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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
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S. T. Akhatov[1], V. G. Solonenko[1], N. M. Makhmetova[1],
S. A. Kosenko[2], N. V. Ivanovtseva[1], A. A. Malik[1]

[1] Kazakh Academy of Transport and Communications named after M. Tynyshpaev, Almaty, Kazakhstan;
[2] Siberian State University of Railway Transport, Novosibirsk, Russia.
E-mail: makhmetova_n1958@mail.ru

APPLICATION OF LINEAR ASYNCHRONOUS MOTORS FOR HIGH-SPEED GROUND TRANSPORT

Abstract. Magnetic suspension in high-speed ground transport systems is an alternative to the rail wheel. The successful solution to the development of high-speed ground transport is largely determined by the creation of operationally efficient linear motors, the main task of which is to convert electrical energy into mechanical energy and create tractive force to ensure the movement of the crew according to a given program in the range of operating speeds.

The article investigates linear asynchronous motors with longitudinal closure of magnetic flux of single-ended design. As a result of investigation of physical processes in linear motors caused by edge problems it was found that the cause of the transverse edge effect is the finite width dimensions of the reactive bus, the change of which causes closure of eddy currents within the active area of inductor, leads to weakening of magnetic field in the central zone and to reduction of tractive force.

The discrepancy between the calculated and experimental indicators of physical processes in linear asynchronous motors due to significant idealization of mathematical models led to the development of a three-dimensional theory, brought to the calculation programs. The developed calculation program of electromechanical characteristics of linear induction motors with inductor and reactive bus layout, as well as their geometrical and physical parameters allows to determine the necessary integral motor characteristics in the form of a levitation function.

Key words: high-speed ground transport, linear induction motor, reactive bus, edge effects, inductor, traction drive.

The most investigated are linear asynchronous motors with unilateral action and double-sided stators - linear asynchronous motors with longitudinal closure of magnetic flux in unilateral and double-sided version. The methods of calculation of electromechanical characteristics in traction and braking modes, ventilation and thermal calculations were developed with respect to them. Experiments were conducted on models of linear induction motors at power supply of thyristor frequency converters.

Conducted researches [1-3] showed that for the nearest perspective the most rational for high-speed ground transport is application of one-way linear induction motor, located on the crew. Developments of linear motor with superconducting excitation winding and active track structure are also known. The one-way induction motor has a number of positive features:

- flat track structure, convenient for cleaning from ice and snow;
- possibility of relatively simple and reliable mounting of the superconducting excitation winding on the crew;
- small sensitivity to crew vibrations due to a large air gap.

Powerful electromagnetic field created by a superconducting electromagnet gives linear motors the following advantages: absence of iron components in the anchor winding; possibility of operation with air gap an order of magnitude greater than similar arrangements; operation of superconducting electromagnet in "frozen flow" mode allows to solve current collector problem; high value of energy factor 0,5-0,8. The disadvantages of linear motors include: the need to cool the superconducting electromagnet to the temperature of liquid helium and related equipment; the complexity of the control system; the problem of transition by the crew of the joints of the powered sections and shielding of the passenger compartment. For the theoretical analysis of linear motors with a superconducting excitation winding, preference is given to the energy approach, which allows for high calculation accuracy, maximum approximation to the real design of linear motors, analysis of their operation in steady-state and transient modes.

Principle construction of linear motors with superconducting excitation winding consists of three-phase anchor winding located on track structure, sectioned and powered by static frequency converter, which allows to regulate voltage *U* and frequency *f*. Superconducting electromagnets of the excitation system are located on the crew.

Structurally, linear induction motors consist of the following units: inductor core and winding, housing, auxiliary devices and the secondary part. The inductor core is assembled from varnish-insulated electrotechnical steel plates of thickness 0,3-0,5 mm with chiseled grooves, as a rule, of rectangular shape [4]. The teeth in the upper part have a notch for mounting wedges, fixing the winding. Assembly of the inductor package is performed with insulated studs, passing through the grooves of the same shape on the outer surface of the package.

