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The Effect of Design Parameters of an Integrated Linear Electromagnetic Motor, At the Process of Pulling Away Anchor, From Its Breakaway Stage

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***Abstract*:** *This paper assess the influence of design parameters of ferromagnetic guide housing at the possess of pulling away the anchor from the holding device which is integrated in the design of the motor. The design of an integrated circuit and the equivalent magnetic circuit of the integrated LEMM on breakaway stage was built, mathematical models of system were laid out. An expression for its magnetic induction, with which you can set the beginning of saturation of the shunt, defining moment of pulling away anchor from the holding area. an expression is derived for its magnetic induction, with which you can set the beginning of saturation of the shunt, define moment of anchor pulling away from the holding area, the zone of permissible combinations of cross-sectional area of the upper magnetic shunt and holding area, and the zone of change in the magnetic induction in the yoke at the pulling away moment of the motor anchor.*

***Index Terms*:** *Linear electromagnetic motor, pulling away anchor, breakaway stage, holding force, holding device, ferromagnetic guide housing.*

I. Introduction

Electromagnetic linear machine generates linear motions directly without rotation-to-translation conversion mechanisms, which significantly simplifies system structure and improves system efficiency. It has wide applications in aeronautics [1, 2], transportation [3-5], medical devices [6,7] and so on. linear electric motors are able to accumulate energy for the usage, When the generated force is in opposite direction as the suspension velocity [8].

One way of increasing the specific power and energy performance of these linear motors is to force the accumulating of magnetic energy in the working gaps of pulsed electromagnetic linear motors (LEMM) by retaining its anchor, which implement the principle of increasing artificially accumulated magnetic energy of running clearances on breakaway stage by motors loading [9]. In this breakaway stage, the anchor artificially creates a static reaction force (holding force F_H), which decreases abruptly to zero after the start of the armature. Consequently, the anchor will start moving under the influence of an increased tractive force [10, 11].

The Integration of the holding device of the anchor (HDOA) in the motor design in the magnetic core and MMF proposed in [12, 13], has allowed to simplify the design of pulse LEMM at the same time to increase its power and energy performance. Design parameters of both holding device of anchor and ferromagnetic guide housing of pulsed LEMM have an effect on the holding force of the motor's anchor.

II. Problem Statement

Experimental research of the linear electromagnetic motor is a complicated task requiring use of special experimental equipment [14]. As mentioned in [15] experimental studies of such integrated LEMM showed that the regulation of holding force is difficult because it depends on several design parameters of the motor. Therefore, conducting such experimental research is not feasible (it is not practically possible) ,as such verification will take a long time.

The influence of varying the value of the holding area S_H ,which holds the anchor and creates changes of the holding force F_H on breakaway stage, is the defined and determined in [16]. The motor which has this design is called integrated LEMM.

However obtained expressions in [16], do not allow us to investigate the influence of the design parameters of the ferromagnetic shunt during the process of pulling away the integrated LEMM anchor. The flux magnitude of the upper shunt Φ_{ush} and its cross-section S_{ush} have effect on the magnetization process and determine the moment when the breakaway anchor stage reaches saturation of the ferromagnetic guide housing.

As the value S_{ush} ,especially at smaller Φ_{ush} decreases, the shunt is saturated eventually causing holding force F_H , to be limited to the tractive force F_{st} in the moment of pulling away motor anchor. In [17] it is shown that with increasing F_{st} increased energy performance of pulsed LEMM is obtained.

The purpose of this paper, is to assess the influence of design parameters of ferromagnetic guide housing at the possess of pulling away the anchor from the holding device which is integrated in the design of the motor.

III. Mathematical Models System

In such motor design, anchor on breakaway stage is held by its own magnetic field ferromagnetic guide housing 2 Fig.1, which is called an upper magnetic shunt relative to the upper running clearance δ_u . Lower magnetic shunt is a ferromagnetic anchor guide 3. Thus, the LEMM in this design has two working clearances shunted by motor parts design - the upper and lower magnetic shunts. During operation in this LEMM with holding device (holding device integrated in design), both shunts saturate an eventually affect motor performance . In this LEMM design, holding force F_H occurs between mating surfaces, which is formed by the upper part of the flat anchor 1 and the top of the inside of the ferromagnetic shunt (2) when they are in contact or almost in contact the gap δ_0 .

