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GEOMETRIC AND ELECTROPHYSICAL PARAMETERS OF ARMATURE WINDING OF ELECTROMECHANICAL CONVERTER OF INERTIAL ENERGY STORAGE FOR SUBURBAN TRAINS

Purpose. To establish analytical expressions of machine constant and electromagnetic parameters for a specific circuit of the armature winding of an electromechanical converter of an inertial energy storage device, which is a DC electric machine with a semiconductor switch and excitation from permanent magnets. Methodology. For research the theory of electrical circuits is used to create a mathematical model of the processes of electromechanical energy conversion in an inertial storage device. The plots method is used to find the mutual inductance of the armature winding coils, which are presented in the form of infinitely thin single-turn contours of rectangular shape, located in three-dimensional space. Results. Mathematical models of the processes of electromechanical energy conversion in an inertial storage device are obtained reflecting the relationship between the exchange energy and drive power with geometric and electrophysical parameters of both the energy accumulator and the system of its electromechanical converter. A connection of the parameters of machine constant, active and inductive resistances with the configuration, wiring diagram and the geometric dimensions of the armature winding has been established. The wiring of sections in the phase of the armature winding depends on the required value of the voltage and current of the machine. The possibility of regulating the voltage of the drive by switching on and off the working phases of the system of electromechanical converter, as well as by changing the angle of the load is shown. Originality. Mathematical models are obtained that relate the indicators of the energy of exchange and the power of the drive to the geometrical and electro physical parameters of both the energy accumulator and the system of its electromechanical converter. A feature of these models is operating with an average value of induction and machine constants when determining the electromotive force and electromagnetic moment. Practical value. Recommendations are developed for determining the machine constant and electromagnetic parameters of electromechanical inertial energy storage devices. This allows to evaluate the properties of devices of this type in the modes of storage and delivery of energy during their operation on board the rolling stock. References 7, table 1, figures 5.

Key words: **inertial electromechanical energy storage, electromechanical converter, armature winding, machine constants, active resistance, inductive resistance.**

Мета. Встановлення аналітичних виразів машинних постійних і електромагнітних параметрів для специфічної схеми обмотки якоря електромеханічного перетворювача інерційного накопичувача енергії у вигляді оберненої електричної машини постійного струму з напівпровідниковим комутатором і збудженням від постійних магнітів. Методика. Для проведення досліджень використана теорія електричних кіл, метод ділянок для знаходження взаємної індуктивності котушок обмотки якоря. Результати. Встановлено зв'язок параметрів машинних постійних, активного та індуктивного опорів з конфігурацією, схемою з'єднання і геометричними розмірами обмотки якоря. Наукова новизна. Для специфічних схем якірних обмоток системи електромеханічного перетворення енергії інерційних накопичувачів знайдені аналітичні вирази машинних постійних і електромагнітних параметрів, які визначають показники енергії обміну і потужності накопичувача. Практичне значення. Розроблені рекомендації щодо визначення машинних постійних і електромагнітних параметрів інерційних електромеханічних накопичувачів енергії дозволяють оцінити властивості пристроїв такого типу на борту рухомого складу. Бібл. 7, табл. 1, рис. 5.

Ключові слова: **інерційний електромеханічний накопичувач енергії, електромеханічний перетворювач, обмотка якоря, машинні постійні, активний опір, індуктивний опір.**

Цель. Установление аналитических выражений машинных постоянных и электромагнитных параметров для специфической схемы обмотки якоря электромеханического преобразователя инерционного накопителя энергии в виде обращенной электрической машины постоянного тока с полупроводниковым коммутатором и возбуждением от постоянных магнитов. Методика. Для проведения исследований использована теория электрических цепей, метод участков для нахождения взаимной индуктивности катушек обмотки якоря. Результаты. Установлена связь параметров машинных постоянных, активного и индуктивного сопротивлений с конфигурацией, схемой соединения и геометрическими размерами обмотки якоря. Научная новизна. Для специфических схем якорных обмоток системы электромеханического преобразования энергии инерционного накопителя найдены аналитические выражения машинных постоянных и электромагнитных параметров, которые определяют показатели энергии обмена и мощности накопителя. Практическое значение. Разработанные рекомендации по определению машинных постоянных и электромагнитных параметров инерционных электромеханических накопителей энергии позволяют оценить свойства устройств такого типа на борту подвижного состава. Библ. 7, табл. 1, рис. 5.

