ISSN 1392 – 1215 ELECTRONICS AND ELECTRICAL ENGINEERING 2007. No. 6(78)
ELEKTRONIKA IR ELEKTROTECHNIKA

T 190 ELECTRICAL ENGINEERING
ELEKTROS INŽINERIJA

Linear Induction Motor at Present Time

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Introduction

In engineering, especially in electrical and mechanical automated structures such as industrial robots, fast manipulators and machine tools, linear movements are very usual. Linear speeds up to 10 m/s and displacement accuracies down to 10 µm are not uncommon. These movements are mostly obtained by using rotating motors in combination with rotation-to-translation mechanisms.

However, in case where high speed and accuracy are required of these mechanisms, serious problems may arise with stiffness, mass, friction and backlash.

Obviously a linear actuator will overcome many of these problems. Unfortunately, as with direct drive rotating motors, mechanical fixation of the actuator load in a power off situation, such as that obtainable from self braking screw spindle mechanisms is not available. This is a drawback that results from the above-named advantages.

In many countries 60 % of the electrical energy is changed by electrical drives in mechanical energy. The electrical drive are able adapt speed and torque very tight to the machine or process need. Thus energy can be saved in an amount of several percents to 30 %. This important for the global economy and means a high responsibility of the drive engineers to save energy.

The article discusses present-day possibilities and methods of investigation as well as samples of application linear induction motors and drives.

Structure of linear drives

The linear drive consists as its revolving partner of the actuator, the inverter including the controller for open or closed-loop mode and the measuring system.

As Fig. 1 shows, a classic drive has a mechanical drive between the motor and machine. Even more it can be any mechanism to perform revolving motion to linear motion. In the structure there are power loss sources in the motor, mechanical drive or mechanism and finely in the machine. Similar it is with the moments of inertia. The energy is at least twice converted.

Much more simple is a system using a direct drive (Fig. 2). That one is characterized by the direct connection of motor and machine. According to this there is at least one source less of losses and inertia.

The mechanical drive is not necessary as well as a mechanisms for changing revolving motion to linear motion are not needed.

Less losses to less energy costs and less inertia gives a higher dynamic performance. But there are some more financial advantages: less space – less investigation amount, less noise, less amount of maintenance and no costs for the mechanical drive or the other mechanism.

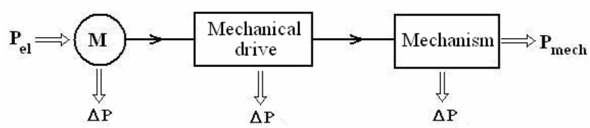

Fig. 1. Drive system with mechanical drive

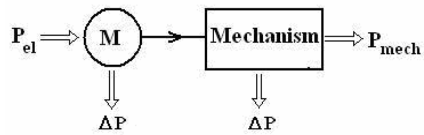

Fig. 2. Direct drive system

One more system design is of interest the combination of a revolving and linear motor as it shows Fig. 3. Here it is necessary to design the revolving motor in that way that its rotor can be moved with the linear motor without to leave the stator boring [9].

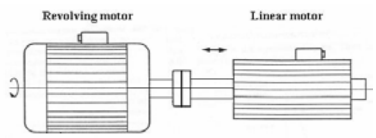

Fig. 3. Combination of linear and revolving drive

Moving permanent magnet (PM) linear actuators has moving magnets. The mover weight is expected to be low. It has a thrust independent of motion. Care must be exercised in maintaining the PM temperature within safe limits to avoid demagnetization. The PM-iron mover is rugged but its mass is high so the frequency of oscillations is limited to a few Hertz.

Application areas of linear motors

Application of linear induction motors for translation gives possibly to diminish weight of drive moving parts and drives, enlarge operating speeds and accelerations. In many cases a new construction of equipment is developed where the linear induction motor becomes an incorporated part of that.

Nowadays, drives with linear induction motors are used in these areas: rapid transport systems and catapults, systems of industrial transport, industry of semiconductors and electronics, explosions localizing systems, industrial robots and machine-tools, protection and control systems of power energetic, medical instruments, computer engineering. Carried out analysis of LIM application areas indicate problems of developing and investigation of linear drives being topical and important.

