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# DETERMINATION OF ELECTROMAGNETIC PARAMETERS OF A LINEAR STEPPER DEVICE

***Purpose.*** *Consideration of the design and determination of the electromagnetic parameters of a linear stepper device during step-by-step movement of the moving link, obtainingformulas in analytical form for their calculation and improving the operating efficiency of the linear stepper device.*

***Methodology***. *When conducting research on a linear stepper device with the step-by-step movement of a moving link, the theory of electrical and magnetic circuits was used, and calculation of electromagnetic parameters was carried out taking into account the design parameters of the switched-on stator section of a linear stepper device that changes when the moving link moves by the step size.*

***Findings.*** *The design features of n -winding linear stepper devices are considered and the operation of the three-section structure of a linear stepper device is analyzed. An analysis of changes in the electromagnetic parameters of the magnetic circuit in the section of the switched-on stator winding of a linear stepper device has been carried out, and the dependence of the magnetic resistance in individual sections of the magnetic circuit on the design parameters has been found, and the position of the moving link of the linear stepper device. The correspondence between the change in inductive parameters when moving the moving link and the change in electrical characteristics in the section of the switched-on stator winding of a linear stepper device has been established.*

***Originality.*** *The intervals of change in magnetic resistance when moving the moving link of a linear stepper device by a step value are determined and analytical expressions for their calculation are obtained. The change in inductive parameters when moving the moving link of a linear stepper device by a step size has been studied, and analytical expressions have been found for calculating the inductance and its derivative for the convenience of calculations, presented in dimensionless form.*

***Practical value.*** *The results obtained can be used in the development of new designs of linear stepper devices, and monitoring changes in electromagnetic parameters and electrical characteristics in the switched-on winding section of linear stepper devices increases the efficiency of their operation.*

***Keywords:*** *electromagnetic parameters**;** magnetic resistance; linear stepper device; moving link; step-by-step movements.*

**Introduction.** The widespread use of linear electromagnetic drives in various fields of industry is due to severaladvantages: the elimination of intermediate mechanical and other gears from the drive system to convert rotational motion into linear motion; environmentally friendly and quiet operation; simplicity and reliability of design; manufacturability and wide functionality combined with a simple control system. There are a large number of mechanisms that use a change in the magnetic field in themto create a torque or synchronizing force [1–11]. Changes in the magnetic field and electromagnetic processes during the operation of electrical machines [1, 2], for electric machines with transverse magnetic flux [3–6], a change in characteristics is achieved through design changes: the cross-section of the coils, the air gap, the distance between the poles. When moving a moving link step by step, both rotationally [7–9] and linearly [10, 11], stepper devices are used. However, the issue of the operation of these devices during linear step-by-step movement of the movable link of the executive body has not been sufficiently considered. Particularly in need of additional research is the change in electromagnetic parameters, which is based on a discrete change in the state of the electromagnetic field in the working gap due to pulse excitation when moving the moving link by a step size, which is a relevant scientific and technical task.

**Statement of the task**. When designing automated systems that include electromagnetic linear stepper devices (LSD) with step-by-step movement of the moving link (ML) to ensure continuous operation of the LSD, the latter is taken into account as a variable active-inductive load, which, depending on the design parameters of the LSD, will change significantly when moving the moving link. The purpose of this work is to determine the change in magnetic resistance and inductive parameters at intervals of movement of the moving link of the LSD, their influence on changes in electrical characteristics, and current in the switched-on winding of the LSD, with step-by-step movement of the moving link and increasing the efficiency of the LSD functioning.

**Research results.** From the whole variety of linear electromagnetic devices, we will consider a cylinder-shaped structure [10, 11], inside which an ML moves, consisting of magnetic and non-magnetic cylindrical inserts alternating along the length, and the cylinder itself, the stator of the device, is assembled from separate sections and depending on their number can perform different functions. For example, when $n$ = 1 (single-section structure), it can be used as an electromagnetic valve, which is equipped with a return spring to return to its original position. The valve operates under the influence of electromagnetic forces of the switched-on section and returns to its original position under the action of a return spring. At $n$ = 2 (two-section structure), used as a reciprocating structure or as a vibrator, where one or the other section is turned on alternately and the ML moves back and forth. At $n$ = 3 (three-section structure), which is shown in Fig. 1, allows the ML to make various movements during the movement step or work out individual parts of the step when switching several sections simultaneously. When you set two structures in each of which $n$ =3 sections, it is possible to obtain movement of the ML with a split step [7, 8], which is important, for example, when developing robotic complexes.