Ключевые слова: **инерционный электромеханический накопитель энергии, электромеханический преобразователь, обмотка якоря, машинные постоянны, активное сопротивление, индуктивное сопротивление.**

Introduction. The use of energy storage devices, both in the traction network and on the rolling stock of railways, is one of the effective means of saving energy resources and protecting the environment. Of the four types of storage devices known to date that are suitable for these purposes (two-layer capacitors, lithium-ion batteries, flywheels, and superconducting magnets), only the first three types are now implemented [1-3]. Moreover, on the prototype suburban rolling stock – only of inertial type, which is an aggregate that consists of a cylindrical flywheel connected on one shaft with a synchronous electric machine [4].

A more compact design of the inertial electromechanical energy storage device (IEMESD) takes place when the electromechanical converter, representing a DC machine with a thyristor switch, is located inside a hollow cylindrical flywheel. The design of such a storage device was previously developed at NTU «KhPI» for the traction network of the subway [5]. However, its parameters and performance are selected in such a way as to interact with the load – the traction network, as a rule, with insignificantly changing voltage.

The operation of IEMESD on electric rolling stock (ERS) is characterized by other conditions for the process of energy exchange between the storage device and the load – traction motors. Here, in the braking and acceleration mode of the ERS, significant changes in the nature and level of voltages on the traction motors and the storage device take place. The use of IEMESD on rolling stock makes it possible to utilize the braking energy and use it after that to accelerate the train, which provides an efficient energy-saving technology of electric transport. The accumulated energy circulates in the traction electric drive system, which saves up to 30% of the energy spent on traction [6].

Therefore, the study of the parameters of such drives in the conditions of their operation on the ERS is today a promising direction.

In the papers, the authors investigate IEMESD which is a combination of a flywheel and an electromechanical energy conversion system (EMECS), which is taken as a reversed DC electric machine with a semiconductor switch on IGBT transistors and excitation from permanent magnets (Fig. 1). Along with the magnetic system of the inductor, the configuration, connection diagram, and geometrical dimensions of the armature winding are decisive in obtaining the required power of EMECS.

The goal of the work is the establishment of analytical expressions of machine constants and electromagnetic parameters for specific circuits of armaturer windings of an electromechanical converter of an inertial energy storage device.

The mathematical model of EMECS storage device. A mathematical model of the processes of electromechanical energy conversion in EMECS connects its geometric and electrophysical parameters with power and energy indicators, and also determines the operating properties of EMECS in various operating modes.

An expression relating the rotational speed of the rotor n_n to the geometric and electromagnetic parameters of the storage device is obtained on the basis of the equation of equilibrium of moments.

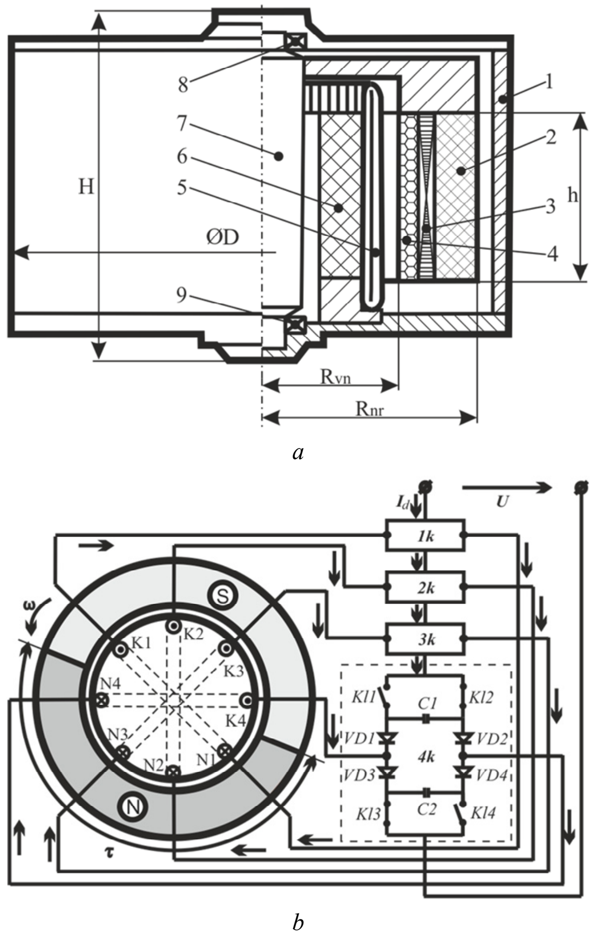
The relationship between the voltage u_n and the current i_n in EMECS as a component of the instantaneous values of electromagnetic power is obtained from the equations of equilibrium of voltages in the armature winding.