Applications of linear motors in high speed transport are known the most widely. Nevertheless, the linear motors are successfully applied in many other areas, presented in Fig. 4.

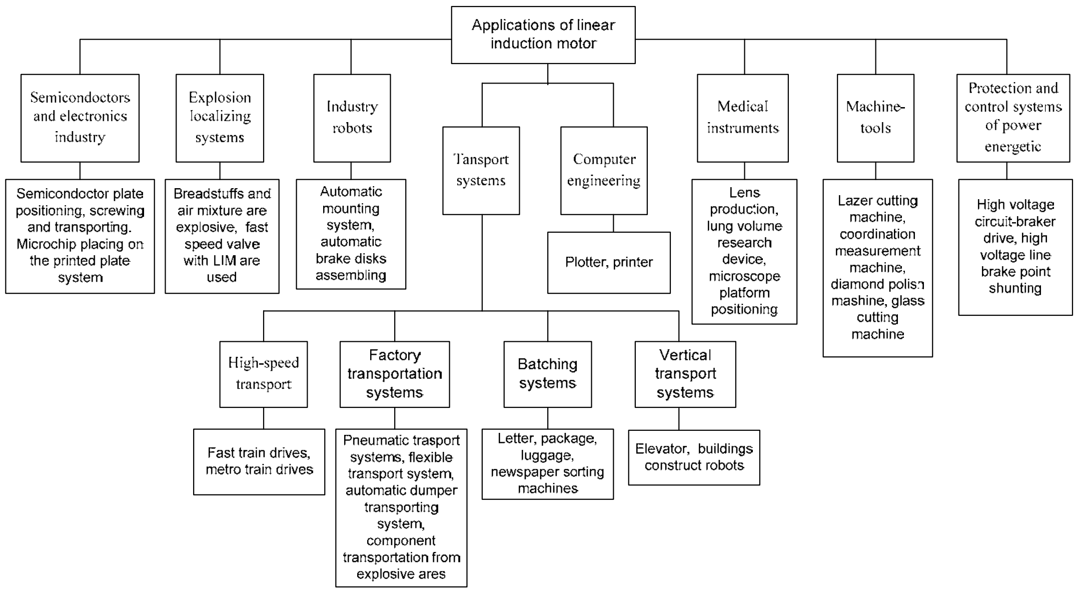

Fig. 4. Areas of application of linear induction drives

Problems of investigation of linear induction drives

All calculations of linear induction motors are based on solution of electromagnetic field equations. Method of solution of traveling magnetic field equations depends on complexity of problem and boundary conditions.

The main theoretical methods, used to explore linear induction motors, are: direct solution of equations of electromagnetic field; spectral method; numerical methods, for example, finite elements method; other methods, as Fourier series; idealization of current load by delta function of discrete sections.

The point of the spectral method is application of Fourier integral and its transform to solve problems of electro-mechanics if the primary current load density exists in a finite length of considered coordinate.

With application of direct Fourier transform, the elementary component of primary current density is found. In this way the total spectrum of space elementary components of magnetic field intensity is obtained. Each component has different space frequency and corresponds to traveling sine magnetic field, existing in range from $-\infty$ to $+\infty$. All methods of solution of ideal motor model can be applied here. Then with inverse Fourier transform the primary current density, magnetic field intensity and spectral characteristics of force and other integral values are calculated.

These methods can be used to investigate motoring or braking modes of linear induction motors.

The direct current density at braking in the inductor can be described as:

$$j_1(x) = J_{1m} \exp(-i\alpha x); \tag{1}$$

where J_{1m} stands for the complex amplitude of current density; τ – for pole pitch; $\alpha = \alpha/\pi$.

This analysis of electromagnetic processes is being carried out by means of the spectral method based on bilateral Fourier transformation. Primary current density (1) is presented in the form of a continuous spectrum of the elementary components of the secondary magnetic field, the strength of which is determined by way of solving equations, whilst the whole strength of the secondary field in the active zone of the motor is assessed by way of adding their integral values. The characteristics of primary current density, the strength of the primary field and the braking force are also being presented. Analytical expressions have been obtained for the braking force and force attenuation factor.