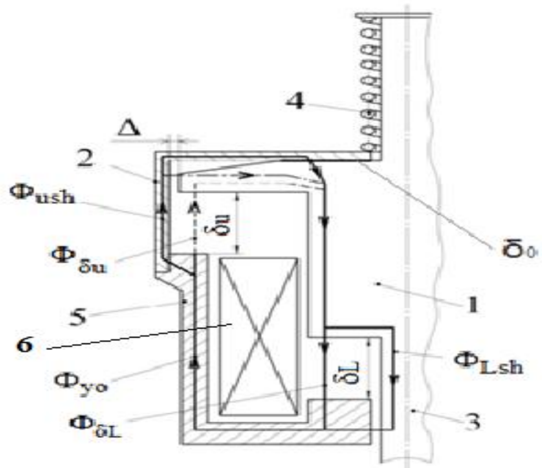

Fig. 1: The design of an integrated circuit LEMM

In such a motor design, when we connect the coil to the power supply for the first time and until the initial magnetic field has not yet unfolded, both the magnetic shunts are also not saturated and have small magnetic reluctance R_{ush} R_{Lsh}, hence $R_{ush} = R_{ush1} + R_{ush2}$.

From the equivalent of the magnetic circuit LEMM and with neglecting the leakage flux Fig.2 which is corresponding to the design scheme in Fig. 1, the magnetic flux Φ_{yo} yoke 5 appears as two components:

$$\Phi_{yo} = \Phi_{ush} + \Phi_{\delta u} = \Phi_{Lsh} + \Phi_{\delta L} \qquad (1)$$

these two components pass in the anchor LEMM almost entirely through the upper shunt (R_{ush} and $R_{up\delta}$), bypassing the upper working clearances δ_u , which in this case have much bigger reluctance $R_{\delta u}$ compared to the reluctance of the upper branch of the R_{ub} shunt Fig.2 and the technological gap Δ:

$$R_{ub} = R_{ush} + R_{up\delta} \qquad (2)$$

$$R_{up\delta} = \frac{\delta_{up}}{\mu_0 S_H};$$

$$R_{\Delta} = \frac{\Delta}{\mu_0 S_{upsh}} \qquad (3)$$

Where $R_{up\delta}$, the reluctance of the air gap δ_{up}, creates the holding force and forms mating surfaces of the upper shunt and the top of the anchor 1 .

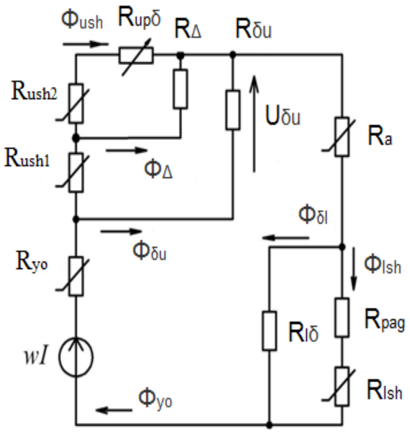

Fig. 2: The equivalent magnetic circuit of the integrated LEMM on breakaway stage

$R_{up\delta}$ at a given moment is much smaller than shunt R_{ush}; due to minimal value of air gap δ_{up}, which is selected in the initial state of a return spring 4 and smaller than the reluctance technological gap R_{Δ} .
Therefore, the expressions (1) and (2) can be written as:

$$\Phi_{yo} \approx \Phi_{ush} \quad ; \quad R_{ub} = R_{ush}$$

Then by the electromagnetic holding force which occurs between the upper shunt and the upper shunt of part anchor, the anchor is attracted to the stationary shunt, and despite the increase of the current in the coil anchor it is held in this position. The magnitude of holding force F_H in this case depends on the magnitude of the magnetic flux of the upper shunt Φ_{ush} and its contact area with the flat part of the anchor - (Holding area) S_H (in Fig.1 shows a heavy line). The magnitude Φ_{ush} with a certain saturation induction B_0 material of the guide housing (upper shunt) is determined by its cross-sectional area S_{ush}. Accordingly, the value of holding force under these conditions will be a function of two design parameters - area S_H and area S_{ush}.