The mathematical model that describes the processes in the EMECS of the storage device in the modes of energy storage and delivery has the form:

$$\begin{cases} \dfrac{dn_n}{dt} = \dfrac{C_{mn} B_{sr} i_n}{\pi/30\, J}; \\ \dfrac{di_n}{dt} = \dfrac{u_n - C_{en} B_{sr} n_n \sin\theta - R_n i_n}{L_n}, \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{dn_n}{dt} = -\dfrac{C_{mn} B_{sr} i_n}{\pi/30\, J}; \\ \dfrac{di_n}{dt} = \dfrac{C_{en} B_{sr} n_n \sin\theta - u_n - R_n i_n}{L_n}, \end{cases} \tag{2}$$

where C_{mn}, C_{en} are the machine constants; B_{sr} is the average value of magnetic flux density; J is the moment of inertia of the flywheel; θ is the load angle between the axis of the magnetic field of the inductor and the magnetic field created by the armature current; R_n, L_n are the resistance and inductance of the winding.



a

b

Fig. 1. Inertial energy storage:
a) battery design; *b*) EMECS scheme:
1 – vacuum casing; 2 – flywheel; 3 – ferromagnetic screen; 4 – permanent magnets; 5 – armature winding; 6 – stator housing; 7 – shaft; 8, 9 – bearing units; *H*, *D* – overall height and diameter of the storage device; R_{vn}, R_{nr} – inner, outer radii of the flywheel, *h* – height of the flywheel; ω – rotor speed; τ – pole division;
1*k*…4*k* – switches; *Kl1*, *Kl2*, *Kl3*, *Kl4* – keys; *VD1*, *VD2*, *VD3*, *VD4* – diodes; *C1*, *C2* – capacitors; I_d – source current; *U* – voltage at the terminals

The storage device parameters included in relations (1), (2) are determined by the shape and dimensions of its rotor and stator, inductor excitation system, circuit and configuration of the armature winding, and the level of electromagnetic and mechanical loads of all the listed drive components.

The paper pays attention to establishing the connection of the parameters C_{mn}, C_{en}, L_n and R_n with the configuration, connection diagram and geometric dimensions of the armature winding.

The configuration and connection diagrams of the armature winding of EMECS. The armature winding, being the determining element of the EMECS of the storage device, must satisfy the following requirements:

- provide the specified values of load voltage and current at the terminals of the machine, corresponding to the required power;
- provide satisfactory conditions for changing the direction of current flow in phases, that is, the switching process;
- possess the necessary mechanical, electrical and thermal strength, with a minimum consumption of material, as well as manufacturability.

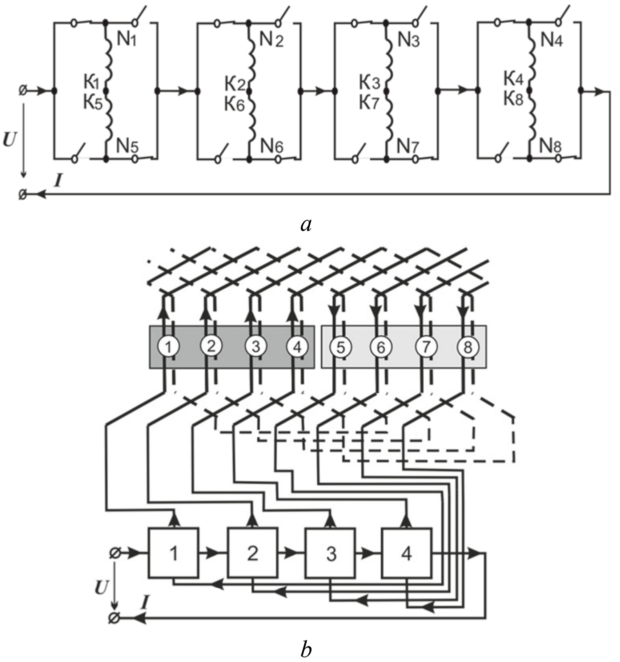
The main element of the armature winding here, as in conventional DC machines, is the section, which consists of one or a number of series-connected turns. The active sides of the section are located in two layers of slots under the poles of different polarity at a distance of pole division τ. According to the external shape of the contours, the windings can be wave and loop.

The sections of the windings having electric and magnetic symmetry, the adjacent sides of which are located in different layers of the same slot, connecting either counter-series or counter-parallel, form the phase of the winding. The connection diagram of the sections in the phase of the armature winding depends on the required voltage and current of the machine.

Each phase is connected as a load in the diagonal of the bridge current inverters, which, in turn, connected in series, form the armature winding.

