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PECULIARITIES OF DYNAMICS OF A FAST-DRIVEN INDUCTION-DYNAMIC DRIVE WITH A BISTABLE LATCH OF CONTACTS POSITION OF A CIRCUIT BREAKER BASED ON PERMANENT MAGNETS

Introduction. Recently, in the literature, inductive-dynamic mechanisms (IDMs), known in foreign literature as a Thomson-drive, as a drive for various electrical devices are often researched and developed. The simplicity and reliability of the design, high speed make such devices indispensable in high-speed electrical devices standing in DC networks, in which emergency overcorrects are not limited by the reactance and can reach significant values. The novelty of the proposed work consists in the development of a mathematical model and the study of the Thompson drive, in which a bistable two-position mechanism consisting of a magnetic system with permanent magnets, is used as the final position latches. The movement of objects is carried out by deforming the computational mesh. The problem is a multiphysical one, in which a parallel solution of several tasks of different nature is considered. Purpose. Analysis of the fundamental possibility of creating a switching device with an induction-dynamic drive on the basis of a mathematical model which allows to increase the reliability of the entire mechanism operation and significantly simplify the design. Methods. The solution of the problem was carried out by the Finite Element Method in the COMSOL package in a cylindrical coordinate system. Results. A mathematical model of a new fast-driven induction-dynamic drive with a bistable mechanism, based on the equations of the electromagnetic field, electric circuit, equations of motion, was developed and partially studied. The model allows to calculate the dynamic parameters of the drive based on the initial data. Conclusions. The principal possibility of creating a high-speed actuator of switching devices based on an induction-dynamic mechanism and a polarized bistable mechanism based on permanent magnets is demonstrated. The research directions of the model were determined for the subsequent implementation of the results in experimental samples. References 11, table 1, figures 13.

Key words: **induction-dynamic drive, bistable latch, permanent magnets.**

У статті досліджено оригінальну математичну модель швидкодіючого індукційно-динамічного приводу вимикача з бістабільним фіксатором з двома котушками на базі постійних магнітів. Індукційно-динамічні механізми, відомі в іноземній літературі як Thomson-drive, використовуються в якості приводу вимикачів постійного струму завдяки високій швидкодії, простоті і надійності конструкції. Метою статті є аналіз принципової можливості створення комутаційного апарату з індукційно-динамічним приводом на базі математичної моделі, що дозволяє підвищити надійність роботи всього механізму і істотно спростити конструкцію. Розглядається можливість створення пропонованого комбінованого приводного механізму і визначення основних напрямків подальших досліджень з метою отримання дослідних зразків. Конструкція досліджуваного індукційно-динамічного приводу раніше в літературі не розглядалась. Вирішувана задача є мультифізичною, що включає розрахунок: статичного магнітного поля; електричного кола з урахуванням зміни напруги на конденсаторі і наведеної в котушках проти-ЕРС; динаміки руху якорів бістабільного фіксатора і привода з урахуванням зміни маси; нестаціонарного електромагнітного поля в неоднорідному нелінійному середовищі з урахуванням постійних магнітів і руху струмопровідних тіл в електромагнітному полі. Напрямки подальших досліджень представляються у вигляді оптимізації геометрії, параметрів котушок привода і конденсаторів, геометрії бістабільного фіксатора, об'єму і залишкової індукції постійних магнітів для забезпечення необхідних значень швидкодії, контактного натискання і габаритів апарата. Бібл. 11, табл. 1, рис. 13.

Ключові слова: **індукційно-динамічний привод, бістабільний фіксатор, постійні магніти.**

В статье исследована оригинальная математическая модель быстродействующего индукционно-динамического привода выключателя с бистабильным фиксатором с двумя катушками на базе постоянных магнитов. Индукционно-динамические механизмы, известные в иностранной литературе как Thomson-drive, применяются в качестве привода выключателей постоянного тока благодаря высокому быстродействию, простоте и надежности конструкции. Целью статьи является анализ принципиальной возможности создания коммутационного аппарата с индукционно-динамическим приводом на базе математической модели, что позволяет повысить надежность работы всего механизма и существенно упростить конструкцию. Рассматривается возможность создания предлагаемого комбинированного приводного механизма и определение основных направлений дальнейших исследований с целью получения опытных образцов. Конструкция исследуемого индукционно-динамического привода ранее в литературе не рассматривалась. Решаемая задача является мультифизической, включающей расчет: статического магнитного поля; электрической цепи с учетом изменения напряжения на конденсаторе и наведенной в катушках противо-ЭДС; динамики движения якорей бистабильного фиксатора и привода с учетом изменения массы; нестационарного электромагнитного поля в неоднородной нелинейной среде с учетом постоянных магнитов и движения проводящих тел в электромагнитном поле. Направления дальнейших исследований представляются в виде оптимизации геометрии, параметров катушек привода и конденсаторов, геометрии бистабильного механизма, объема и остаточной индукции постоянных магнитов для обеспечения требуемых значений быстродействия, контактного нажатия и габаритов аппарата. Библ. 11, табл. 1, рис. 13.