The ideal braking force of linear induction asynchronous motors can be described as:

$$F_0 = \frac{J_{1m}^2 \mu_0 \varepsilon L \delta c}{\alpha_1}\ , \tag{2}$$

and the real electromagnetic braking force of the motor as:

$$F_{em} = -\frac{1}{2}\operatorname{Re}\int_{-\frac{L}{2}}^{+\frac{L}{2}}\int_{-c}^{+c}\int_{-\frac{\delta}{2}}^{+\frac{\delta}{2}} \underline{H}_2 \cdot \overset{*}{j_1}\, dxdydz. \tag{3}$$

The rate applied here

$$\varepsilon = \frac{\mu_0 \gamma_0 v}{\alpha_1}, \tag{4}$$

assesses the quality of the linear induction motor and is called Reynold's magnetic number, known in scientific literature as the goodness factor.

Force coefficient k_F depends on ε, the electromagnetic rates, the number of active zones (poles) and the dimension of the motor. If the length of the active zones are finite, the related braking force generally equals

$$F_{em} = -\frac{1}{2}\operatorname{Re}\frac{J_{1m}^2 \mu_0 \varepsilon L \delta (1+i\varepsilon)}{\alpha_1(1+\varepsilon^2)} \times$$

$$\times \int_{-c}^{+c}\left[1 - \frac{ch\left[\alpha_1(b-c)\sqrt{1-i\varepsilon}\right]\cdot ch(\alpha_1 y\sqrt{1-i\varepsilon})}{ch(\alpha_1 b\sqrt{1-i\varepsilon})}\right]\cdot dy +$$

$$+\frac{4J_{im}\mu_0\varepsilon\delta}{\pi\alpha_1}\cdot\sum_{k=0}^{\infty}\frac{\sin\left[\frac{\pi c}{2b}(2k+1)\right]}{(2k+1)\sqrt{\varepsilon^2+m^2}}\cdot\int_{-a}^{+a}\cos\left[\frac{\pi y}{2b}(2k+1)\right]\cdot dy.$$

$$\operatorname{Re}\left[\frac{(\varepsilon+\sqrt{\varepsilon^2+m^2}-2i)\cdot e^{i\alpha_1\frac{L}{2}}\cdot e^{\alpha_1\frac{L}{4}(\varepsilon-\sqrt{\varepsilon^2+m^2})}}{4+2\varepsilon^2+m^2-2\varepsilon\sqrt{\varepsilon^2+m^2}}\times\right.$$

$$\times\int_{-\frac{L}{2}}^{+\frac{L}{2}} e^{\frac{\alpha_1}{2}(\varepsilon-\sqrt{\varepsilon^2+m^2}+2i)}dx -$$

$$-\frac{(\varepsilon+\sqrt{\varepsilon^2+m^2}-2i)\cdot e^{-\alpha_1\frac{L}{2}}\cdot e^{\frac{\alpha_1}{4}(\varepsilon+\sqrt{\varepsilon^2+m^2})}}{4+2\varepsilon^2+m^2-2\varepsilon\sqrt{\varepsilon^2+m^2}}\times$$

$$\left.\times\int_{-\frac{L}{2}}^{+\frac{L}{2}} e^{\frac{\alpha_1}{2}(\varepsilon+\sqrt{\varepsilon^2+m^2}+2i)}dx\right]. \tag{5}$$

All parameters in expressions (1-5) are described in [4]. From (5) it is apparent that the related force is reversely proportionate to the length of the inductor L, i. e., to the number of active zones (poles).

Application of spectral method gave possibility to solve various problems of electro mechanics in proper way: to determine steady-state and dynamic characteristics of the motor as well as duration of transients. At present the great attention is paid to solve problems of application of linear induction motors and to investigate special modes of operation as well as to calculate magnetic field of that.

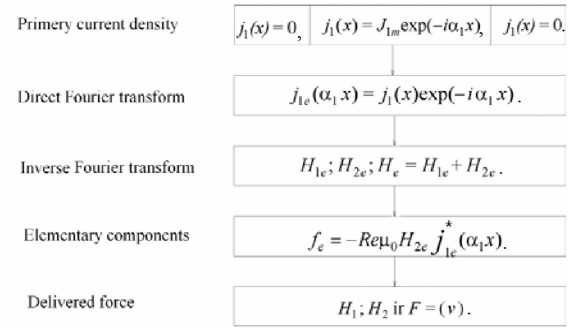

Fig. 5. Algorithm for calculation of LIM characteristics

Special operation modes comprise the non-symmetrical modes of operation at supplying phase windings of motor by unbalanced three phase or single phase alternating current and direct current. Non-symmetrical mode of operation is considered in [1, 3].