For example, Fig. 2 shows the windings of the wave and loop types, the phases of which are formed by counter-sequential connection of sections. Here the ends of the sections $K1$, $K2$, $K3$, $K4$ are connected in series with the ends of the sections $K5$, $K6$, $K7$, $K8$, respectively, and the beginning of the sections $N1$ and $N5$, $N2$ and $N6$, $N3$ and $N7$, $N4$ and $N8$ are connected as a load to the diagonal of the inverters bridge type *1*, *2*, *3* and *4*, respectively.

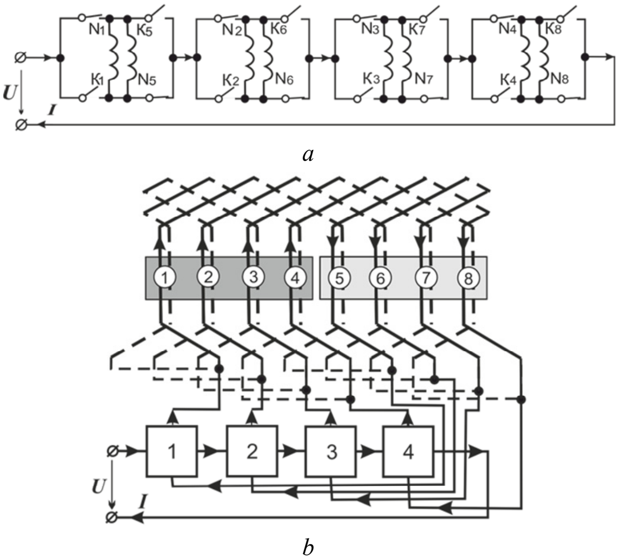
In Fig. 3 windings of wave and loop types are shown, the phases of which are formed by counter-parallel connection of sections. Here, the beginnings of sections $N1$, $N2$, $N3$, $N4$ are combined into nodes by the ends of sections $K5$, $K6$, $K7$, $K8$, respectively, and the ends of sections $K1$, $K2$, $K3$, $K4$ also into nodes with the beginnings of sections $N5$, $N6$, $N7$, $N8$, respectively . By nodes $N1$ $K5$ and $K1$ $N5$, $N2$ $K6$ and $K2$ $N6$, $N3$ $K7$ and $K3$ $N7$, $N4$ $K8$ and $K4$ $N8$ the phases are connected as a load in the diagonal of bridge inverters *1*, *2*, *3* and *4*, respectively.



a

b

Fig. 2. Counter-series connection of phases (*a*), and wave type winding (*b*)



a

b

Fig. 3. Counter-parallel connection of phases (*a*), and loop type winding (*b*)

From the above circuits it is obvious that:

- circuits of winding made of sections of the wave and loop type, practically do not differ from each other;
- when phases are formed from sections at their serial connection, it is possible to obtain higher voltage at the input of the machine than with parallel connection, and with parallel connection – a higher current;
- the number of sections in the winding phase is determined by the number of poles of the machine.

Such winding connection circuits make it possible to regulate the voltage during the operation of the storage device by switching on and off the operating phases of the EMECS, as well as by changing the load angle θ.

Analytical determination of machine constants and electromagnetic parameters. The machine constant C_{en} is determined based on the expression for the instantaneous value of the EMF induced in rectilinear conductors of length l_{ef} moving in the magnetic field with the value of B_{sr} with velocity V

$$e = 2B_{sr} l_{ef} V . \tag{3}$$

The effective conductor length here is determined by the formula

$$l_{ef} = \frac{2pwN_f l_a}{a} , \tag{4}$$

where $2p$ is the number of poles; w is the number of turns in the section; N_f is the number of phases; l_a is the active length of the armature winding; a is the number of parallel branches in phase.

Expressing the linear velocity V through the rotor speed n_n

$$V = \frac{p\tau n_n}{30} , \tag{5}$$

and substituting (4), (5) in (3), we obtain

$$e = \frac{0{,}13 p^2 wN_f \tau l_a}{a} B_{sr} n_n \sin\theta . \tag{6}$$

Relationship

$$C_{en} = \frac{2p^2 wN_f \tau l_a}{15a} , \tag{7}$$

which is determined only by the geometric parameters of the machine and does not depend on the modes of its operation, we call the machine constant C_{en}.

The machine constant C_{mn} is determined from the expression for the electromagnetic torque

$$M_{em} = F_e \frac{D_a}{2} , \tag{8}$$

where D_a is the diameter of the armature; F_e is the equivalent force acting on an effective conductor of length l_e with current i_a in the magnetic field B_{sr}

$$F_e = B_{sr} l_e i_a , \tag{9}$$

where $i_a = I/a$ is the current in the parallel phase branch.