Ключевые слова: **индукционно-динамический привод, бистабильный фиксатор, постоянные магниты.**

Introduction. Recently, in the literature quite often induction-dynamic mechanisms (IDMs) are investigated and developed, known in foreign literature as a *Thomson-drive*, used as a drive for various electrical devices [1-4]. The simplicity and reliability of the design, high speed make such devices indispensable in electrical devices installed in DC networks, in which emergency overcurrents are not limited by reactance and can reach tens of kiloamperes.

Despite the obvious advantages, such devices have a number of significant disadvantages: significant shock load on the structural elements; the need to fix the position of the mechanism at the start and end points of the movement trajectory with the possibility of returning to the starting position. The solution to the first problem is either to use damping devices at the final stage of movement, or using optimal control of the movement by connecting a braking coil. The second problem is solved through the use of bistable mechanical latches, known for a long time [3-5]. A mathematical model of the drive with optimal control of the IDM armature speed and mechanical bistable latch was considered in [4] and investigated in [6], where the main disadvantages of such a model are shown. In [7], a Thompson-drive was considered, and an electromagnetic latch is used as a position latch. But, according to the authors, the most promising drive designs for high-speed circuit breakers are drives that combine the speed of induction-dynamic systems and the reliability of magnetic systems with permanent magnets [8, 9]. For example, in [8] the calculation of such a drive consists of two parts: static calculation of the flux and electromagnetic force; dynamics calculation based on the ordinary differential equations of the motion and the electrical circuit. This approach is not new [10] and has a number of significant drawbacks associated with the determination of the braking effect of eddy currents in the system, especially in high-speed systems. In addition, the system is quite complex: two IDM coils are located inside two magnetic cores; the actuator also has two coils and consists of two magnetic cores with permanent magnets.

The IDM design flaws identified during the review significantly affect the reliability of the switching device. One way to solve the problem is the possibility of creating a drive mechanism with a bistable position latch based on permanent magnets.

The goal of the paper is analysis of the fundamental possibility of creating a switching device with an induction-dynamic drive on the basis of a mathematical model which allows to increase the reliability of the entire mechanism operation and significantly simplify the design.

Subject of investigations. This paper carries out a comprehensive study of the Thompson-drive with optimal control of the closing speed of electrical contacts, which uses a magnetic device consisting of a magnetic system, an armature with a non-magnetic rod and permanent magnets as the bistable latch of the movable system of the apparatus in the initial and final positions.

The mathematical model of the mechanism under study is solved by deformation of the computational mesh. The deformation of the mesh depends on the travel and speed of the armatures, which, in turn, determine the parameters of the system (electromagnetic forces, air gaps, etc.). This problem is multiphysical, i.e. the task of sequentially-parallel solution of several different in nature problems: calculation of static magnetic field; calculation of the electric circuit, taking into account the change in voltage on the capacitor and taking into account the counter-EMF induced in the coils; calculation of the dynamics of movement of the armatures of a bistable latch and drive taking into account the change in mass; calculation of transient electromagnetic field in an inhomogeneous nonlinear medium taking into account permanent magnets and the motion of conductive bodies in the electromagnetic field. The algorithm for solving the defined problem lies in the fact that at the initial stage, the stationary field of permanent magnets is calculated and the results obtained are used as initial conditions for the remaining parallel problems.

This paper can be classified as debatable, since it explores the very possibility of creating a new type of drive.

Basic calculation relationships and assumptions. Figure 1 shows a diagram of an apparatus with a drive system (in a cylindrical coordinate system) and overall dimensions in mm are indicated. The coils of the induction-dynamic drive 1, 2 perform the function of switching on and off the device on and off, as well as the function of optimally controlling the movement of the drive armature and bistable latch (reducing the speed of the contacts before closing).