Consideration of dynamic modes is based on reference frame transform theory, applied to coordinates of generalized linear induction motor [1, 3, 4, 6].

The aim and advantage of this transform lies in simplification of mathematical model, possibility to deal with non-sinusoidal variables, but their amplitudes and avoid dependence of inductances upon their space position.

The main differential equations, ascribing dynamics of linear induction motor with neglected end effects in the synchronous reference frame, are [3]:

$$\begin{cases} \dfrac{d\Psi_{x1}}{dt} = U_{1m}\cos\gamma - \dfrac{\pi}{\tau}v_0\alpha_s{}'\Psi_{x1} + \dfrac{\pi}{\tau}v_0\alpha_s{}'K_r\Psi_{x2} + \dfrac{\pi}{\tau}v_0\Psi_{y1}; \\ \dfrac{d\Psi_{y1}}{dt} = U_{1m}\sin\gamma - \dfrac{\pi}{\tau}v_0\alpha_s{}'\Psi_{x1} + \dfrac{\pi}{\tau}v_0\alpha_s{}'K_r\Psi_{y2} - \dfrac{\pi}{\tau}v_0\Psi_{x1}; \\ \dfrac{d\Psi_{x2}}{dt} = -\dfrac{\pi}{\tau}v_0\alpha_r{}'\Psi_{x2} + \dfrac{\pi}{\tau}v_0\alpha_r{}'K_s\Psi_{x1} + \dfrac{\pi}{\tau}(v-v_0)\Psi_{y2}; \\ \dfrac{d\Psi_{y2}}{dt} = -\dfrac{\pi}{\tau}v_0\alpha_r{}'\Psi_{y2} + \dfrac{\pi}{\tau}v_0\alpha_r{}'K_s\Psi_{x1} - \dfrac{\pi}{\tau}(v-v_0)\Psi_{x2}; \\ F = \dfrac{3}{2}\dfrac{\pi\omega_0 K_r}{\tau\sigma x_s}(\Psi_{x2}\Psi_{y1} - \Psi_{x1}\Psi_{y2}), \end{cases} \tag{6}$$

where $\alpha_s = \frac{R_1}{X_s}$; $\alpha_r = \frac{R_2{}'}{X_s}$; $\sigma = 1 - \frac{X_m^2}{X_r X_m}$; $K_s = \frac{X_m}{X_s}$; $K_r = \frac{X_m}{X_r}$; $\alpha_r{}' = \frac{\alpha_r}{\sigma}$; $\alpha_s{}' = \frac{\alpha_s}{\sigma}$. Other assumed notations: X_m – the magnetizing reactance; $X_s = X_m + X_1$ – total reactance of inductor; $X_r = X_m + X_2{}'$ – total reactance of secondary, X_1, $X_2{}'$ – leakage reactance of inductor and secondary.

Equations for reverse component are obtained from that of direct component, replacing slip s by 2-s and $v - v_0$ by $v + v_0$.

The zero components do not develop force and is used just to calculate currents. According to Eqs. (6), the computer model to simulate non-symmetrical dynamic modes is presented in Fig. 6.

The results of simulation of dynamic modes of linear electric drive at single phase breaking and at direct current braking are presented in Fig.7 and Fig.8.