The effective conductor length is defined as

$$l_e = 2pwN_f l_a . \tag{10}$$

After substituting (10) and (9) into (8), we obtain

$$M_{em} = \frac{2pwN_f l_a D_a}{a} B_{sr} I . \tag{11}$$

Relationship

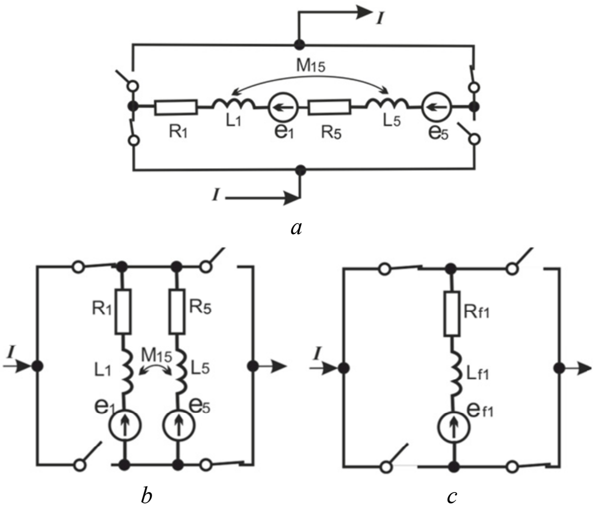
$$C_{mn} = \frac{2pwN_f l_a D_a}{a} , \tag{12}$$

determined only by the geometric parameters of the machine and independent of the modes of its operation, we call the machine constant C_{mn}.

The active resistance R_n and inductance L_n of the EMECS are determined by summing these parameters for individual phase elements, the equivalent circuits of which are shown in Fig. 4. Since the parameters indicated in this Figure significantly depend on the geometry of the winding sections, one of the important questions for us was the following: what calculation configuration to replace the real configuration of the section? We took a rectangle with sides $2a$ and $2b$ as the calculation configuration. Moreover, side $2b$ was taken equal to the pole division τ. The equivalence of the calculation configuration and the real one was provided by increasing the side of rectangle $2a$ by two lengths of the difference between the length of the frontal part of the armature winding l_b and the pole division τ

$$l_b = \frac{1}{2}\mathrm{tg}\left(\arcsin\frac{(\Delta_l + b_l)Z_P}{2\pi R_l}\right), \tag{13}$$

where Δ_l is the distance between the frontal parts of two adjacent coil sides; b_l is the width of the coil side in the frontal part; Z_P is the number of slots of the armature; R_l is the radius of the circle on which the frontal part of the winding is located.



a

b *c*

Fig. 4. Equivalent circuit of:
a – two winding sections connected in series and belonging to the same phase; *b* – two winding sections connected in parallel and belonging to the same phase;
c – phase winding; R_1, R_5 – active resistance of sections; L_1, L_5 –inductance of sections; e_1, e_5 – EMF of sections; M_{15} – mutual inductance of sections of one phase; R_{f1}, L_{f1}, e_{f1} – equivalent active resistance, inductance, EMF of the phase, respectively

Thus, to calculate the active resistance and inductance in the equivalent circuits of the armature winding, a rectangle with dimensions $2a\times2b$ was taken as a section. Side $2b$ was assumed equal to pole division, and side $2a$ was determined as the reduced length of the armature

$$l'_a = l_a + 2(l_b - \tau). \tag{14}$$

The calculation of the active resistance for the armature winding at a parallel branches and cross-section s_a of the effective copper conductor of the winding with specific resistance ρ is carried out according to the following formula

$$R_n = \rho \frac{N_f 2pwl'_a}{s_a a^2} . \tag{15}$$

As for the inductance of both the phase and the winding as a whole, both the intrinsic and mutual inductances of the coils of the armature winding contribute to its value.

The winding phase inductance is determined as

$$L_f = N_k L_k + N_k \sum_{k=1}^{Nk-1} M_{k,k+Nf} , \tag{16}$$

where N_k is the number of coils in phase; L_k is the intrinsic inductance of the coil; $M_{k,k+Nf}$ is the mutual inductance of the coils in phase.

The intrinsic inductance of the coil is determined according to the formula

$$L_k = \frac{2\mu_0}{\pi} w^2 (a+b) \left[\ln \frac{8ab}{h_1 + h_2} - \frac{b}{a+b} \times \right.$$
$$\times \left(0{,}693 + \ln \left(b + \sqrt{a^2 + b^2} \right) \right) - \frac{a}{a+b} \times$$
$$\times \left(0{,}693 + \ln \left(a + \sqrt{a^2 + b^2} \right) \right) + \frac{2\sqrt{a^2+b^2}}{a+b} - \tag{17}$$
$$\left. - 0{,}5 + 0{,}224 \frac{h_1 + h_2}{a+b} \right];$$

where h_1 are h_2 are the height and width of the cross-section of the coil section; $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant.