The study of electromagnetic forces and technical and energy performance on the basis of energy approach shows that the energy of two interconnected circuits of superconducting, located on the crew, and traction - on the track, assuming that currents in the first I_c, in the second I_a are constant in time and determined by the ratio:

$$W_M = \frac{1}{2}\left[L_c(I_c)^2 + 2M_i I_c I_a + L_T(I_a)^2\right], \tag{1}$$

where L_c and $L_{\text{т}}$ are the inductances, respectively, of the superconducting and traction circuits; M_i is the mutual induction coefficient between the superconducting conductor and the i-th circuit of the complete anchor winding.

The total force acting on the superconducting field winding is given as:

$$\bar{F}_{x,y,z}(x) = \sum_{m=1}^{3} k_c I_c i_m grad M_i(x), \tag{2}$$

where k_c – number of superconducting electromagnets; i_m – the current in m-th phase of the armature winding.

With the sinusoidal form of current in the armature winding of the linear motor forces are determined by the higher harmonics of the derivatives from M_i, which can be minimized by the methods known from the theory of rotating machines. According to expression (2) the derivatives from $M_i(x)$ were determined and after some transformations for the first harmonics the total force is represented in projections as

$$\left.\begin{aligned} F_x &= \frac{3}{\sqrt{2}} N k_c I_c I_{\text{т}} \frac{\partial M_{\text{ст}}}{\partial x} sin\theta_{\text{м}} \\ F_z &= \frac{3}{\sqrt{2}} N k_c I_c I_{\text{т}} \frac{\partial M_{\text{ст}}}{\partial z} cos\theta_{\text{м}} \\ F_y &= \frac{3}{\sqrt{2}} N k_c I_c I_{\text{т}} \frac{\partial M_{\text{ст}}}{\partial y} cos\theta_{\text{м}} \end{aligned}\right\}, \tag{3}$$

where N is the number of crews; $I_{\text{т}}$ is the effective value of the anchor winding current; $\theta_{\text{м}}$ is the angle between the axes of the magnetic flux of the superconducting circuit and the resulting flux of the anchor winding.

The primary boundary effect is characterized by the appearance in the active zone, in addition to the main running wave of induction, of its components that are stationary in space and pulsating in time. The secondary longitudinal marginal effect is caused by successive entry and then exit of the reactive bus elements, respectively, into and out of the zone of the running magnetic field of the inductor, which leads to deformation of the machine magnetic field, its removal beyond the running edge of the inductor, occurrence of forces in the synchronous speed mode, and additional power losses in the reactive bus [5]. The transverse edge effect is caused by the finite width dimensions of the reactive busbar, due to which the eddy currents are short-circuited within the active zone of the inductor, resulting in a weakening of the magnetic field in the central zone and a decrease in the tractive force at low slip.

The existing methods for calculating rotating induction motors do not take into account the edge effect and are not suitable for the calculation of high-speed linear induction motors. In this connection it is offered to use special methods, based on analytical or numerical solution of Maxwell equations system for different zones of the machine and allowing to make calculation of integral electromechanical characteristics of linear induction motors with sufficient for practice degree of accuracy [6]. The complexity of real physical processes in high-speed linear induction motors initially predetermined a significant idealization of calculated mathematical models, but because of the discrepancy between the calculated and experimental indicators, we then had to move to more complex models. At the first stage of research, one-dimensional theories of linear induction motors were used, which were developed over time to three-dimensional ones [3]. In this publication three-dimensional theory was developed and brought to computational computer programs for linear induction motors of various designs with an arbitrary number of poles, with or without additional three-phase compensation winding, with two- or one-sided inductor and return magnetic core made of roasted or solid steel, as well as with layered reactive bus bar.