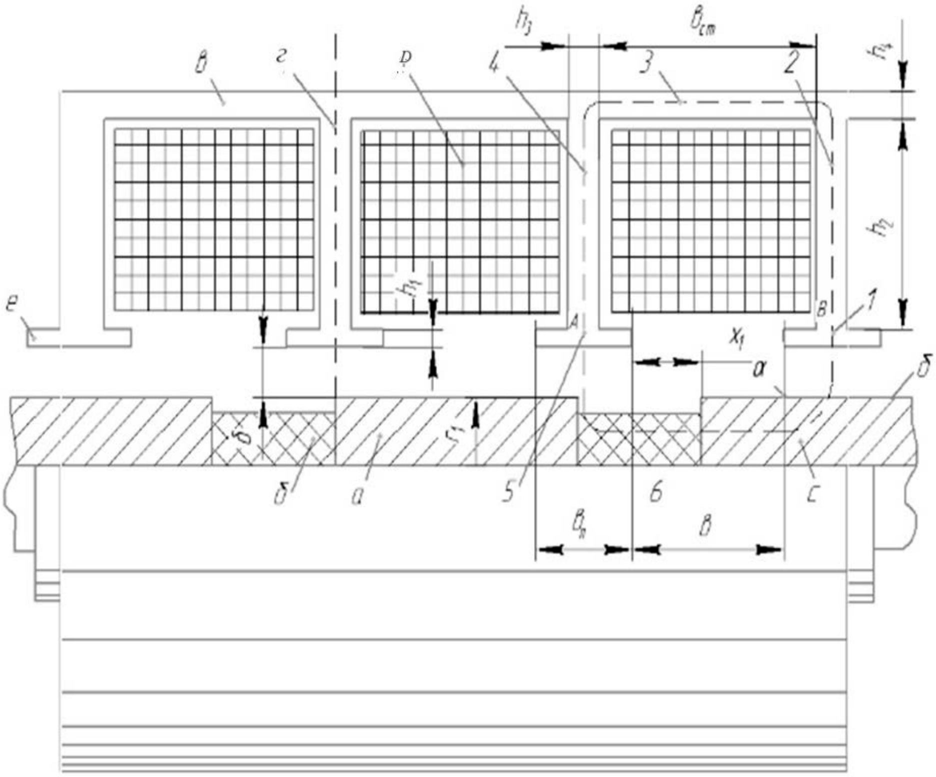

Fig. 1. **Three-section structure of linear stepper device**

Three-section structure of the linear stepper deviceis presented in Fig. 1, it has a cylindrical shape, the moving element of which is made up of alternating non-magnetic and ferromagnetic elements, one of which: *a* – is located in the magnetic equilibrium position of the previous turned on section of the LSD stator, and the other: *c* – in the position before the start of movement when working out a step movements in the LSD stator section that is switched on according to the order of operation;

ferromagnetic elements separated by non-magnetic inserts – $\delta$. Stator sections – $B$ with magnetic poles – $\mathcal{E}$, between which are located field windings – $D$ and pole pieces – $e$, turned towards the moving element. Design parameters that make up the structure of the stator section: $h_1$ – thickness of the pole piece; $h_2$ – pole length; $h_3 = h_4$ – thickness of pole and rim stator sections; $b_n$ – width of the pole piece; $b$ – the distance between poles (pole pieces ); $b_{ст}$ – the distance between the poles of the stator section; $r_1$ – radius of the moving link; $\sigma$ – technological gap between the stator section and the moving link; $x_1$ – the gap between the ferromagnetic element of the moving link and the pole piece; $x$ – step of movement, which changes during the movement of the moving link when development of which, ferromagnetic elementoccupies a magnetic equilibrium position under the pole pieces, for example, in the middle section in Fig. 1.