Parameters a and b are determined as:

$$a = \frac{l'_a}{2}; \; b = \frac{\tau}{2}.$$

To find the mutual inductance of the winding coils, we represent them in the form of infinitely thin single-turn rectangular-shaped contours located in 3D space XYZ and offset from each other by a distance of x_s, y_s, z_s along the x, y, and z axes, respectively [7].

Connecting the beginning of the Cartesian coordinate system with the geometric center of the contour, which coincides with the middle turn of the first coil of the winding, and assuming that the position of the contour replacing the second coil of the winding is oriented according to the coordinates of its center, we find the mutual inductance between them according to

$$M_{15} = \frac{\mu_0}{4\pi} \oint\limits_{l_1 l_2}\!\!\oint \frac{dl_1 \cdot dl_2}{r}, \tag{18}$$

where l_1 and l_2 are the contours of the first and second winding coils, respectively; r is the distance between the elements dl_1 and dl_2 along the OZ axis.

We use the method of plots. Since the numerator of integrand (18) contains the scalar product of vectors, the terms corresponding to the interaction of the parallel sides of the contours l_1 и l_2 make a non-zero contribution to the mutual inductance. We represent the double contour integral as a sum

$$I = I^{(1)} + I^{(2)}, \tag{19}$$

where $I^{(1)}$ is the sum of the integrals over those rectilinear sections of the contours that are parallel to the x axis; $I^{(2)}$ is the sum of the integrals over the sections parallel to the y axis.

Taking into account the numbering of the contour sections, we can write

$$I^{(1)} = I_{11} + I_{12} + I_{22} + I_{21},$$
$$I^{(2)} = I_{33} + I_{34} + I_{44} + I_{43},$$

where I_{mn} are the integrals over rectilinear parallel sections of the contours, and here the index m corresponds to the number of the section of the contour of the first winding, and the index n corresponds to the number of the section of the second winding. All these integrals have a general form

$$I_{mn} = \int\limits_{\alpha_1}^{\beta_1}\int\limits_{\alpha_2}^{\beta_2} \frac{d\varepsilon_1 \cdot d\varepsilon_2}{\sqrt{(\varepsilon_2 - \varepsilon_1)^2 + \Delta^2 + Z^2}}, \tag{20}$$

where α_1, β_1, α_2, β_2 are the limits of integration; $\varepsilon_1 = x_1$, $\varepsilon_2 = x_2$ are the integration variables for sections parallel to the x axis; $\varepsilon_1 = y_1$, $\varepsilon_2 = y_2$ are the integration variables for sections parallel to the y axis; Δ – for sections parallel to the x axis is taken as the difference of the y coordinates, for sections parallel to the y axis is taken as the difference of the x coordinates.

Assuming that the distance along the Z axis between the coils is known and $\Gamma = \Delta^2 + Z^2$, integral (20) can be represented as

$$I_{mn} = (\alpha_2 - \alpha 1) \ln \left[(\alpha_2 - \alpha_1) + \sqrt{(\alpha_2 - \alpha_1)^2 + \Gamma} \right] - \sqrt{(\alpha_2 - \alpha_1)^2 + \Gamma} -$$
$$- (\alpha_2 - \beta_1) \ln \left[(\alpha_2 - \beta_1) + \sqrt{(\alpha_2 - \beta_1)^2 + \Gamma} \right] + \sqrt{(\alpha_2 - \beta_1)^2 + \Gamma} -$$
$$- (\beta_2 - \beta_1) \ln \left[(\beta_2 - \beta_1) + \sqrt{(\beta_2 - \beta_1)^2 + \Gamma} \right] + \sqrt{(\beta_2 - \beta_1)^2 + \Gamma} +$$
$$+ (\beta_2 - \alpha_1) \ln \left[(\beta_2 - \alpha_1) + \sqrt{(\beta_2 - \alpha_1)^2 + \Gamma} \right] - \sqrt{(\beta_2 - \alpha_1)^2 + \Gamma}.$$

The limits of integration for the integrals I_{mn} are presented in Table 1, where k is the number of the integral.