In formulating the problem and constructing the calculation model (figure 1), the following assumptions have been made:

(a) The area of existence of the magnetic field is bounded by two infinite perfectly stratified ferromagnetic surfaces, with magnetic constant $\mu_c = \infty$ and conductive material density $\gamma_c = 0$;

b) the inductor windings are fed by three-phase symmetrical current systems and produce sinusoidal running waves - m.e.f. in the form $F_M f(y) \exp j(\omega t - \frac{\pi}{\tau} x)$;

c) the change of m.p.s. in transverse direction with period 2L is given by function *f(y)* in the core: at $|y| \leq a \cdot f(y) = 1{,}0$; at $|y| > a \cdot f(y) = 0{,}83 exp((c-y)/\Delta)$; and $a = c + (2\delta + d) ln 0.83$;

d) the components I_{1z}, I_{2z}, I_{3z} of current densities and A_{1z}, A_{2z}, A_{3z} of vector magnetic potential in the primary and reactive bus bars are negligibly small;

e) the model is periodized in the longitudinal direction with period $l = L_S + L_L$.

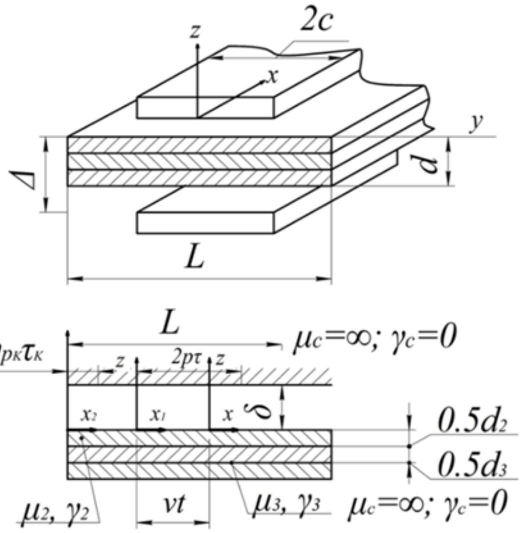

Figure 1 – Model of a linear induction motor

In order to obtain the calculated relations of a linear induction motor for a given type of M.P.H., the system for the vector magnetic potential is solved by the Fourier method:

$$\overline{\nabla}^2 \bar{A}_\delta = 0;\ diV \bar{A}_\delta = 0, \tag{4}$$

$$\overline{\nabla}^2 A_{2(3)} = \gamma_{2(3)} \mu_{2(3)} \frac{\partial A_{2(3)}}{dt}, diV A_{2(3)} = 0, \tag{5}$$

and by the known $A_{x(\delta,2,3)}$ and $A_{y(\delta,2,3)}$ the corresponding components of induction $B_{(x,y,z)}$magnetic $H_{(x,y,z)}$ and electric $E_{(x,y,z)}$ field strengths, and reactive bus current densities $I_{(x,y)}$ are determined. The total electromagnetic power $S_{\text{ЭМ}}$, found through the Poynting vector, as well as the thrust and normal forces (F_x, F_z) of the linear induction motor, for the finding of which the Maxwell stress tensor was used, are defined by the following expressions:

$$S_{ЭМ} = j\frac{\omega_1 C_{20}^2 l^3}{16\pi^2\mu_0}\sum_n^{n_M}\sum_\nu^{\nu_M} z_\Pi^2 \lambda G_{n\nu}\left|k_{\nu_0}\right|\frac{ch\lambda\delta + c_{12}sh\lambda\delta}{ch\lambda\delta + c_{12}\lambda\delta}; \quad (6)$$

$$F_x = -\frac{l^2 L c_{20}^2}{8\pi\mu_0}\sum_n^{n_M}\sum_\nu^{\nu_M} z_\Pi^2 \frac{\nu\lambda\delta n\nu\left|k_{\nu_0}\right|^2 Im(c_{12})}{|sh\lambda\delta + c_{12}ch\lambda\delta|^2}; \quad (7)$$

$$F_y = \frac{L l^3 c_{20}^2}{32\pi^2\mu_0}\sum_n^{n_M}\sum_0^{\nu_M} z_\Pi^2 \lambda^2 G_{n\nu}\left|k_{\nu_0}\right|^2; \quad (8)$$