The dependence of inductance on the magnetic resistance of the load circuit is known [12], and has the form:

$$L = W^2/Rm, \tag{1}$$

where is $Rm = \sum_{k=1}^{n} R_{mk} = l_1/\mu_1 S_1 + ... + l_n/\mu_n S_n$ – magnetic resistance of segments of the magnetic circuit of the stator section of the switched-on winding of the LSD;

$\mu_n$ – magnetic permeability of the medium;
$S_n$ – cross-sectional area of the magnetic flux;
$l_n$ – average length of the magnetic field line of each segment of the magnetic circuit;
$W$ *is* the number of turns of the excitation winding of the magnetic circuit.

The magnetic flux is closed through all segments of the magnetic circuit (Fig. 1, segments 1–6), to find the total magnetic resistance, we determine the magnetic resistance at each segment [13]. As can be seen from the given structure of the LSD, the geometric dimensions of the stator section are fixed, then we get five segments of the magnetic circuit: $R_{mI} = R_{m1} + R_{m2} + + R_{m3} + R_{m4} + R_{m5}$– the values of which do not change when the ML of the LSD is moved. For these segments, we determine the average length of the magnetic field line and the cross-sectional area through the geometric dimensions of the stator section: $l_1 = l_5 = h_1$; $S_1 = S_5 = 2\pi b_n(\sigma + +r_1)$; $l_2 = l_4 = h_2$; $S_2 = S_4 = 2\pi h_3(\sigma + + r_1 + h_1)$; $l_3 = b_{ст} + h_3$; $S_3 = \pi h_4^2$; $\mu_1 -$ is the magnetic permeability of the medium in five areas, then the total magnetic flux in areas where the geometric dimensions do not change when moving the moving link, has the form

$$R_{m1} = \sum_{k=1}^{5} R_{mk} = \frac{1}{\mu_1 \pi} \cdot \left[\frac{h_1}{b_n(\sigma + r_1)} + \frac{h_2}{h_3(\sigma + r_1 + h_1)} + \frac{b_{ст} + h_3}{h_4^2}\right]. \tag{2}$$

To calculate the magnetic resistance in the sixth segment of Fig. 1, the geometric parameters of which changewhen moving the ML of the LSD, letus represent magnetic field lines as circular arcs [12, 14]. Circular arcs create elementary tubes of magnetic conductivity, which makes it possible to approximately write them in analytical form. The edge conductivities between the corresponding faces of the stator section are found by integrating elementary tubes that determine the relative position of the faces of the poles, pole pieces and the ferromagnetic element in the direction of movement of the moving linkof the LSD. We will determine the edge conductivities for three ranges of changes in the position of the moving link of the LSD: the first range – before the start of movement; second range – movement by step size; the third range is the position of magnetic equilibrium in the section of the switched-on stator winding of the LSD.

Let's consider the operation of the LSD using the example of the switched-on right section in Fig. 1, where the ferromagnetic element of the ML moves to the left until the magnetic equilibrium position is reached under the pole pieces of poles A and B. We write the total magnetic resistance in the sixth segment as,

$$R_{m2} = 1/G_1 + 1/G_2, \tag{3}$$

where is $G_1$ –the conductivity of the first pole of the stator section of the LSD;
$G_2$ – conductivity of the second pole of the stator section of the LSD.

For the first range of changes in the position of the ML within $0 \le X_1 \le b/2$ the right section in Fig. 1, magnetic resistance through the conductivity of the faces of the first (A), second (B) poles and faces (C) of the ferromagnetic element of the moving link

$$R_{m21} = \frac{1}{G(B_1C_1) + G(B_2C_2) + G(B_3C_3) + G_\alpha + G_6} + \frac{1}{G(A_1C_1) + G(A_2C_2) + G(A_2C_1)}, \tag{4}$$

where $A_1$, $B_1$, $C_1$ are the faces of the pole pieces of poles A and B turned towards the moving linkof the LSD and the left end surface C of the ferromagnetic element of the moving link in Fig. 1;

$A_2$, $B_2$, $C_2$– the internal faces of the poles A and B and the surface C of the ferromagnetic element of the moving link facing the pole pieces A and B;

$A_3$, $B_3$, $C_3$– the outer edges of the poles A and B and the right end surface C of the ferromagnetic element of the moving link;

$G(B_1C_1), G(B_2C_2), G(B_3C_3), G(A_1C_1), G(A_2C_2), G(A_2C_1)$– conductivity between the corresponding faces;

$G_\alpha$, $G_6$ – conductivity on the surface of the ferromagnetic element of the moving link under the pole piece B, the field lines of which are concentric circles centered at these points.