Table 1

Integral parameter values

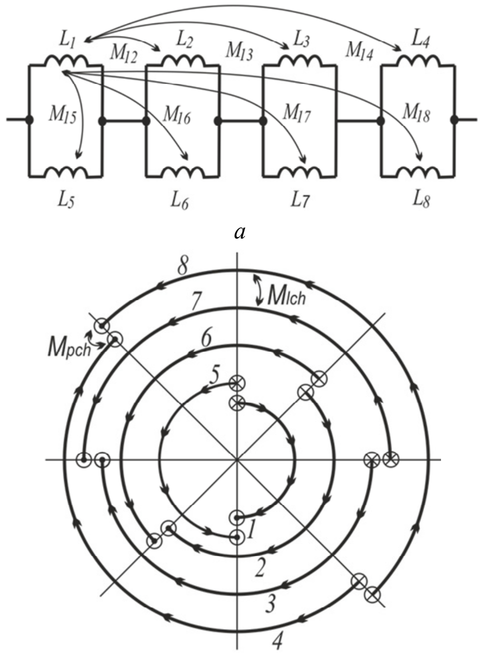
I_{mn}	α_1	β_1	α_2	β_2	Δ	k	j	Sign
I_{11}	$-a$	a	x_s-c	x_s+c	y_s+d-b	1	1	+
I_{12}	$-a$	a	x_s-c	x_s+c	y_s-d-b	2	1	–
I_{22}	$-a$	a	x_s-c	x_s+c	y_s-d+b	3	1	+
I_{21}	$-a$	a	x_s-c	x_s+c	y_s+d+b	4	1	–
I_{33}	$-b$	b	y_s-d	y_s+d	x_s-c+a	1	2	+
I_{34}	$-b$	b	y_s-d	y_s+d	x_s+c+a	2	2	–
I_{44}	$-b$	b	y_s-d	y_s+d	x_s+c-a	3	2	+
I_{43}	$-b$	b	y_s-d	y_s+d	x_s-c-a	4	2	–

In view of Table 1, instead of formula (18) we can write

$$M_{15} = \frac{\mu_0}{4\pi} \sum_{j=1}^{2} \sum_{k=1}^{4} (-1)^{k+1} I_k^{(j)}. \tag{21}$$

Based on the obtained relations, we find the terms of mutual inductances in formula (16) using the example of a four-phase two-pole machine with counter-parallel connection of the armature phase coils.

The magnetic coupling diagram of this winding is shown in Fig. 5,*a*. The mutual inductance between the sections of the winding is presented in the form of two components: slot M_{pch} and frontal M_{lch}. If the contribution of the slot part in the creation of mutual induction flows between the sections is obvious, then the contribution of the frontal parts is clearly illustrated in Fig. 5,*b*.



b

Fig. 5. Full magnetic connections of the coils of the armature winding (*a*), connections in the frontal parts (*b*)

Assuming that the proportion of mutual induction between the frontal parts of the sections is proportional to the length of their mutual overlap, we obtain the following results. Firstly, it is obvious that when finding the inductance of the armature winding phase, only the flows of mutual induction of the slot parts of adjacent coils are affected, and the frontal parts do not participate. Secondly, when finding the total inductance of one coil of the armature winding, the mutual induction coefficients of the frontal parts are compensated, and the total inductance of the coil is defined as

$$\begin{aligned} M_{1\Sigma} &= \frac{3}{4}M_{lch} - \frac{2}{4}M_{lch} + \frac{1}{4}M_{lch} + \\ & 2M_{pch} - \frac{1}{4}M_{lch} - \frac{2}{4}M_{lch} - \frac{3}{4}M_{lch}. \\ M_{1\Sigma} &= 2M_{pch} \end{aligned} \tag{22}$$

As a result, for the case of counter-parallel and counter-series connection of the coils, the expressions of the equivalent phase inductance, respectively, take the form:

$$L_{fpr} = \frac{L_k + 2w^2 M_{pch}}{N_k}; \tag{23}$$

$$L_{fps} = N_k \left(L_k + 2w^2 M_{pch} \right). \tag{24}$$

Equivalent inductances of the winding of the machine as a whole with counter-series and counter-parallel connection of coils in phase, respectively, equal to:

$$L_{Mps} = N_f N_k \left(L_k + 2w^2 M_{pch} \right), \tag{25}$$

$$L_{Mpr} = \frac{N_f \left(L_k + 2w^2 M_{pch} \right)}{N_k}. \tag{26}$$

Results obtained. Using the example of a four-pole electric machine of a test storage device, it is proposed to establish a connection between the parameters of the machine constants C_{mn} and C_{en}, the inductance L_n and the active resistance R_n with the configuration, connection diagram, and geometric dimensions of the armature winding using the analytical expressions obtained above.

As the initial data for the IEMESD test model, we take the value of energy that is released during stopping electrodynamic braking of the ER2T electric train section, consisting of head and motor cars, weighing 117 tons from speed of 45 km/h to 0 km/h on a horizontal track section 675 m long. This value corresponds to the exchange energy of the designed storage system. For two traction motors, it is 5.2 MJ. The system of electromechanical energy conversion should provide the issuance and reception of electrical energy at maximum voltage of 700 V and rated current of 400 A.