With increasing mmf motors winding 6 on breakaway anchors stage, the magnetic flux of the upper shunt Φ_{ush} also increases. Thus, the holding force increases and saturates this ferromagnetic shunt, and reluctance R_{ush} begins to increase. As a result, shunt flux slowdown and a simultaneous redistribution of Φ_{ush} and $\Phi_{\delta u}$ occurs according to equation (1). That is, all the bulk of the flux in the yoke Φ_{yo} in particular the flux component $\Phi_{\delta u}$ extends through upper working clearance (the dotted line in Fig.1) which is represented by $R_{\delta u}$ element in the equivalent magnetic circuit (Fig.2), that creates additional tractive force down, acting on a combined anchor 1 motor. Similar processes occur in the lower shunt with the difference that it is saturated before the upper shunt, and the reluctance of the parasitic air gap R_{pag} Fig.2 remains unchanged when the motor is operated and accordingly the tractive force in the parasitic air gap is not created.

To assess the influence of cross-sectional area S_{ush} at the anchor, at the instance of pulling-away, it is first necessary to establish the beginning of saturation of the upper shunt. According to the magnetization curve schedules, and particularly at its tabulated values it is difficult to find these conditions of saturation. By an approximation to the magnetization curve of a magnetic steel of ferromagnetic guide housing 2 (Fig. 1), these conditions are defined easily. For this purpose, the magnetization curve of the material shunt in saturation parts, is approximated by piecewise-linear segments and each segment is represented by polynomial of a certain degree as in the following form:

$$B(H) = B_0 + \mu_K \mu_0 H \qquad (4)$$

where μ_K relative permeability of the material of the magnetic shunt at the part of its saturation flux density corresponding to the maximum B_K, H magnetic field strength, $\mu_0 = 4\pi \times 10^{-7} \frac{H}{m}$ permeability of free space, B_0 magnetic induction value (magnetic flux density), where saturation begins of the upper shunt.

Equation (4) is the equation of the line tangent to the magnetization curve at $B = B_K$, corresponding to the maximum induction indicated by this curve. The maximum magnetic induction B_K is usually given in the design of pulse LEMM [10, 18].

The value of B_0 in equation (4) can be found by using power polynomial for the curve $B = B_K$, when the magnetic field strength of the material shunt equals zero.
Then the magnetic flux of the upper shunt is:

$$\Phi_{ush} = (B_0 + \mu_K \mu_0 H_{ush}) S_{ush} \qquad (5)$$

where S_{ush} is the cross sectional area of the upper shunt.

To determine the magnetic field strength in the upper shunt H_{ush} we use the equivalent circuit shown in Figure 2, which implies that, the upper working clearance with reluctance $R_{\delta u}$ and shunt branch R_{ub} both are under the same magnetic field strength. By KCL (when leakage flux neglected), we obtain for this section of the magnetic circuit the following relationship:

$$H_{ush} L_{ush} + H_0 \delta_0 = H_{\delta u} L_{\delta u} \qquad (6)$$

where $H_{\delta u}$ magnetic field strength in the upper working clearance δ_u, H_0 magnetic field strength in the air gap δ_0 (shown as a heavy line between the inner mating surfaces of the upper shunt and the top of the anchor 1 Fig.1), and H_{ush} magnetic field strength in the upper magnetic shunt, $L_{\delta u} = \delta_u$ the length of the magnetic line of the upper working clearance, L_{ush} the length of the magnetic line of the upper magnetic shunt.
At breakaway stage of the anchor, the magnetic field strength $H_0 \delta_0$ on the air gap δ_0 between the inner mating surfaces of the upper shunt and the top of the anchor is very small compared to the magnetic field strength on the upper shunt $H_{ush} L_{ush}$, therefore can be ignored. Accordingly, equation (6) can be simplified to :

$$H_{ush} L_{ush} = H_{\delta u} L_{\delta u} \qquad (7)$$

The fact that $L_{ush} > L_{\delta u}$, result in longer length of the magnetic field line of the upper shunt . Which results in magnetic field strength in the upper shunt H_{ush} less than the magnetic field strength the upper working clearances $H_{\delta u}$ which has shorter magnetic field line as indicated by the following equation.