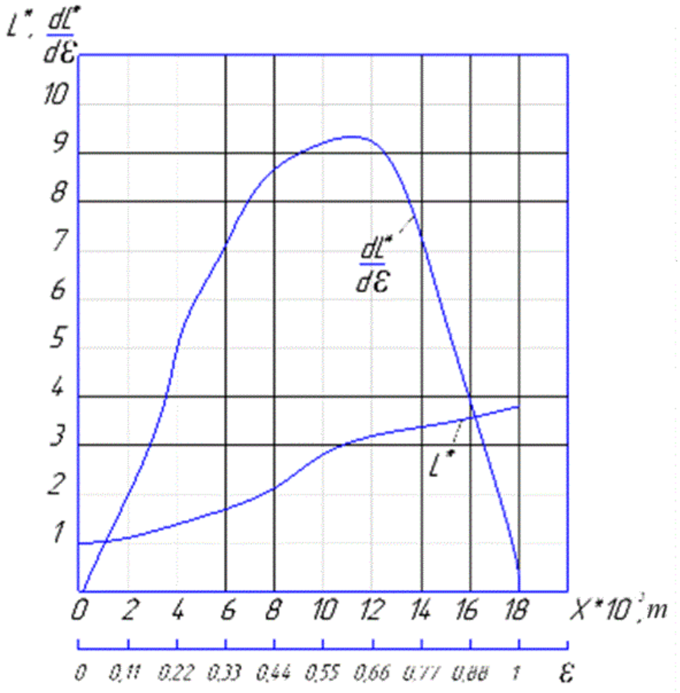


Fig. 2. **Graphics of inductance and its derivative in dimensionless form**

Then the total magnetic resistance for the first range, taking into account expressions (2) and (4): $R_{mI} = R_{m1} + R_{m21}$, and the inductance $L_I = W^2/R_{mI} = W^2/(R_{m1} + R_{m21})$ has a minimum value on the graph – $L^*$, Fig. 2, before the moving link of the LSD begins to move. To determine the relationship between electromagnetic parameters, consider the value of inductance $L_I$ and its relationship with the change in electrical parameters in the winding of the switched-on section of the

LSD. As can be seen from changes in the current value in the switched-on windings of the LSD [7, 15, 16], with minimal inductance, the current increases in the winding of the switched-on stator section in the absence of movement of the moving link.

The second range, when $\mathrm{X}_1 < b/2$ characterizes the movement of the moving link by a step size in the direction of the pole piece A of the switched-on right section of the LSD, where the inductance of the magnetic circuit increases, and the current in the switched-on excitation winding decreases [7, 15, 16]. Then the magnetic resistance has the form:

$$R_{m22} = \frac{1}{G(\mathrm{A}_1C_1) + G(\mathrm{A}_1C_2) + G(\mathrm{A}_2C_2) + 2G_\alpha} + \\ + \frac{1}{G(\mathrm{B}_2C_2) + G(\mathrm{B}_1C_2) + G(\mathrm{B}_1C_3) + G(\mathrm{B}_3C_3) + 2G_\alpha}. \quad (5)$$

The total magnetic resistance in the second range, taking into account expressions (2) and (5), is defined as $R_{mII} = R_{m1} + R_{m22}$, and the inductance (1) has the form $L_{II} = W^2/R_{mII} = = W^2/(R_{m1} + R_{m22})$ and continues to increase on the graph – $L^*$, Fig. 2.