Based on the level of exchange energy of the storage device and the installation volume allocated for the storage system on the rolling stock of a suburban electric train, we take the following geometric dimensions of the flywheel: the outer radius of the rotor is 0.225 m, the inner radius is 0.11 m, the height is 0.335 m. The rotor speed is 18550 rpm.

Based on the obtained relationships, geometric and electromagnetic parameters were found for the electromechanical energy conversion system of the test storage device. This is a four-pole machine with a loop winding, made according to the circuit of counter-series connection of coils in phase, with the following geometric parameters: diameter of the armature is 0.214 m; active armature length is 0.255 m; the number of phases is 4; the number of coils in phase is 4; the number of turns in the coil is 2; coil dimensions excluding the frontal part are 0.253×0.168 m; coil cross-section is 80 mm^2; «offset» of the frontal part of the coil is 0.075 m. The geometric constants C_{mn} и C_{en} are obtained: 1.75 m^2 and 0.182 m^2, respectively, as well as the active resistance of 0.005 Ω and the equivalent inductance of $3.05 \cdot 10^{-5}$ H.

When choosing the geometric dimensions and winding connection diagrams, it is necessary to be guided by the following: obtaining high voltage value is possible by forming phases from counter-series connected coils, and of significant current by their counter-parallel connection. If it is necessary to obtain the required power components, it is also possible to realize mixed connection of the coils in phase. The number of coils in the phase must be a multiple of the number of poles of the machine. In view of the fact that the stator does not contain ferromagnetic, the armature winding should be positioned closer to its outer surface, that is, to the source of the magnetic field.

Conclusions.

1. The developed mathematical model of the inertial electromechanical energy storage device reflects the relationship of its indicators of exchange energy and power with the geometric and electrophysical parameters of both the energy storage and the electromechanical converter system. A feature of the model is the operation of machine constants in determining the electromotive force and electromagnetic torque. The mathematical model allows further study of the operating modes of the inertial electromechanical energy storage device as part of

the traction drive in the braking and acceleration modes of the electric rolling stock.

2. A relationship has been established between the geometrical dimensions of the coils, as well as the circuits of their connection when forming the armature winding with such parameters as the values of machine constants, active resistance and inductance of both individual phases and the armature winding as a whole.

3. It is shown that obtaining the required power components (current and voltage) of the electromechanical energy conversion system is provided by the formation of phases from counter-series or from counter-parallel connected adjacent coils of the armature winding, the number of which in phase must be a multiple of the number of poles of the inductor.

4. The proposed specific winding connection circuits make it possible to regulate the voltage during the storage device operation by switching on and off the operating phases of the electromechanical energy conversion system, as well as by changing the load angle θ.

REFERENCES

1. Doki T., Takahara E., Yamada J. A study for electric double layer capacitor series connection for railway traction. *Proc. of IEE 2003 Japan Industry Appl. Soc. Conf.*, 2003, vol. 3, pp. 179-182.

2. Sameshima H., Ogasa M., Yamamoto T. On-board characteristics of rechargeable lithium ion batteries for improving energy regenerative efficiency. *Quarterly Report of RTRI*, 2004, vol. 45, no. 2, pp. 45-52. **doi: 10.2219/rtriqr.45.45**.

3. Witthuhn M. Schwungradspeicher in Diesel triebfahrzeugen. *Elektrische bahnen*, 2002, no. 3, pp. 110-113. (Ger).

4. Lenhard D., Engel B., Langwost J., Söffker C. Elektrische Ausüstung des Triebyuges LIREX Baureihe 618/619 für DB Regio. *Elektrische Bahnen*, 2000, no. 8, pp. 279-289. (Ger).

5. Omelianenko V.I., Omelianenko G.V. Electromechanical energy converter of inertial storage for traction power supply networks. *Russian Electromechanics*, 2001, no. 4-5, pp. 67-74. (Rus).

6. Omelyanenko V.I., Ryabov E.S., Overyanova L.V. Local train with electromechanical inertial energy storage unit. *Vestnik VELNII*, 2014, no. 2(68), pp. 89-102. (Rus).

7. Dzenzerskii V.A., Omelianenko V.I., Vasiliev V.I., Matin V.I., Sergeev S.A. *Vysokoskorostnoi magnitnyi transport s elektrodinamicheskoi levitatsiei* [High-speed magnetic transport with electrodynamic levitation]. Kyiv, Fiz.-mat. i tekh. lit. Publ., 2001. 479 p. (Rus).

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