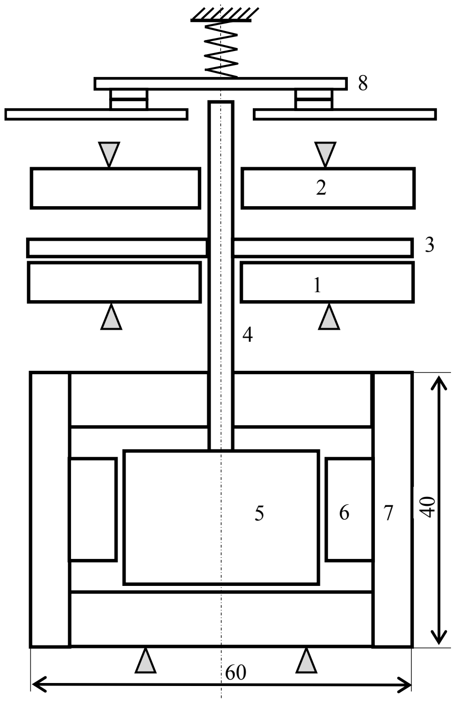


Fig. 1. Diagram of a switching device with an induction-dynamic drive and a bistable magnetic latch: 1, 2 – drive coils; 3– drive armature (conductive disk); 4 – non-magnetic rod; 5 – armature of the latch connected by a non-magnetic rod to the drive armature; 5 – permanent magnets located around the perimeter of the armature of the latch; 7 – fixed magnetic system; 8 – contact system of the switching device

The armature of the induction-dynamic drive 3, made in the shape of a disk, is connected to the armature of the bistable latch 5 by a non-magnetic rod 4. The armatures 3 and 5 are fixed in the extreme positions (lower and upper) due to the action of permanent magnets 6 fixed in the housing. Such a drive mechanism consumes energy only during operation. To reduce the speed of contact closure when switched on, a reverse polarity (relative to coil 1) voltage is applied to the coil of winding 2, which slows down the speed of the system before touching the rod with contacts 8.

In the calculation, the following assumptions were made: a uniform distribution of the current density over the area of the coil winding space (the coil is wound with a wire whose cross-sectional area is much smaller than the coil winding space); the absence of hysteresis in ferromagnetic.

The main calculation relation is the equation of transient electromagnetic field written in the term of the magnetic vector potential [11] under the condition that there is no field at the outer boundary of the calculation domain

$$\sigma_k \cdot \frac{\mathrm{d}\boldsymbol{A}_k}{\mathrm{d}t} + \cdot\nabla\times\left(\frac{1}{\mu_k}\cdot\left(\nabla\times\boldsymbol{A}_k - \boldsymbol{B}_\mathrm{r}\right)\right) = \boldsymbol{\delta}_k\,, \qquad (1)$$

where σ_k is the electrical conductance of the material; $\boldsymbol{A}_k$ is the magnetic vector potential; μ_k is the absolute magnetic permeability; $\boldsymbol{B}_\mathrm{r}$ is the residual magnetic flux density of the permanent magnet; $\boldsymbol{\delta}_k = (i\cdot N/S)\cdot\mathbf{1}_\varphi$ is the current density of the external source; $\mathbf{1}_\varphi$ is the azimuthal unit vector – a unit vector directed perpendicular to the plane in which the calculation area is located; i is the current in the coil winding; N is the number of turns of the winding; S is the area of the winding space of the coil.

The form of the system of equations (1) is determined by the computational domain (air, coils, conductive disk, magnetic circuit, permanent magnet). In (1), the total time derivative is indicated in the case of calculation of the field in the moving domain (drive armature and bistable latch).

Electrical circuit equations

$$L_1\cdot\frac{\mathrm{d}i_1}{\mathrm{d}t} + R_1\cdot i_1 + E_1 = \left(E_{C01} - \frac{1}{C_1}\cdot\int_t i_1\cdot\mathrm{d}t\right)\cdot\eta_1;$$

$$L_2\cdot\frac{\mathrm{d}i_2}{\mathrm{d}t} + \left(R_2 + R_\mathrm{d}\cdot\eta_2\right)\cdot i_2 + E_2 = \qquad (2)$$

$$= \left(-E_{C02} - \frac{1}{C_2}\cdot\int_t i_2\cdot\mathrm{d}t\right)\cdot\eta_1,$$