where

$$Z_n = \frac{1}{n}\frac{1}{1+\left(\frac{\pi n\Delta}{L}\right)^2}\left[sin\left(\frac{\pi na}{L}\right) + \frac{\pi n\Delta}{L}cos\left(\frac{\pi na}{L}\right) + 0{,}83\left(\frac{\pi n\Delta}{L}\right)^2 sin\left(\frac{\pi n}{2}\right)exp\frac{2c-L}{2\Delta}\right];$$

$$\omega_c = \frac{1}{n}\frac{1}{1+\left(\frac{\pi n\Delta^1}{L}\right)^2}\left[sin\frac{\pi na}{L} + \frac{\pi n\Delta^1}{L}cos\frac{\pi na}{L} + 0{,}83\left(\frac{\pi n\Delta^1}{L}\right)sin\frac{\pi n}{2}exp\frac{2c-L}{2\Delta}\right];$$

$c_{20} = \mu_0\frac{16\sqrt{2}\tau^2 A k_{o\delta 1}}{\pi^2 l^2}$; $\lambda = \sqrt{\left(\frac{\pi n}{L}\right)^2 + \left(\frac{2\pi\nu}{l}\right)^2}$; $G_{n\nu} = \frac{sin\left(\frac{\pi n}{n_M+1}\right)}{\pi n/(n_M+1)}\cdot\frac{sin\left(\frac{\pi\nu}{\nu_M+1}\right)}{\pi n/(\nu_M+1)}$ - Lantzsch sigma-multipliers; A - linear current load; c_{12} and k_{ν_0}, respectively, integration constant and winding factor [7].

The program for calculating the electromechanical characteristics of linear induction motors assumes the known layout of inductor and reactive bus, their basic geometrical and physical parameters, winding data and allows to determine the necessary integral motor characteristics as a slip function: total electromagnetic power S_EM and its components $P_{ЭМ}, Q_{ЭМ}$, traction and normal forces F_x, F_z, $cos\varphi_1$, voltage U_1, at $I_1 = const$, as well as distribution of the normal component of induction along the inductor length.

The electromechanical characteristics of the one-way motor, calculated according to the three-dimensional theory with a reversed magnet wire, are shown in figure 2.

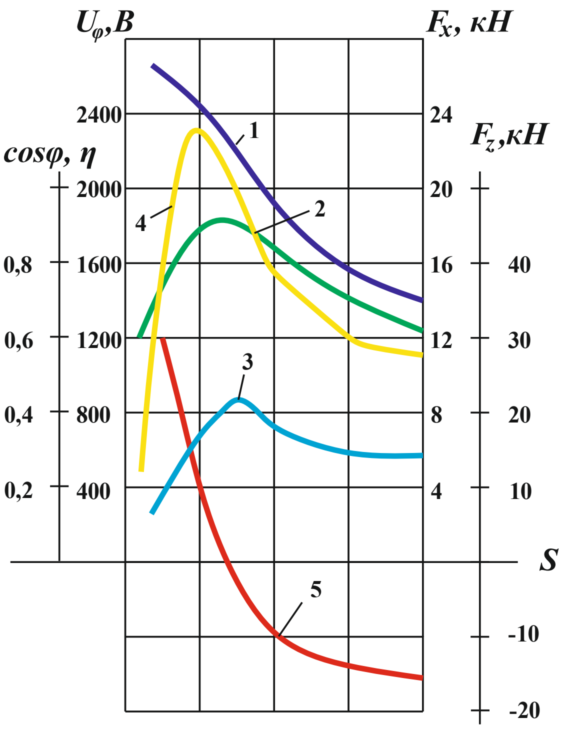

Figure 2 –
Electromechanical characteristics
of the calculated linear asynchronous motor
as a function of slip *S*:
1 – phase voltage U_φ; 2 – efficiency η;
3 – power factor $cos\varphi$; 4 – thrust force F_x;
5 – normal force *F*

To reduce the heating of linear induction motor elements and to improve its mass-size and energy performance, intensive forced cooling is used. With liquid cooling the current density in the inductor winding should be increased to 15-25A/mm^2. In this case, the liquid supplied by the pump circulates through hollow conductors, takes the heat and transfers it to the cooler. Despite the need for additional equipment, design and technological complexity, it provides a gain in size and mass of the linear motor about 20% in comparison with air cooling with a decrease in the motor efficiency by about 8-10% [8].