$$H_{\delta u} = \frac{B_{\delta u}}{\mu_0} = \frac{\Phi_{\delta u}}{\mu_0 S_{yo}}$$

Then from equation (7), and above relationship we got:

$$H_{ush} = H_{\delta u} \frac{L_{\delta u}}{L_{ush}} = \frac{\Phi_{\delta u}}{\mu_0 S_{yo}} \times \frac{L_{\delta u}}{L_{ush}} \qquad (8)$$

Considering the length of the magnetic line of the upper working clearance $L_{\delta u} = \delta_u$ and taking L_{ush} relative to $L_{\delta u}$ the following result can be obtained $L^*_{ush} = \frac{L_{ush}}{L_{\delta u}}$,and the relative magnitude of L^*_{ush} is greater than one.

Solving equation (8) for the magnetic field strength in the material of the upper magnetic shunt H_{ush}, under the condition implemented in equation (1) results in the following:

$$H_{ush} = \frac{\Phi_{\delta u}}{\mu_0 S_{yo}} \times \frac{1}{L^*_{ush}} = \frac{\Phi_{yo} - \Phi_{ush}}{\mu_0 S_{yo} L^*_{ush}}$$

$$H_{ush} = \frac{(1 - \Phi^*_{ush}) B_{yo}}{\mu_0 L^*_{ush}} \qquad (9)$$

where: $\Phi^*_{yo} = \frac{\Phi_{ush}}{\Phi_{yo}}$

B_{yo} is the magnetic field density in the motor yoke
substituting equation (9) in to (5) we obtain the following expression for Φ_{ush}:

$$\Phi_{ush} = (B_0 + \mu_k \frac{(1 - \Phi^*_{ush}) B_{yo}}{L^*_{ush}}) S_{ush} \qquad (10)$$

Solving equation (10) for the flux density of the yoke B_{yo} as a function of design parameters of the upper magnetic shunt results in the following:

$$B_{yo} = B_0 \frac{S^*_{ush}}{\Phi^*_{ush} - S^*_{ush}\mu_K \frac{(1-\Phi^*_{ush})}{L^*_{ush}}} \qquad (11)$$

where $S^*_{yo} = \frac{S_{ush}}{S_{yo}}$

The expression for B_{yo} in (11) on the structure coincides with the ratio obtained in [19], and shows the induction value in the yoke LEMM above which the anchor will pull away from the holding area and will start moving. This induction in accordance with (11) depends on the cross-sectional area of the upper shunt S_{ush} , its average length of the magnetic line L_{ush}, the material of the shunt (coefficient μ_K), and early induction saturation B_0. Upper limit for the value S_{ush} is required , as any value higher than the permissible value S_{ush} will not cause saturation , which means that the anchor on the breakaway stage will not pull away from the holding area of the shunt. when the current in the coil causes saturation in the upper shunt before the yoke, then the induction in the upper shunt will be lower than the induction in the yoke LEMM, so the $B_{yo} < B_0$ or:

$$\frac{B_{yo}}{B_0} < 1 \qquad (12)$$

Then from equation (11) under the condition implemented in equation (12) the following equation results:

$$\frac{S^*_{ush}}{\Phi^*_{ush} - S^*_{ush}\mu_K \frac{(1-\Phi^*_{ush})}{L^*_{ush}}} < 1 \qquad (13)$$

Manipulating (13) under the condition for pulling the anchor away :

$$S^*_{ush} < \frac{\Phi^*_{ush} L^*_{ush}}{L^*_{ush} + \mu_K (1-\Phi^*_{ush})} \qquad (14)$$