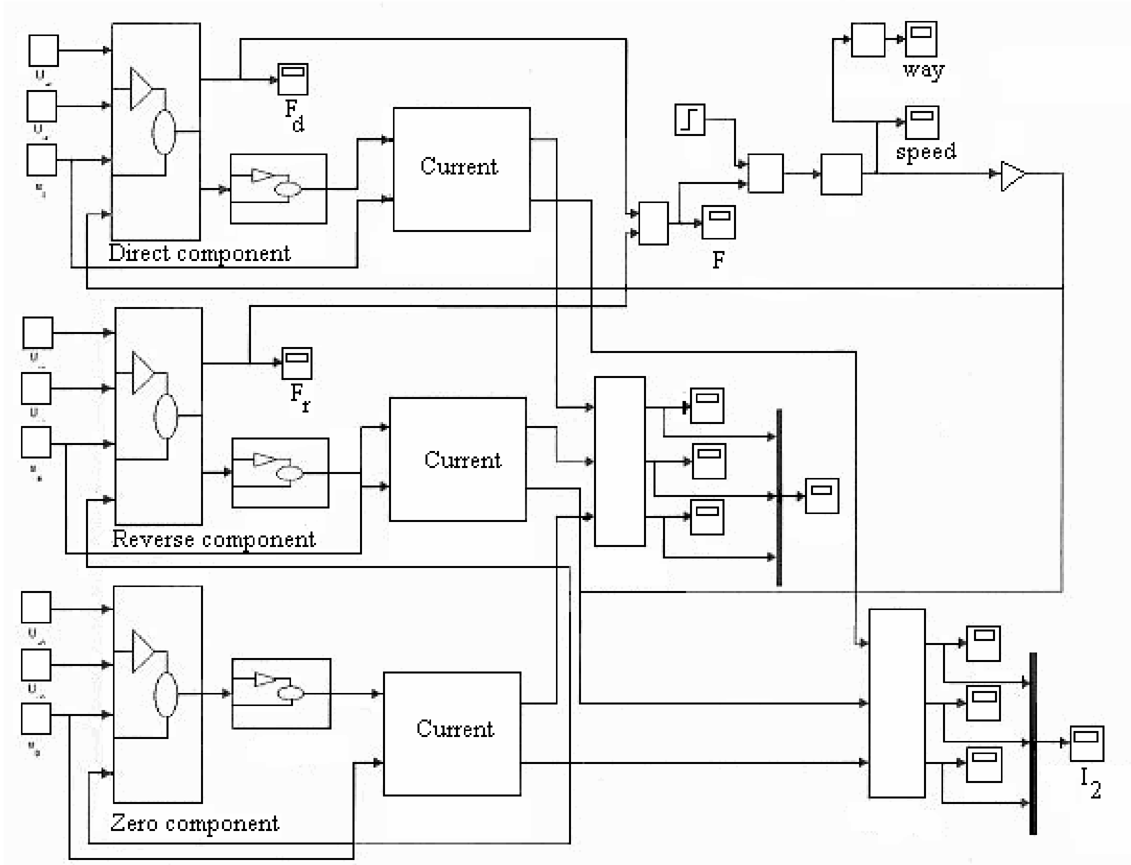

Fig. 6. Computer model of investigation non-symmetrical modes of linear drive

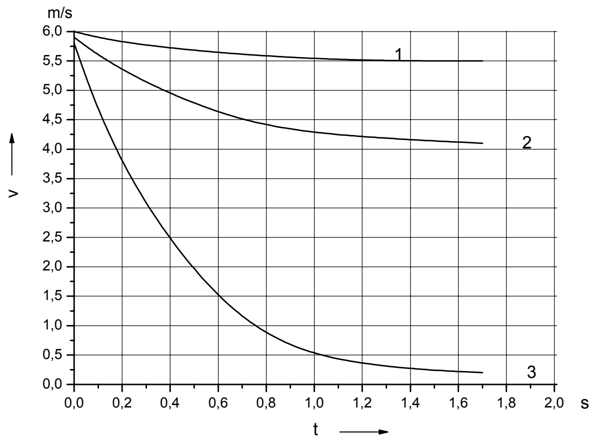

Fig. 7. Transients of speed at no load for all three ways of winding connection during single phase breaking: 1 – at supplying series-parallel connected windings, 2 – at supplying series connected windings, 3 – at supplying one phase winding

Simulation of magnetic field in the air gap of linear induction motor is more difficult, than of magnetic field of rotating induction motor. Traveling magnetic field can be explored with a lot of analytic methods.

Examining of magnetic field of linear induction motor is more complicated, because the requirements to investigate the magnetic field outside the inductor (end and transversal effects).