The secondary part of a linear induction motor is a T-shaped reactive bus made of aluminum alloys. To increase F_x, alloys with small electrical conductivity are used or made in the form of a hollow section. The reactive bus consists of a non-magnetic pad, made of aluminum alloys and a ferromagnetic solid magnetic core.

According to experimental and calculated data, in order to obtain high traction and energy indices, it is advisable to make the reverse magnetic core fully charged [9].

Conclusions. Structural solution on installation of additional equipment, change of design and material of reactive bus for creation of continuous magnetic wire in motor secondary winding allows to increase levitation indices of linear induction motor, which is confirmed by preliminary calculations.

According to data of Japan, the USA, Germany, China and Russia the main indices of linear induction motors are on the average level: specific thrust $F_x < 12$ kN/m^2; $cos\varphi_1 \leq 0{,}6, \eta \leq 0{,}87$; ratio of mass of linear motor movable elements to effective power $M/P_2 > 1{,}0$ kg/kW.

As a development of perspective direction and radical improvement of linear motors performance it is reasonable to apply a phase design of the secondary element with inclusion of capacitors in the secondary winding. The proposed design in combination with intensification of inductor cooling opens up possibilities of improvement of specific traction force F_x up to 40-60 kN/m^2 and can be put in a basis of the priority decision of a problem of creation of the traction drive of the crew for a high-speed land transport.

С. Т. Ахатов[1], В. Г. Солоненко[1], Н. М. Махметова[1],
С. А. Косенко[2], Н. В. Ивановцева[1], А. А. Малик[1]

[1] М. Тынышбаев ат. Қазақ көлік және коммуникациялар академиясы, Алматы, Қазақстан,
[2] Сібір мемлекеттік қатынас жолдары университеті, Новосибирск, Ресей Федерациясы.

ЖОҒАРЫ ЖЫЛДАМДЫҚТЫ ЖЕР ҮСТІ КӨЛІГІ ҮШІН ЖЕЛІЛІК АСИНХРОНДЫ ҚОЗҒАЛТҚЫШТАРДЫ ҚОЛДАНУ

Аннотация. Жоғары жылдамдықты жердегі көлік жүйелеріндегі магниттік суспензия рельсті көлік доңғалағына балама болып табылады. Жоғары жылдамдықты жер үсті көлігін дамытудың сәтті шешімі көбінесе тиімді жұмыс істейтін желілік қозғалтқыштарды құрумен анықталады, олардың негізгі міндеті электр энергиясын механикалық энергияға айналдыру және экипаждың берілген бағдарлама бойынша жұмыс жылдамдығының диапазонында қозғалысын қамтамасыз ететін Тарту күшін құру болып табылады.

Мақалада бір жақты магнит ағынының бойлық тұйықталуы бар сызықты асинхронды қозғалтқыштар зерттеледі. Шекаралық міндеттерге байланысты сызықтық қозғалтқыштардағы физикалық процестерді зерттеу нәтижесінде көлденең жиек әсерінің себебі ені бойынша реактивті шинаның соңғы өлшемдері болып табылады, олардың өзгеруі индуктордың белсенді аймағында құйынды токтардың жабылуына әкеліп соғады, орталық аймақтағы магнит өрісінің әлсіреуіне және тартылыс күшінің төмендеуіне әкеледі.

Математикалық модельдердің едәуір идеализациясына байланысты сызықтық асинхронды қозғалтқыштардағы физикалық процестердің есептік және эксперименттік көрсеткіштерінің сәйкессіздігі есептеу бағдарламаларына келтірілген үш өлшемді теорияның дамуына әкелді. Индуктор мен реактивті автобустың орналасуы бар сызықтық асинхронды қозғалтқыштардың электромеханикалық сипаттамаларының, сондай-ақ олардың геометриялық және физикалық параметрлерінің жобаланған бағдарламасы левитация функциясы түрінде қозғалтқыштың қажетті интегралды сипаттамаларын анықтауға мүмкіндік береді.