Without fulfillment of (14), saturation of the upper shunt will not occur for any value of the current in the coil LEMM, and the anchor will not pull away (move). Using (14) we obtain the range of possible combinations of parameters S^*_{ush} and Φ^*_{ush} for given values of the parameters L^*_{ush} and μ_K . If we use steel St10 as material shunt, and according to [19] $B_0 = 1.65T$, and $\mu_K = 9$, $L^*_{ush} = 1.5$, resulting in a simpler form , of equation (14) as follows:

$$S^*_{ush} < \frac{\Phi^*_{ush}}{1 + 6(1-\Phi^*_{ush})} \qquad (15)$$

From the condition of the pulling away anchor from holding area:

$$\Phi^*_{ush} < \frac{-1 + \sqrt{\frac{2}{S^*_H} - 1}}{\frac{1}{S^*_H} - 1} \qquad (16)$$

and by using (15) we define the various zones for cross-sectional area of the magnetic shunt S^*_{ush} and the value of holding area S^*_H for this case. This zone is in the form of inequality (17) as shown in Fig. 4 hatched, and the dotted line shows the boundary of the zone change of flux $\Phi^*_{ush} = f(S^*_H)$, constructed by (16).

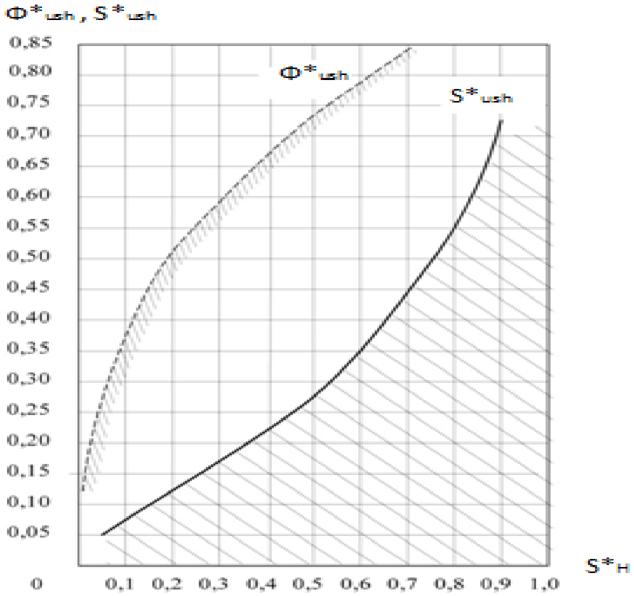

Fig. 4: change of zone cross sectional area of the magnetic shunt and its flux at the pulling away anchor moment when changing the values of holding area.

$$S^*_{ush} < \frac{1-\sqrt{\dfrac{2}{S^*_H}-1}}{1-\dfrac{7}{S^*_H}+6\sqrt{\dfrac{2}{S^*_H}-1}} \qquad (17)$$

At the border of the zone, when $B_0 = B_{yo}$ the anchor will not pull away anchor from the holding device.

By using the limitations and recommendations set out above, we obtain from (11) the dependence of the relative magnetic flux in the yoke LEMM at the design parameters of the shunt S^*_{ush} and S^*_H when $\mu_K = 9$, $L^*_{ush} = 1.5$ and $B_0 = 1.65T$ when the pulling away of anchor happens:

$$\frac{B_{yo}}{B_0} < \frac{S^*_{ush}}{\Phi^*_{ush} - 6S^*_{ush}(1-\Phi^*_{ush})} \qquad (18)$$

To do this, we express the flux Φ^*_{ush} through the shunt design parameter S^*_H using (16) and Substituting the flux into (18) we obtain:

$$\frac{B_{yo}}{B_0} < \frac{S^*_{ush}(1-\dfrac{1}{S^*_H})}{1-(1+6S^*_{ush})\sqrt{\dfrac{2}{S^*_H}-1}+\dfrac{6S^*_H}{S^*_H}} \qquad (19)$$

Figures 5a and 5b show the change in the zones relative to the change in the magnetic induction in the yoke LEMM anchor at the moment of pulling away for various zones of design parameters.