In the third range, when $\mathrm{X} = \mathrm{X}_{max}$ the ferromagnetic element of the moving link of the LSD took a step of movement and reached the position of magnetic equilibrium in the section of the switched-on excitation winding. The current in the switched-on winding begins to increase [7, 15, 16], and the inductance reaches its maximum value on the graph – $L^*$, Fig. 2. Magnetic resistance at a given position of the moving link

$$R_{m23} = \frac{1}{G(\mathrm{A}_1C_1) + G(\mathrm{A}_1C_2) + G(\mathrm{A}_2C_2) + G(\mathrm{A}_1C_3) + 2G_\alpha} + \\ + \frac{1}{G(\mathrm{B}_2C_2) + G(\mathrm{B}_1C_2) + G(\mathrm{B}_1C_3) + 2G_\alpha}. \quad (6)$$

The total magnetic resistance in the third range, taking into account expressions (2) and (6), is defined as $R_{mIII} = R_{m1} + R_{m23}$, and the inductance (1) has the form $L_{III} = W^2/R_{mIII} = = W^2/(R_{m1} + R_{m23})$.

Conductivity $(\mathrm{A}_1C_1)$ is due to the interaction between the corresponding faces and for $x_1 > \sigma$, has the form:

$$G(A_1 C_1) = \int_{\mathrm{x}_1}^{r_1+\sigma} (\mu_0\, l dr)/(r\, \pi/2) = (2\mu_0\, l/\pi)\ \ln((r_1 + \sigma)/x_1), \quad (7)$$

where $r_1$is the current radius of the circular arc of the elementary tubes that come from the end of the ferromagnetic element $C_1$ of the moving linkon the edge of the pole piece $A_1$ pole A;

$l$– effective length in the direction normal to the power lines;

$\mu_0 = 4\pi 10^{-7}$H/m – magnetic constant.

The effective length can be taken equal to the circumference of a circle with radius $r_1 + +\sigma$, minus the radius of the average field line found as the geometric mean between $x_1$ and $(r_1 + +\sigma)$ , then $l = 2\,\pi\left[r_1 + \sigma - \sqrt{x_1\,(r_1 + \sigma)}\right]$. Thus, the conductivity (7) between the faces has the form: $G(A_1 C_1) = 4\mu_0\,[r_1 + \sigma - \sqrt{x_1\,(r_1 + \sigma)}]\ \ln((r_1 + \sigma)/x_1)$.

After appropriate transformations, it is possible to calculate the conductivities between other faces of the ferromagnetic element of the moving link, the poles and pole pieces at the step of moving the ML of the LSD.

Let us imagine the electrical equivalent circuit of the switched-on winding of the stator section of the LSD in the form of a series connection of inductance and active resistance of the winding [12]. Then the equation of the electrical circuit has the form:

$$iR_H + L \cdot di/dt + i \cdot \ dL/dt = U_n \text{ or } di/dt + i\, dLdx/Ldxdt + i\, R_H/L = U_n/L, \tag{8}$$

where is $U_n$ −the rated voltage of the power supply;

$R_H$ − active resistance of the excitation winding;

$i$ − field winding current;

$L$ − inductance;

$dL$– derivative of the inductance of the magnetic circuit of the switched-on section of the LSD.

Taking into account the equation of an electrical circuit (8), the change in the parameters of the magnetic circuit, expression (2 – 6) and the analysis of experimental data on the change in inductance depending on the position of the ML of the LSD [1, 13], at a step of movement in the range $\xi < x \ \leq (b_{\text{ст}} + h_3 - b_n)/2$, the inductance and its derivative can be represented in the form (9) and (10):

$$L = L_{III} - \Delta L_I \cos\left(\frac{\pi(x-\xi)}{b_{\text{ст}} + h_3 + b_n - 2\xi}\right), \tag{9}$$

$$\frac{dL}{dx} = \frac{\pi}{2(b_{\text{ст}} + h_3 - b_n - 2\sigma)} \Delta L_I \sin\left(\frac{\pi(x-\xi)}{b_{\text{ст}} + h_3 - b_n - 2\xi}\right), \tag{10}$$

and for the range $(b_{\text{ст}} + h_3 - b_n)/2 \leq x < (b_{\text{ст}} + h_3)/2$, in the form (11) and (12)

$$L = L_I + \Delta L_{II} \sin\left(\frac{\pi(2x + b_n - b_{\text{ст}} - h_3)}{2b_n}\right), \tag{11}$$

$$\frac{dL}{dx} = \frac{\pi}{2b_n} \Delta L_{II} \cos\left(\frac{\pi(2x + b_n - b_{\text{ст}} - h_3)}{2b_n}\right), \tag{12}$$

where $x$ is the displacement of the moving link along the switched-on stator section;