where L_1, L_2 are the external circuit leakage inductances; R_1, R_2 are the resistances of windings of drive coils; $E_{1,2}$ are the counter-EMF of windings:

$$E_{1,2} = \frac{N}{S}\cdot\int_V \frac{\partial A_\varphi}{\partial t}\cdot\mathrm{d}V\,, \qquad (3)$$

where V is the volume of the coil winding (1 or 2); E_{C0} is the initial voltage on the capacitance; i_1, i_2 are the currents in the windings of the coils; R_d is the additional resistance; η_1, η_2 are the unit functions simulating the aperiodic discharge of the capacitor and the beginning of the discharge of the second capacitance to the winding of the braking coil.

$$\eta_1 = \begin{cases}1, U_c > 0\\ 0, U_c < 0\end{cases},\quad \eta_2 = \begin{cases}1,\ z(t) > z_1\\ 0,\ z(t)\le z_1\end{cases}. \qquad (4)$$

The equations of motion are equations of the dynamics of a body with a variable mass, because after the contacts are closed, the mass reduced to the IDM armature changes

$$\begin{cases}\dfrac{\mathrm{d}}{\mathrm{d}t}\cdot\left(m(z(t))\cdot v(t)\right) = \left[F_\mathrm{em} - F_0\cdot\eta_4 + F\left(z(t)\right)\right]\cdot\eta_3;\\ \dfrac{\mathrm{d}z(t)}{\mathrm{d}t} = v(t)\end{cases}, \qquad (5)$$

where $m(z(t))$ is the changing mass of the system; $v(t)$ is the speed of the movable system; $F_\mathrm{em} - F_0\cdot\eta_4 + F\left(y(t)\right)$ is the total force; η_3 is the function that prohibits movement beyond permissible limits (stops); η_4 is the function that determines the beginning of the collision of contacts and the beginning of the action of the force of contact pressing; $F\left(z(t)\right)$ is the force acting on the bistable latch's armature reduced to the drive armature.

The system of equations (1)-(5) is a mathematical model of a high-speed induction-dynamic drive with a bistable latch with permanent magnets.

Initial conditions and input data. As the input data, the masses moving along with the drive armature and the mass of contacts were specified. The moment of impact is extended by 0.3 ms in time, and the derivative of the mass along the coordinate was selected based on the law of conservation of moment of momentum.

Based on the geometry of the coils (Fig. 1) and the cross section of the winding wire, the resistances of the windings and the number of turns were determined taking into account the fill factor. Since each of the coils can be either accelerating or braking, the initial voltage and capacitance of the capacitors were chosen the same: 600 V, 400 μF.

Graphs of changes in mass and its derivative are shown in Fig. 2.

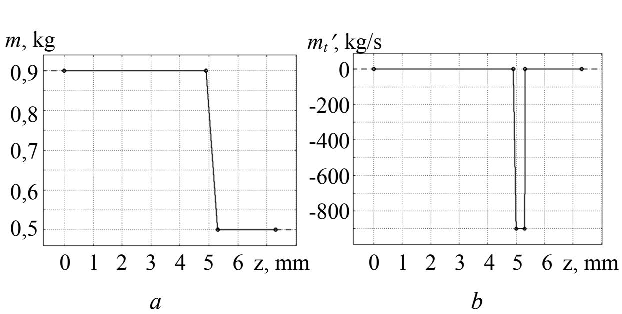


Fig. 2. Graphs of change in mass (a) and its derivative (b)

The software allows optimization calculations with a change in the cross section of the winding wire. One of the main parameters to be set is the full stroke of the system's armatures equal to 7 mm [6] and the stroke to the contact touch of 5 mm. The force of contact pressing was assumed to be constant and equal to 200 N, the initial mass is 0.9 kg (see Fig. 2).

Results. Static calculations. These calculations are necessary for the following reasons: 1) the results obtained are the initial values for calculating the dynamics; 2) they make it possible to obtain a static power characteristic of a bistable latch as a function of the magnetic flux density of a permanent magnet. Figure 3 shows a picture of the magnetic field in the extreme positions of the bistable latch's armature.

Obviously, the redistribution of the magnetic field (Fig. 3) leads to a change in the sign of the electromagnetic force (Fig. 4). Changing the sign of the electromagnetic force of the latch provides bistable operation of the drive.

