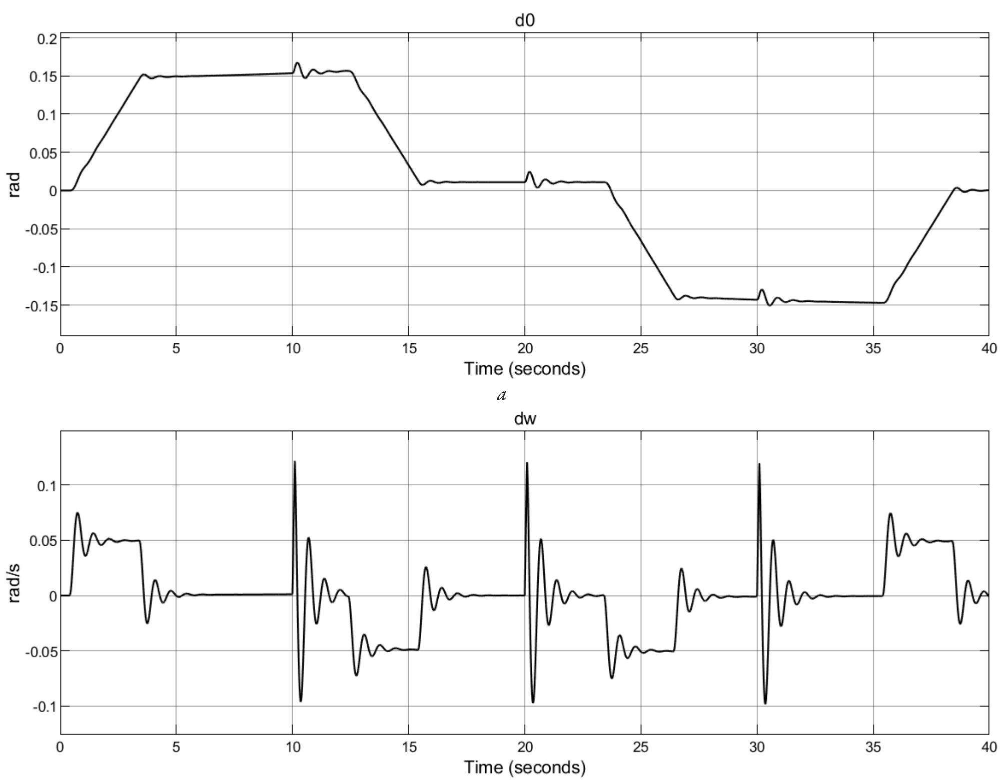


Fig. 17. Comparison of electric motor torques for a system with a mechanical gearbox T_e^* and a magnetic gearbox T_{mag}^* with high damping b_m = 500 Nms/rad



a

b

Fig. 18. The effect of a short-term disturbance at high damping b_m = 500 Nms/rad on:
a – angle difference; *b* – speed difference of the shafts of the magnetic gearbox

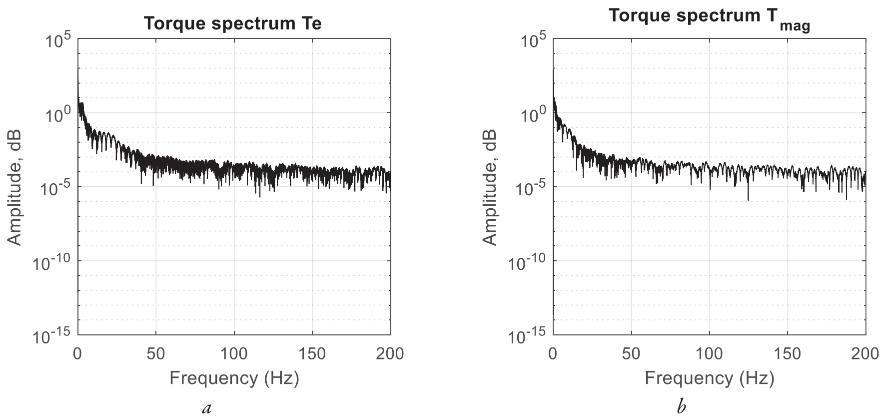


Fig. 19. Spectrum of torque oscillations of an electric motor:
a – with a mechanical gearbox T_e^*; *b* – with a magnetic gearbox T_{mag}^* with high damping b_m = 500 Nms/rad