Түйін сөздер: жоғары жылдамдықты жер үсті көлігі, сызықты асинхронды қозғалтқыш, реактивті автобус, шекті эффектілер, индуктор, тартқыш.

С. Т. Ахатов[1], В. Г. Солоненко[1], Н. М. Махметова[1], С. А. Косенко[2], Н. В. Ивановцева[1], А. А. Малик[1]

[1] Казахская академия транспорта и коммуникаций им. М. Тынышпаева, Алматы, Казахстан,
[2] Сибирский государственный университет путей сообщения, Новосибирск, Российская Федерация.

ПРИМЕНЕНИЕ ЛИНЕЙНЫХ АСИНХРОННЫХ ДВИГАТЕЛЕЙ ДЛЯ ВЫСОКОСКОРОСТНОГО НАЗЕМНОГО ТРАНСПОРТА

Аннотация. Магнитное подвешивание в системах высокоскоростного наземного транспорта является альтернативой колеса рельсового транспорта. Успешное решение развития высокоскоростного наземного транспорта в значительной мере определяется созданием эффективных в эксплуатации линейных двигателей, основной задачей которых является преобразование электрической энергии в механическую и создание силы тяги, обеспечивающей движение экипажа по заданной программе в диапазоне эксплуатационных скоростей.

В статье исследуются линейные асинхронные двигатели с продольным замыканием магнитного потока одностороннего исполнения. В результате исследования физических процессов в линейных двигателях, обусловленных краевыми задачами, установлено, что причиной поперечного краевого эффекта является конечные размеры реактивной шины по ширине, изменение которых вызывает замыкание вихревых токов в пределах активной зоны индуктора, приводит к ослаблению магнитного поля в центральной зоне и уменьшению тягового усилия.

Несоответствие расчётных и экспериментальных показателей физических процессов в линейных асинхронных двигателях из-за значительной идеализации математических моделей привело к разработке трехмерной теории, доведенной до расчётных программ. Разработанная расчетная программа электромеханических характеристик линейных асинхронных двигателей с компоновкой индуктора и реактивной шины, а также их геометрических и физических параметров позволяет определить необходимые интегральные характеристики двигателя в виде функции левитации.

Ключевые слова: высокоскоростной наземный транспорт, линейный асинхронный двигатель, реактивная шина, краевые эффекты, индуктор, тяговый привод.

Information about authors:

Akhatov Semyat Turganzhanovich, assistant-teacher, Kazakh Academy of Transport and Communications named by M. Tynyshpaev, Almaty, Kazakhstan; semyat@mail.ru; https://orcid.org/0000-0002-6371-0849

Solonenko Vladimir Gelevich, Professor, Doctor of Technical Sciences, Kazakh Academy of Transport and Communications named by M. Tynyshpayev, Almaty, Kazakhstan; v.solonenko@mail.ru; https://orcid.org/0000-0001-6503-6598

Makhmetova Narzankul Musaevna, Professor, Doctor of Technical Sciences, Kazakh Academy of Transport and Communications named by M. Tynyshpayev, Almaty, Kazakhstan; makhmetova_n1958@mail.ru; https://orcid.org/0000-0001-7324-5832

Kosenko Sergey Alexeyevich, Professor, Doctor of Technical Sciences, Siberian State University of Railway Transport, Novosibirsk, Russia; kosenko.s.a@mail.ru; https://orcid.org/0000-0003-2987-1435

Ivanovtseva Natalia Viktorovna, associate professor, Kazakh Academy of Transport and Communications named by M. Tynyshpaev, Almaty, Kazakhstan; stupchenko_n@mail.ru; https://orcid.org/0000-0002-0395-1720

Malik Arman Aydinovich, assistant-teacher, Kazakh Academy of Transport and Communications named by M. Tynyshpaev, Almaty, Kazakhstan; arman.kz_1677@mail.ru; https://orcid.org/0000-0003-3651-1702

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