The static traction characteristic of the bistable latch as a function of the armature stroke is given for the value of the permanent magnet residual magnetic flux density B_r = 0.5 T. The values of the initial force depending on the value of the residual magnetic flux density of the permanent magnet are given in Table 1. Moreover, when the value of the residual magnetic flux density changes, the form of the characteristic does not change, but only the force values change.

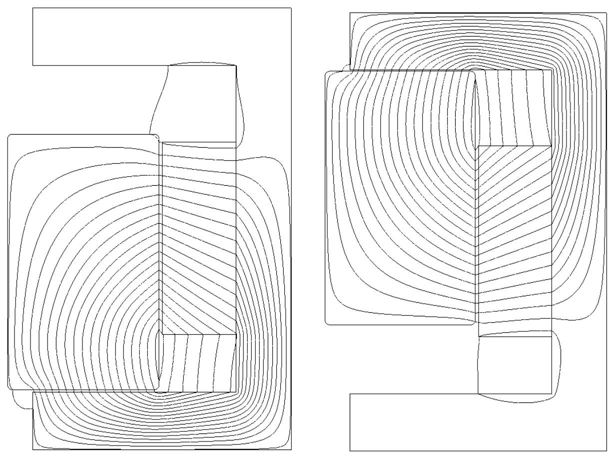


Fig. 3. Picture of the magnetic field of the bistable latch in the extreme positions of the armature (in static)

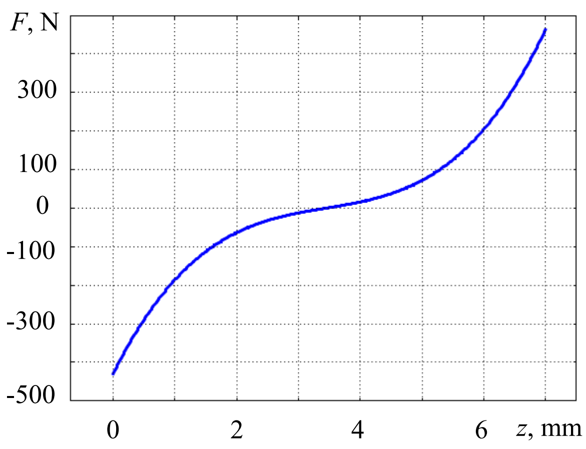


Fig. 4. Static traction characteristic of the bistable latch as a function of the armature stroke

Table 1

Values of initial force as a function of B_r

B_r, T	0.5	0.6	0.7	0.8	0.9	1.0
$F(0)$, N	429	571	689	776	844	899

The calculation of the dynamics. Switching on. Calculations show that the fields of the drive coils are closed through the magnetic circuit of the bistable latch which significantly affects the processes in it. Figure 5 shows the dependencies of the stroke of the bistable clatch's armature as a function of time for various types of magnetic circuit – solid and burnt ones. In the case of a solid magnetic circuit of a bistable clatch due to the demagnetizing effect of eddy currents that coincide in direction with the currents of the braking coil, there is a significant decrease in speed and the reverse movement of the armatures of the drive and bistable latch and no operation (curve 1). An increase in the resistance to eddy currents, for example, due to the use of steel with high specific resistance, lamination of the magnetic circuit or making radial cuts in it, ensures a clear operation of the switching device (curve 2).

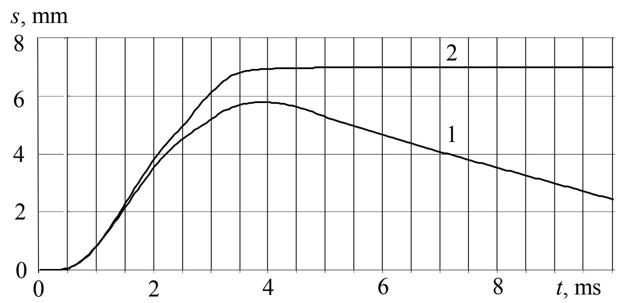
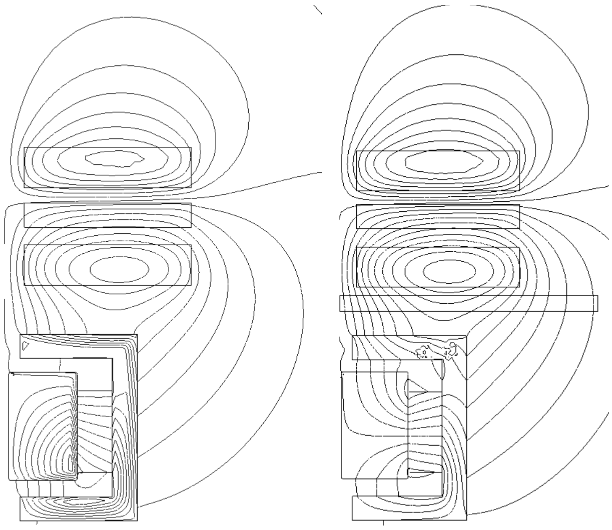