The research results show that an increase in the damping coefficient of the magnetic transmission leads to an increase in the cost of damping and to a faster damping of torque fluctuations. The period of natural oscillations and the deviation of the angles and speeds of the shafts of the magnetic gearbox do not depend on the damping coefficient. These characteristics depend only on the stiffness coefficient of the magnetic transmission and decrease exponentially with its increase.

The effectiveness of the use of a magnetic gearbox can be assessed by the damping coefficient. It depends on both parameters of the magnetic gearbox – the stiffness coefficient and the damping coefficient, which affect the amplitudes of the transient process

$$\beta = \ln\left(\frac{A_1}{A_2}\right), \quad (11)$$

where A_1 – the first amplitude of the transient process of the torque; A_2 – the second amplitude of the transient process of the torque (Fig. 5, 8, 11, 14, 17).

Fig. 20 presents the dependences of the oscillation period, the oscillation damping coefficient, the difference in angles and speeds of the magnetic gearbox shafts on the stiffness coefficient of the magnetic transmission.

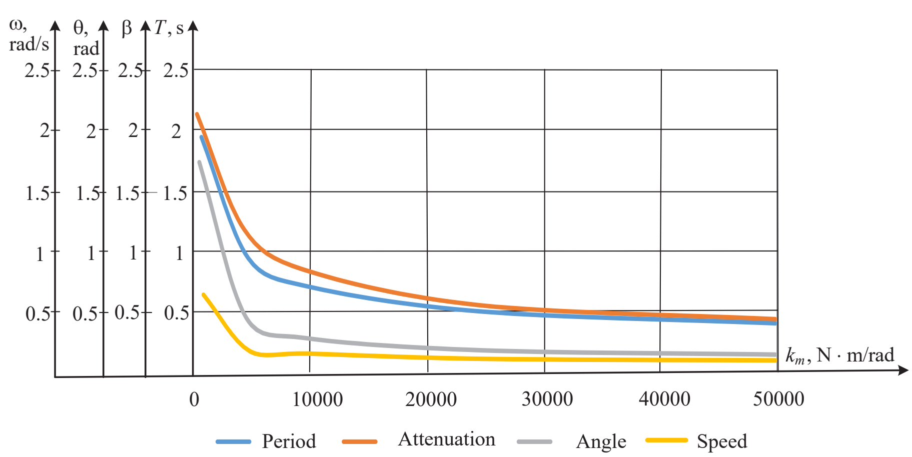


Fig. 20. Dependences of the electromechanical system indicators on the stiffness coefficient of the magnetic transmission

As can be seen, a significant influence on these indicators, in addition to the damping coefficient, is also exerted by the low value of the stiffness coefficient of the magnetic transmission. The dependence of the damping of the transient process on the damping coefficient is shown in Fig. 21. The graphs are constructed according to experimental data.