As the influence of these fields to the main magnetic field of linear induction motor arise. End effects influence to linear induction motor depends on speed of secondary element and parameters of inductor and secondary element of linear induction motor [9]. The result of ends effect is reduction of attraction force, increased phase impedance and leading currents of phases to inequality at balanced supply voltage.

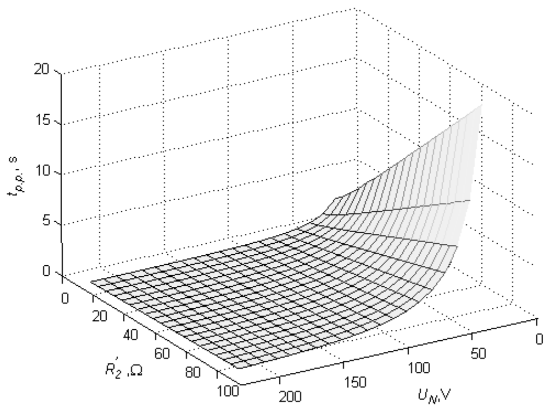

Fig. 8. Breaking time dependence upon breaking voltage attached to two phase windings, connected in series and resistance of the secondary element

There are many investigations of magnetic field character outside the inductor carried out, but there is not enough information about this field at the different instants of time.

New technologies of investigation change the viewpoint of these problems solving.

Now it is possible to simulate phenomena's using specialized software, easy change options of the simulation, get the results chosen in cross-sections.

The model of the one-sided flat-type linear induction motor with one inductor, secondary element and magnetic shunt (magnetic shunt are used to reduce reluctance) is developed and results of simulation are discussed in this article.

Inductor comprises six slots and the three-phase winding is built in these slots, to develop the traveling magnetic field. This construction corresponds to two-pole motor. Secondary element is copper, copper's specific permeability – 56000000 S/m^2, thickness of secondary element is 6 mm, air gap between inductor and secondary element δ – 0,25 mm. The windings of inductor are supplied by alternating current (of frequency 50 Hz); current of the winding density is 5000000 A/m^2.

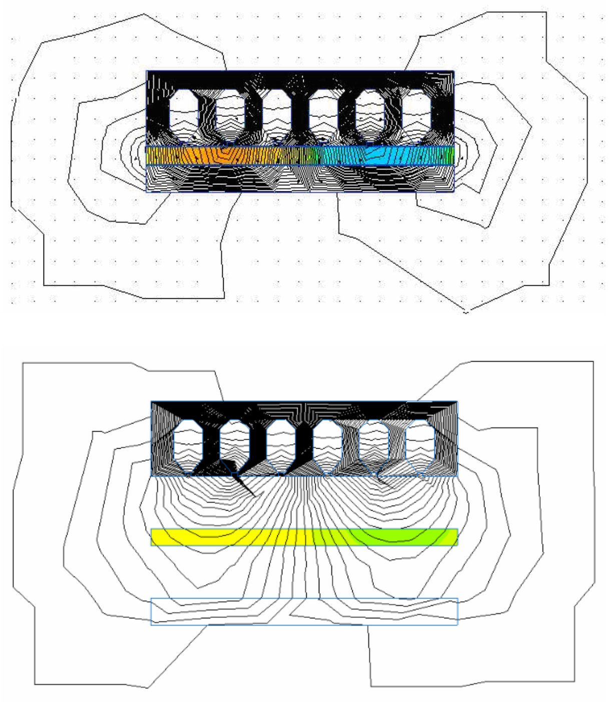

Fig. 9. The envelope of magnetic flux density outside inductor at different air gap width δ, in the model with secondary element

Conclusions

1. The great variety of constructions of linear induction motors and considered advantages enable to apply them in many areas of industry and home appliances.

2. Simulation results of single phase breaking indicate possibility to use this mode to reduce the speed of the motor or to stop it in accordance with the way of winding connection and the load. When the breaking voltage is connected to one phase winding, the motor with real parameters always comes to a stand. When the single phase breaking voltage is connected to two series connected windings, the motor speed becomes smaller by 25 % comparing with the case, if voltage is connected to tree series – parallel connected windings. Comparing calculated values of speed from steady state force – speed characteristics for all inductor winding connection ways, and steady-state values of speed, obtained from dynamic characteristics, are the same.