Fig. 5. Armature stroke for various types of magnetic circuit: 1 – solid; 2 – laminated

Figure 6 shows the field lines at the instant of maximum current in the «braking» coil of the induction-dynamic drive. As can be seen from Fig. 6, with the solid magnetic circuit, the field of the permanent magnet practically does not penetrate into the upper part of the latch's magnetic circuit (there is no redistribution of the flux and a change in the sign of force), in contrast to the laminated magnetic circuit, where the redistribution of the flux of the permanent magnet is clearly visible. This is confirmed by the calculated values of forces. At time of ≈1 ms (the field picture is shown in Fig. 6), the force acting on the bistable latch's armature in the case of the solid magnetic circuit is minus 130 N, for the laminated one is is plus 10 N (the force changed its sign).

The diameter of the winding wire (for fixed coil sizes) affects the nature of the movement and in the case of the solid magnetic circuit, the reverse movement of the bistable latch's armature may not be present. However, due to the action of eddy currents, the magnetic force of the bistable latch with the solid magnetic circuit in the final position of the armature is much less (about two times) than that of the bistable latch with the laminated magnetic circuit.



a *b*

Fig. 6. Picture of the field at the moment of maximum current in the «braking» coil: *a* – the solid magnetic circuit; *b* – the laminated magnetic circuit

The influence of the cross section of the winding wire of the coils on the contact closure speed is shown in Fig. 7. The speed graph consists of several sections: acceleration; braking before touching the contacts (the moment of touching is marked with a bold dot on the graphs); an increase in speed at a dip due to a decrease in the total moving mass (by the value of the mass of contacts); stop. In the examples considered, the time before touching the contacts differs by approximately 30 % (from 2.3 to 3 ms).

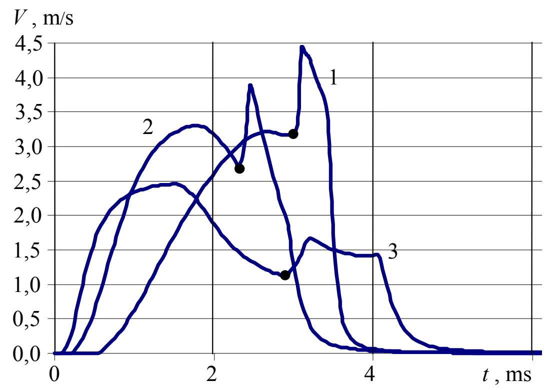


Fig. 7. Dependence of the contact closure speed on wire section: 1 – 0.66 mm^2 (N = 550); 2 – 1 mm^2 (N = 240); 3 – 1.5 mm^2 (N = 106)

As a result of the calculations, it was found that the stroke at which the discharge of the capacitor to the braking coil begins with the path taken and the contact failure affects the response time of the drive (Fig. 8).

Characteristic 1 corresponds to the beginning of the discharge of the capacitor to the braking coil when the armature stroke of the induction-dynamic drive is 0.5 mm (earlier braking). Characteristic 2 is later braking of the armature (2.5 mm stroke).

It can be seen from the graph (Fig. 8) that the operations time differs by about 25 %, which indicates a small effect of the braking coil on the movement of the drive armature (effect is significant with small gaps between the drive armature and the coil).