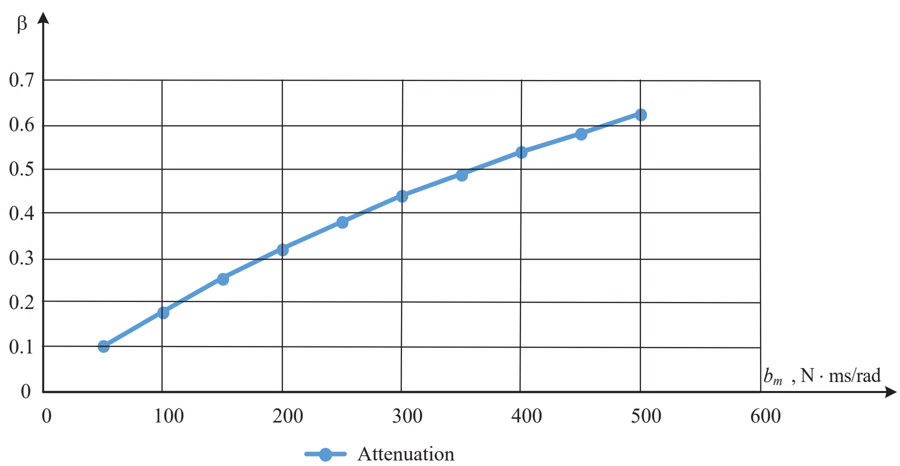


Fig. 21. Dependence of the oscillation damping coefficient on the damping coefficient of the magnetic transmission

The last graph shows that with increasing damping, the damping increases, that is, the time of the transition process is reduced, and accordingly, the electric drive returns to the steady-state operating mode. Thus, the dynamic stability of the electromechanical system increases.

Practical significance. The research results can be used in the design of new electric drive systems, where in the future a magnetic gearbox can be used instead of a mechanical one and it is important to reduce shock loads on the electric motor. For example, in electric transport, wind power, in various industries. It would also be advisable to replace the mechanical gearbox with a magnetic one in existing electric drives.

Research limitations. The limitations are the insufficient distribution of magnetic gearboxes at the current moment and the complexity of the a priori setting of the required stiffness and damping coefficients at the drive design stage.

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Prospects for further research. It will be promising to study the influence of strong disturbances of an electric drive with a magnetic gearbox on the electrical circuit of the power source. Further research also requires the possibility of designing a gearbox with optimal parameters.

4. Conclusions

1. Time dependences of torques, speeds and angles of rotation of the shafts were obtained for different operating modes of the system (acceleration, steady motion and deceleration). The constructed graphs showed the change in the amplitude and frequency of oscillations depending on the change in stiffness and damping of the magnetic gearbox. Reducing the stiffness coefficient of the magnetic gearbox from 10000 Nm/rad to 5000 Nm/rad leads to a decrease in the fundamental frequency of the oscillations of the moving torque and causes a significant decrease in the amplitude of the torque oscillations and stabilization time. Increasing the damping coefficient in the range from 100 Nms/rad to 500 Nms/rad affects only the reduction of the damping time of the transient process.
2. A spectral analysis of torque oscillations was performed to determine the frequency characteristics of the system with a magnetic gearbox. It shows that the presence of an elastic connection in the magnetic gearbox causes a decrease in the frequency of torque oscillations, which means greater inertia and better adaptation of the system to external disturbances.
3. The influence of the parameters of the magnetic gearbox on the dynamic characteristics of the electromechanical system was investigated. Increasing the stiffness brings the behavior of the system closer to mechanical transmission, reducing the difference in speeds and angular positions of the shafts.
4. The effectiveness of using a magnetic reducer as part of a traction electric drive was assessed. The simulation results showed that with a magnetic reducer stiffness of 5000 Nm/rad, the torque amplitude decreased by 59% compared to a mechanical reducer. The period of natural oscillations decreased by 62%, and the damping of the transient process increased by 59%. From the results obtained, it can be concluded that the use of a magnetic reducer with rational parameters increases the dynamic stability of the torque, reduces shock loads on the motor shaft, which increases the smoothness of operation, extends the service life of the electric drive, reduces the cost of its maintenance, and increases the service life of the system as a whole.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

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The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the submitted work.

Authors' contributions

Mykola Ostroverkhov: Conceptualization, Validation, Investigation, Writing – review and editing; ***Liudmyla Spinul***: Conceptualization, Writing – review and editing, Resources; ***Heorhii Veshchykov***: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review and editing.

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