$\xi$ – displacement of the ferromagnetic element of the moving link from the position of magnetic equilibrium in the section of the switched-on winding;

$\Delta L_I$ − the increase in inductance in the section from $L_{min}$ to $L_{II}$ when the ferromagnetic element of the moving link fits the pole piece of the switched section;

$\Delta L_{II}$ − increase in inductance from position $x = \frac{b_n}{2}$ to position of magnetic equilibrium of the switched-on section;

$L_I = L_{min}$– minimum inductance before the moving linkof the LSD begins to move;

$L_{III} = L_{max}$– maximum inductance in the magnetic equilibrium position for the switched-on LSD section.

To maintain equality of changes in inductance (9) and (11) between displacement sections, we use approximating functions: $\Delta L_I/\Delta L_{II} = (b_{\text{ст}} + h_3 - b_n - 2\xi)/b_n$;$\Delta L_I = (L_{II} - L_I)\ \ ((b_{\text{ст}} + \\ + h_3 - b_n - 2\xi)/(b_n - 2\xi))$; $\Delta L_{II} = (L_{II} - L_I)\, b_n/(b_n - 2\xi)$.

To reduce the volume of calculations, we reduce expressions (9–12) to dimensionless form. Coefficients that determine the relationship between dimensional and dimensionless quantities:

$$L^* = L/L_I\,;\ \Delta L_I^* = \ \Delta L_I/L_I\,;\ \Delta L_{II}^* = \Delta L_{II}/L_I\,; \varepsilon = x/x_\sigma\,;\ \xi^* = \xi/x_\sigma\,;\ K = b_n/2x_\sigma, \tag{13}$$

where $x_\sigma = \frac{b_{\text{ст}} + h_3}{2}$ is the movement step,

$L_\sigma = L_{min} = L_I$ – minimum inductance before the moving link begins to move.

After appropriate transformations, taking into account the coefficients (13), at the step of displacement in the range $\xi^* < \varepsilon \leq 1 - K$, inductance and its derivative can be represented in the form

$$L^* = L_{II}^* - \Delta L_I^* \cos\left[\frac{\pi(\varepsilon - \xi^*)}{2(1 - K - \xi^*)}\right];\ \frac{dL^*}{d\varepsilon} = \frac{\pi}{2(1 - K - \xi^*)} \Delta L_I^* \sin\left[\frac{\pi(\varepsilon - \xi^*)}{2(1 - K - \xi^*)}\right], \quad (14)$$

and in the range $1 — K < \varepsilon \leq 1$, in the form

$$L^* = L_I^* + \Delta L_{II}^* \sin\left[\frac{\pi(\varepsilon + K - 1)}{2K}\right];\ \frac{dL^*}{d\varepsilon} = \frac{\pi}{2K} \Delta L_{II}^* \cos\left[\frac{\pi(\varepsilon + K - 1)}{2K}\right]. \quad (15)$$

Using the given expressions (14, 15), dependencies were constructed for inductance, graph – $- L^*$ and its derivative, graph – $dL^*/d\varepsilon$, presented in Fig. 2.

When analyzing the dependence of inductance and its derivative on the coordinate at the movement step in Fig. 2, before the start of movement, the inductance is equal to $L_I -$ is minimal, and its derivative has zero value. After the start of movement, the inductance $L_{II} -$ increases, and the derivative is significantly in creases. When the moving link approaches. pole piece, the inductance does not change significantly, which leads to a rapid change in its derivative, which in the magnetic equilibrium position takes on a zero value. The magnetic circuit closes through areas with low magnetic resistance and the inductance $L_{III} -$ reaches its maximum value. In accordance with the change in the inductive parameters of the LSD in Fig. 2, a change in the electrical characteristics occurs, the current value in the winding of the switched-on LSD.