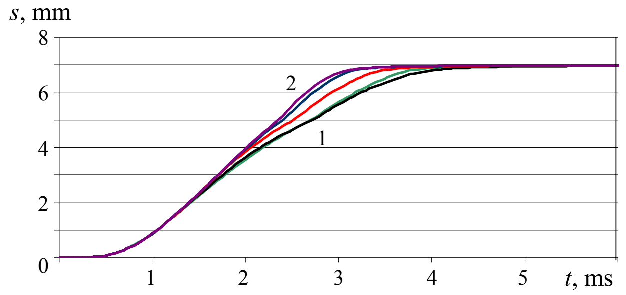


Fig. 8. Changing the value of the armature stroke in the function of the beginning of the signal supply to the braking coil (the beginning of the capacitor discharge): 1 – when the armature reaches the stroke value of 0.5 mm; 2 – when the armature reaches the stroke value of 2.5 mm; other values are intermediate

Further, all calculations of physical processes are carried out for the following values: the beginning of the braking process of the drive armature corresponds to the stroke of 0.5 mm with the coil wire cross section of 1.5 mm^2 (N = 106).

Figure 9 is a graph of the acting forces. As follows from Fig. 9, the force acting on the drive armature and the magnetic force of the bistable latch change their sign depending on the stroke. Characteristic 1 changes its sign due to the discharge of the capacitor to the braking coil, characteristic 2 – due to the redistribution of fluxes in the magnet.

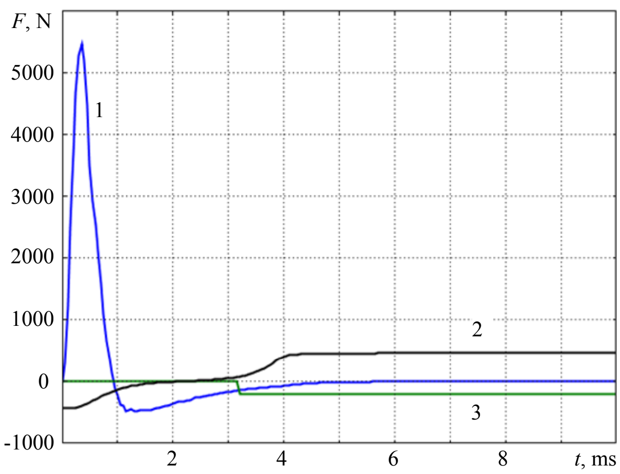


Fig. 9. Graphs of acting forces: 1 – force acting on the drive armature; 2 – magnetic force of the bistable latch; 3 – contact pressure force

Figure 10 shows the current values in the coils of the high-speed drive. As calculations show, coil currents have virtually no effect on each other. The aperiodic shape of the discharge (as the most optimal for using the energy of a capacitive storage and the safest for an electrolytic capacitor) is provided by diodes connected in parallel with the coils. Despite the identical parameters of the coils and capacitive storage, the currents are different in maximum values and the decay rate (Fig. 10), which is associated with the position of the drive armature in the intercoil space (the equivalent inductance of the electrical circuits of the first and second coils is different).

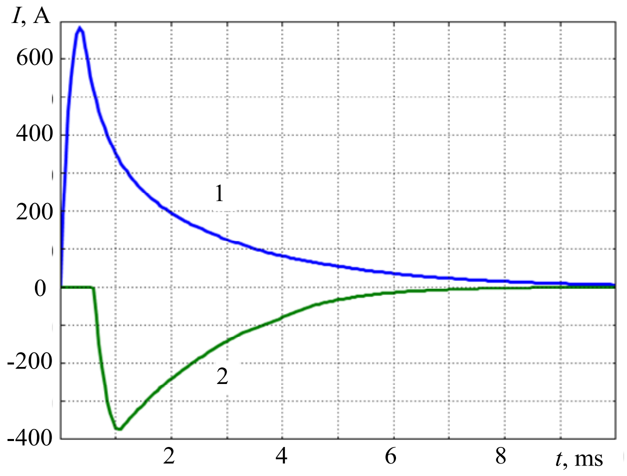


Fig. 10. Currents of the coils: 1 – switching on; 2 – braking

Figure 11 shows the dependencies of the stroke and speed of the drive armature and the bistable latch armature as a function of time during contact closure.