In the boundaries of these zones a sharp increase in the induction of a yoke indicates invalid combination of geometrical dimensions LEMM with ferromagnetic guide housing. Also Equality $B_0 = B_{yo}$ is unacceptable because it occurs during the saturation of the ferromagnetic yoke and the guide housing.

More over the tractive force of the pulse LEMM falls dawn due to the redistribution of the magnetic fluxes in the motor system.

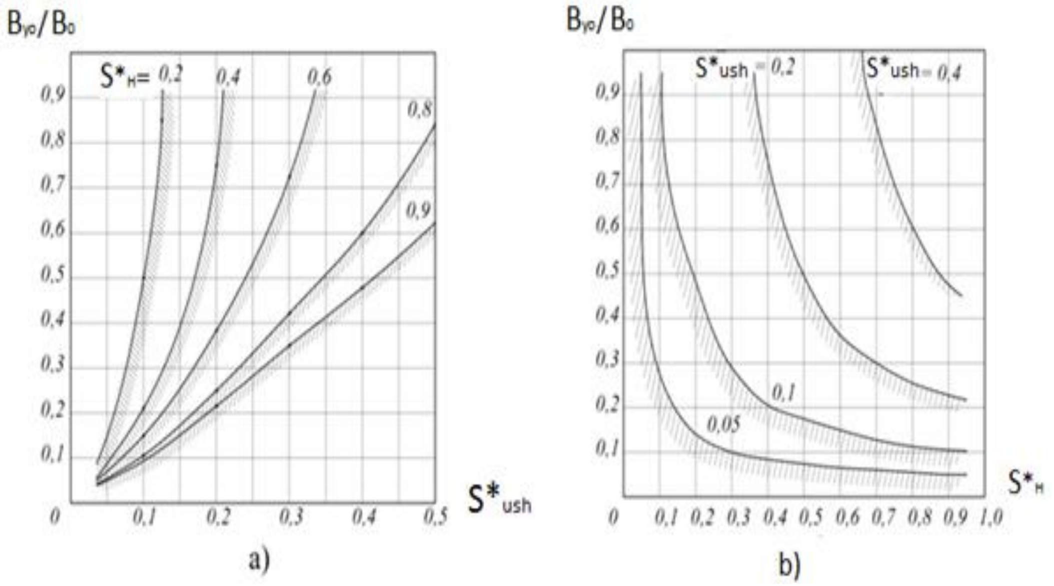

Fig. 5: Change zone of the magnetic induction in the yoke LEMM at the pulling away anchor moment while changing the design parameters S^*_{ush} and S^*_H

IV. Conclusion

Based on a piecewise linear approximation of the magnetization curve of a ferromagnetic material of the guide housing (upper magnetic shunt), an expression is derived for its magnetic induction, with which you can set the beginning of saturation of the shunt, define moment of anchor pulling away from the holding area, the zone of permissible combinations of cross-sectional area of the upper magnetic shunt and holding area, and the zone of change in the magnetic induction in the yoke at the pulling away moment of the motor anchor. Any combination of these design parameters, beyond those zones, the integrated pulse LEMM doesn't work.

REFERENCES

[1] Stumberger, G., M. T. Aydemir, D. Zarko, and T. A. Lipo, \Design of a linear bulk superconductor magnet synchronous motor for electromagnetic aircraft launch systems," IEEE Transactions on Applied Superconductivity, Vol. 14, No. 1, 54-62, 2004.

[2] Kou, B. Q., X. Z. Huang, H. X. Wu, and L. Y. Li, \Thrust and thermal characteristics of electromagnetic launcher based on permanent magnet linear synchronous motors," IEEE Transactions on Magnetics, Vol. 45, No. 1, 358-362, 2009.

[3] Thornton, R., M. T. Thompson, B. M. Perreault, and J. R. Fang, \Linear motor powered transportation," Proceedings of the IEEE, Vol. 97, No. 11, 1754-1757, 2009.

[4] Yan L. G., \The linear motor powered transportation development and application in China," Proceedings of the IEEE, Vol. 97, No. 11, 1872-1880, 2009.