From the analysis of the time intervals of moving the moving link by the step size and changing the current in the winding of the LSD [15], an increase in the current after passing its minimum value corresponds to a decrease in the derivative of the inductance to zero in Fig. 2, switching the LSD windings at this point in time makes it possible to increase the dynamic characteristics of the LSD by 1/3 relative to traditional switching upon achieving a steady current value in the LSD winding, and when switching at the maximum value of the inductance derivative in Fig. 2, which corresponds to the minimum value of the current in the winding of the LSD after the end of the movement of the moving link by the step value, it is possible to increase the dynamic characteristics of the LSD by 1/2, while the energy indicators of the consumed energy of the LSD are correspondingly improved, which is no longer spent on heat losses and heating of the LSD, after completing the move step.

Taking into account the above, when developing LSD control systems that monitor changes in electromagnetic parameters and electrical characteristics, for example, the currents values in the windings of the LSD, it is possible to implement control without additional sensors to control the movement of the moving link and increase the efficiency of the LSD operation.

**Conclusions.**The design of a three-section linear stepping device is considered and a study of its operation at the step of moving the moving link is carried out. An analysis of changes in the electromagnetic parameters of the LSD was carried out and analytical expressions were obtained for calculating magnetic resistance, inductance and its derivative depending on the design parameters of the LSD, when moving the moving link by a step size, for the convenience of calculations presented in dimensionless form. Atanalysis of changes in the inductive parameters of the internal structure of the LSD and electrical characteristics, for example, changes in the current value in the winding of the switched-on stator section of the LSD; their relationship was established, which makes it possible to organize the effective functioning of the LSD by monitoring electromagnetic processes and electrical characteristics in the LSD’s own design without the use of additional complex hardware funds.

At the same time, changes in the air gap between the stator and the moving link of the LSD, design changes in the step of movement of the LSD, the manufacture of windings at different distances between the poles of the LSD require additional research, there is a promising direction for the development of new designs of LSD to improve the functionality, energy efficiency, and speed of the executive bodies of the meansautomation of technological processes of industrial production.

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# ВИЗНАЧЕННЯ ЕЛЕКТРОМАГНІТНИХ ПАРАМЕТРІВ ЛІНІЙНОГО КРОКОВОГО ПРИСТРОЮ

***Мета**. Огляд конструкції та визначення електромагнітних параметрів лінійного крокового пристрою при покроковому пересуванні рухомого ланцюга, отримати формули в аналітичній формі для їх розрахунку та підвищення ефективності функціонування лінійного крокового пристрою.*

***Методика**. При проведенні досліджень лінійного крокового пристрою з покроковим пересуванням рухомої ланки застосовувалась теорія електричних і магнітних ланцюгів, розрахунок електромагнітних параметрів виконаний з урахуванням конструктивних параметрів ввімкнутої секції статора лінійного крокового пристрою, що змінюються при пересуванні рухомої ланки на довжину кроку.*

***Результати**. Розглянути конструктивні особливості n – обмоткових лінійних крокових пристроїв та проведений аналіз роботи трьохсекційної структури лінійного крокового пристрою. Виконаний аналіз змін електромагнітних параметрів магнітного ланцюга в секції ввімкнутої обмотки статора лінійного крокового пристрою, знайдена залежність магнітного опору на окремих ділянках магнітного ланцюга від конструктивних параметрів та положення рухомої ланки лінійного крокового пристрою. Встановлена відповідність змін індуктивних параметрів при пересуванні рухомої ланки, змінам електричних характеристик в секції ввімкнутої обмотки статора лінійного крокового пристрою.*

***Наукова новизна**. Визначені інтервали змін магнітного опору при пересуванні рухомої ланки лінійного крокового пристрою на довжину кроку та отримані аналітичні вирази для їх розрахунку. Досліджено зміни індуктивних параметрів при пересуванні рухомої ланки лінійного крокового пристрою на довжину кроку, знайдені аналітичні вирази для розрахунку індуктивності та її похідної для зручності обчислень наданих в безрозмірному вигляді.*

***Практична значимість.** Отримані результати можуть бути використані при розробці нових конструкцій лінійних крокових пристроїв, а контроль за змінами електромагнітних параметрів та електричних характеристик в секції ввімкнутої обмотки лінійних крокових пристроїв, підвищує ефективність їх функціонування.*

***Ключові слова:** електромагнітні параметри; магнітний опір; лінійний кроковий пристрій; рухомий ланцюг; покрокове пересування.*