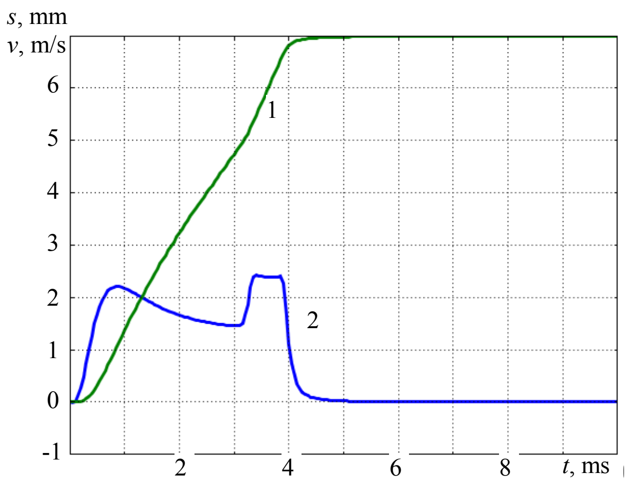


Fig. 11. Drive dynamics during contact closure:
1 – stroke; 2 – speed

The dynamics of the switching off. For high-speed switching devices, an important parameter is the time interval from the moment the signal is sent to the switching off to the moment the beginning of the contacts opening. Since the drive coils are identical, the changes in the model will relate to equations describing the mechanics of movement: – the force of contact pressure on the value of the contact failure will be not opposing, but driving; – the mass change graph will be mirrored with respect to the graph in Fig. 2,*a*, and the derivative of the mass with respect to the displacement (Fig. 2,*b*) will be positive.

Figure 12 shows the drive's switching off dynamics. As follows from Fig. 12, the opening of the contacts occurs in a time of the order of 1 ms, which confirms its speed.

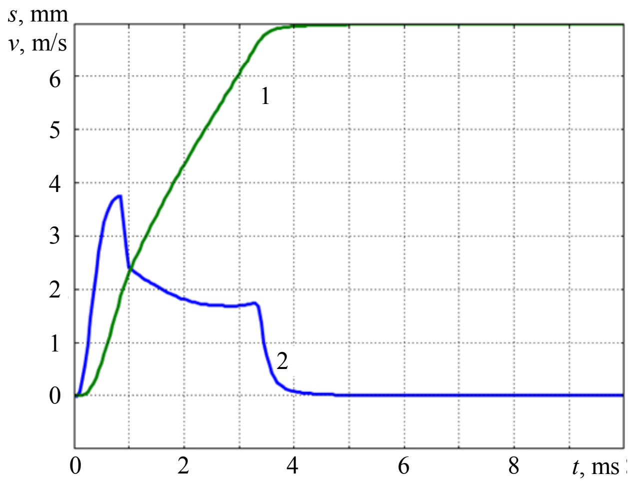


Fig. 12. Switching off dynamics: 1 – stroke; 2 – speed

Figure 13 shows the current in the armature of the induction-dynamic drive during the «switching off» operation.

Despite the current value of 45 kA, the temperature of the armature of the induction-dynamic drive during the movement increases slightly (by 0.8 °C) due to the short duration of its thermal effect.

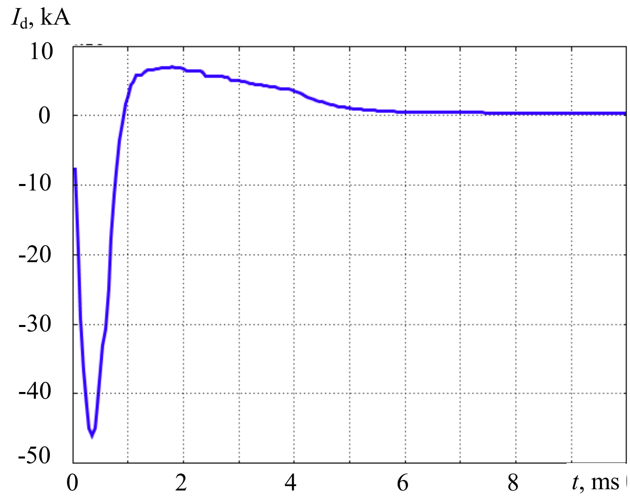


Fig. 13. Drive armature current as a function of time

Conclusions.

1. A mathematical model of a new high-speed induction-dynamic drive with a bistable latch based on permanent magnets based on the equations of the electromagnetic field, the electric circuit and the equations of motion has been developed and partially investigated. The model allows to calculate the dynamic parameters of the drive based on the source data.

2. The fundamental possibility of creating a high-speed drive of this type is shown.

3. Directions for further research may be the following: optimization of the geometry, parameters of the drive coils and capacitors, the geometry of the bistable latch, the volume and residual magnetic flux density of

permanent magnets to ensure the required values of speed, contact pressure and dimensions of the apparatus. A further area of research may also be the study of processes at the contacts of the circuit breaker depending on the parameters of the drive and the calculation of the mechanical forces arising in the drive during starting, movement and braking.

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