3. Distribution of magnetic field depends on air gap width and secondary element parameters.

4. The distance, when magnetic flux density outside inductor is equal to zero depends on instantaneous value of magnetic flux density in the ending tooth of inductor.

5. In the model with secondary element magnetic field lines reaches the longest distance outside inductor ends up to 30 percent of whole inductor length.

6. Obtained results give new information about magnetic fields distribution outside inductors. These results will be useful in further investigations.

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Submitted for publication 2007 03 13

R. Rinkevičienė, A. Smilgevičius. Linear Induction Motor at Present Time // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 6(78). – P. 3–8.

Discusses constructions of linear electric motors and drives, areas of theoretical investigation and problems of practical application. A conventional structure of electric drive with reducer and rectilinear system without reducer, combined system with revolving and linear motor is considered. Comprehensive classification of linear induction motors application areas is carried out. Possible methods of theoretical investigation and advantages of spectral method is presented, some results of investigation into special modes and magnetic field distribution are given. Examination of non-symmetrical dynamic modes is based on generalized dynamic model in synchronous reference frame. Simulation results of linear induction motor at supplying by single phase voltage one winding, two windings, connected in series or series-parallel connected windings are carried out. Graphical distribution of magnetic field beyond inductor ends is obtained by computer simulation and the factors, influencing the distribution, are determined. Ill. 9, bibl. 10 (in English, summaries in English, Russian and Lithuanian).

Р. Ринкявичене, А. Смилгявичюс. Линейные асинхронные двигатели в настоящее время // Электроника и электротехника. – Каунас: Технология, 2007. – № 6(78). – С. 3–8.

Обсуждаются конструкции линейных электродвигателей и приводов с ними, вопросы теоретического исследования и практического применения. Рассматривается структура традиционного электропривода с редуктором, система без редуктора, комбинированная двухдвигательная система электропривода с электродвигателями вращательного и линейного движения. Представлена подробная классификация областей применения линейных асинхронных электродвигателей, возможные методы теоретического исследования и преимущества спектрального метода, результаты исследования некоторых специальных режимов и распределения магнитного поля. Исследование несимметричных динамических режимов основано на координатных преобразованиях обобщенной динамической модели двигателя. Представлены результаты расчета, когда линейный асинхронный двигатель питается от однофазного источника переменного напряжения, а к сети подключена одна фаза индуктора, две последовательно соединенные фазы и смешанное соединение фаз. Графическое распределение магнитного поля за пределами индуктора получено при помощи компьютерного моделирования, определены факторы, влияющие на распределение поля продольной координаты. Ил. 9, библ. 10 (на английском языке; рефераты на английском, русском и литовском яз.).

R. Rinkevičienė, A. Smilgevičius. Šiuolaikiniai tiesiaeigiai asinchroniniai varikliai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 6(78). – P. 3–8.

Aptariamos tiesiaeigių elektros variklių ir pavarų konstrukcijos, teorinio tyrimo sritys ir praktinio taikymo klausimai. Nagrinėjama tradicinė elektros pavaros su reduktoriumi struktūra, tiesioginė sistema be reduktoriaus, kombinuotoji sukiojo ir tiesiaeigio variklio sistema. Sudaryta išsami tiesiaeigių asinchroninių variklių taikymo sričių klasifikacija. Pateikiami galimi tiesiaeigių variklių teorinio tyrimo metodai ir spektrinio metodo pranašumai, kai kurie specialiųjų režimų tyrimo ir magnetinio lauko pasiskirstymo rezultatai. Nesimetrinių dinaminių režimų tyrimas pagrįstas tiesiaeigio asinchroninio variklio apibendrinto dinaminio modelio koordinačių transformacijomis. Pateikiami tiesiaeigio asinchroninio variklio, maitinamo iš vienfazio įtampos šaltinio, skaičiavimo rezultatai, kai maitinama viena fazė, dvi nuosekliai sujungtos fazės ir mišrusis fazių jungimas. Grafinis magnetinio lauko pasiskirstymas už induktoriaus galų gautas naudojant kompiuterinę imitaciją, nustatyti magnetinio lauko pasiskirstymui įtakos turintys veiksniai. Il. 9, bibl. 10 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).