[5] Katerina Hyniova, Antonin Stribrsky, Jaroslav Honcu, Ales Kruczek " Active Suspension System with Linear Electric Motor" WSEAS TRANSACTIONS on SYSTEMS, Vol. 8,No.2 , pp. 278-287, 2009.

[6] Yamada, H., M. Yamaguchi, M. Karita, Y. Matsuura, and S. Fukunaga, \Acute animal experiment using a linear motor-driven total artificial heart," IEEE Translation Journal on Magnetics in Japan, Vol. 9, No. 6, 90-97, 1994.

[7] Yamada, H., M. Yamaguchi, K. Kobayashi, Y. Matsuura, and H. Takano, \Development and test of a linear motor-driven total artificial heart," IEEE Engineering in Medicine and Biology Magazine, Vol. 14, No. 11, 84-90, 1995.

[8] Katerina Hyniova"Experiments Taken on Energy Management in Active Suspension of Vehicles "WSEAS TRANSACTIONS on SYSTEMS, Vol. 11, No. 8, 426-335, 2012.

[9] Ugarov G.G, "Principles of increasing the specific power and energy performance of pulsed electromagnetic linear motors" / / Pulse linear electric machines. Collection of scientific papers. -Novosibirsk: Institute of Mining, Academy of Sciences of the USSR, 1991. - pp. 43-50.

[10] N.P. Ryashentsev .G.G. Ugarov., A.B. Lvytsin "Electromagnetic press", Nauka Publishers, sibirsk branch, Novosibirsk, 1989.- 216p.

[11] Patent RU2018652, E21C 3/16. Electric hammer. / A.F Maer, V. I Moshkin, IP Popov (Russian Federation). 4712733/03; appl. 07.03.89, publ. 30.08.1994.

[12] Patent RU2084071, HO2K 33/02. The linear electromagnetic motor / G.G Ugarov. VY Neumann (Russian Federation). 95110459/07; appl. 22.06.1995, publ. 10.07.1997.

[13] Usanov K. M, Moshkin V. I, Ugarov GG, " Linear electromagnetic pulse drive Autonomous power supply", Monograph. - Kurgan: Publishing House of the KSU Press, 2006. - 284 p.

[14] M. Molis, E. Matkevičius, L. Radzevičius," The Experimental Research of the Linear Motor" ELECTRONICS AND ELECTRICAL ENGINEERING, 2008. No. 7(87), pp.57- 60.
[15] G.G Ugarov , V.IV Moshkin and A. Kh. Massad "The Influence of Holding Device Anchor Parameters On The Holding Force Magnitude, Of An Integrated Linear Electromagnetic Motor" IJES, Vol.3, No.4, 1-6, 2014.
[16] V.I Moshkin and G.G Ugarov, "Estimation of parameters of the device forced accumulation of magnetic energy of a linear electromagnetic motor", Innovative technology in teaching and production, Proceedings of the VI All-Russian scientific-practical conference Kamishyn, 15-16 December 2009 Volume 2. - Volgograd Volgograd State Technical University Publishing House, 2010. - pp 75-78.
[17] Moshkin V.I, Egorov A.A, and Ugarov G.G, "The study of the forced modes of magnetic energy storage in pulse linear electromagnetic motors", Vestnik of the Saratov State Technical University, - Saratov: SSTU 2006, № 1 (10), no.1. - pp. 39-44.
[18] Moshkin V.I, Ugarov G.G.: "By choosing a fundamental base dimensions of linear electromagnetic motors " , Proceedings of the Volgograd State Technical University: Interuniversity. Inter-college. Collection of scientific papers. Art. 8, number (81). - Volgograd: VSTU Publishing House, 2011. pp.108-111. - (Series processes of energy conversion and power plants. Issue 3).
[19] I.M. Husainov and A.Kh. Massad "The accelerated accumulation of magnetic energy in the pulse electromechanical transducer", Problems of the electric power industry. Inter-college. scientific collection, - Saratov: SSTU 2000, pp.36-38.