ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392-1215 2007. No. 3(75)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRICAL ENGINEERING
T 190
ELEKTROS INŽINERIJA

Investigation of Linear Induction Motor Braking Modes by Spectral Method

B. Karaliūnas, E. Matkevičius
Department of Automation, Vilnius Gediminas technical university,
Naugarduko st. 41,LT-03227 Vilnius, Lithuania, tel.: +370 274 50 63, e-mail: vgtufesto@el.vtu.lt

Introduction

Sophisticated mechatronic systems is considered the fundamentals of modern technology and automated processes of manufacturing. One of the most significant elements of mechatronic system is the executive motor which usually operates both under the mode of motor and brake. To achieve linear and sliding motion in the mechatronic systems there are used linear, flat, cylindrical, drum-wound type, segmental, disk, arc induction and other types of special electrical motors, the operation of which is based on the moving magnetic field [1]. The main characteristic of these motors which distinguishes them from the rotor type of ordinary design motors is considered their open magnetic circuit. In the theory of linear asynchronous motors the electromagnetic phenomena related to the finite length of active zone and magnetic core is called as longitudinal edge effect while the phenomena related to the finite width is called as transverse edge effect. Besides that both these effects in between are closely connected when their mutual interaction is considered a non – linear one. So there exist longitudinal and transverse edge effects, disfiguring the normal structure of the magnetic field and reducing the operational efficiency of the motor.

To brake these motors in the mechatronic systems there are applied the following methods [2]:

- dynamic;
- single – phase;
- regenerative (generator);
- capacitor;
- frequency (inverter);
- braking by pulsating current;
- countercurrent braking.

At present in the scientific literature one can find the research works [3, 4, 5], the issues of linear motor theory as well as their braking modes being analysed by the methods of electromagnetic field. One of the most promising research methods is the method of spectral magnetic field analysis. By applying it we are confronted with the issues of calculation of spectral characteristics of braking current, primary and secondary magnetic field, electromagnetic force and power that haven't been investigated widely enough yet.

The aim of the article is to compile the method for calculation spectral characteristics of braking current of the linear induction motor and to summarize the obtained results.

Main assumptions

For the analysis of linear asynchronic motor braking mode there was compiled a theoretical computational model which is presented and widely described in the works [6, 7]. According to this model all the methods of electrical braking have been analysed when based on one dimensional magnetic field analysis to derive the assumptions presented here below:

- electromagnetic braking processes are analysed in the rectangular right – sided Descartes system of coordinates *x, y, z* in connection with a motionless inductor;
- magnetic core of inductor do not have slots and are described as ideal parameters: magnetic permeability is $\mu = \infty$, electric conductance is $\gamma = 0$;
- conductors of inductor windings with the braking current is continuously distributed in the air gap δ_1 between the magnetic cores and in the active zone which length L comprises the wave of volumetric current density;
- non – ferromagnetic isotropic secondary element the parameters of which are μ_0 and $\gamma_2 \neq 0$, fill in the air gap δ_1 and moves towards the positive direction of the axis *ox* with the speed of $\vec{v}(t)$ having negative acceleration;
- in the air gap δ_1 there exist only parallel magnetic field components distinguished by the characteristics of plane field.

Taking into consideration these assumptions, the vector of magnetic field strength in the analysed model has got one component directed alongside the *oz* axis but the vectors of electric field strength and secondary currents have two components each directed alongside *ox* and *oy* axes.

Major equations

At the moment of braking, through the windings of inductor there flows the braking current, actuating the active zone of finite length *L*. Volumetric density of the braking current in the air gap of the motor is presented by the spatial vector, which is described not in realistic but in complex functions, namely phasors. In case of single – phase braking the alternating current creates in the air gap the pulsating wave of volumetric density of the braking current, in case of capacitor braking there is formed an attenuating wave. These are the so called non periodic functions of time satisfying the terms of Dirichlet and existing only at the moment of braking. The Laplace integral transformation is applied for such functions. The work [2] presents the expression received of the complex amplitude of an elementary component of such a single – phase braking current density:

$$\underline{j}_{1\omega}\left(x,t\right)=\frac{\underline{J}_{1m}\omega_t d\omega}{2\pi\left(\omega_t^{\,2}-\omega^2\right)}\left[e^{i\left(\omega t+\alpha_1 x\right)}+e^{i\left(\omega t-\alpha_1 x\right)}\right], \qquad (1)$$

$$\text{when } \left|x\right|\le\frac{L}{2};$$

where $\underline{J}_{1m}$ – is amplitude value of volumetric density of a current; ω_t – angular frequency of power supply network; ω – angular frequency of elementary component; $i=\sqrt{-1}$; $\alpha_1=\pi/\tau$ – angular spatial frequency of inductor winding; τ – pole pitch of an inductor.

The expression of complex amplitude of elementary component of capacitor braking current volumetric density is the following:

$$\underline{j}_{k\omega}\left(x,t\right)=\frac{\underline{J}_{km}\omega_1 d\omega}{2\pi\left[\left(\delta+i\omega\right)^2+\omega_1^{\,2}\right]}e^{i\left(\omega t-\alpha_1 x\right)}, \qquad (2)$$

$$\text{when } \left|x\right|\le\frac{L}{2};$$

where $\underline{J}_{km}$ – is amplitude value of capacitor braking current volumetric density; ω_1 and δ – are the angular frequency of braking current and the coefficient of its attenuation .

Complex amplitude of dynamic braking direct current volumetric density is expressed in the following way:

$$\underline{j}_d\left(x\right)=\underline{J}_{dm}e^{-i\alpha_1 x}, \text{ when } \left|x\right|\le\frac{L}{2}; \qquad (3)$$

where $\underline{J}_{dm}$ – is amplitude value of dynamic braking current volumetric density.

Application of Fourier transformation

(1–3) are the expressions of the function of non-periodic coordinate *x* existing within the boundaries of the active zone and absolutely integrated in the finite interval *L*. According to the direct both sided Fourier transformation of such a function there may be expressed by the continuous spectrum of the elementary components of the space:

$$\underline{I}(i\alpha)=\int_{-\infty}^{+\infty}\underline{j}(x)e^{-i\alpha x}dx; \qquad (4)$$

where $\alpha=\pi/\tau_e$ – is a variable frequency of the space from the infinite sector (- ∞ – + ∞); τ_e – is the length of semi – wave of an elementary component.

Integral (4) is solved together with (1) – (3) expressions. Then in case of dynamic braking there was received such a spectrum characteristic of current volumetric density:

$$\underline{I}(i\alpha)=\frac{2\underline{J}_{dm}}{\alpha+\alpha_1}\sin\left[\left(\alpha+\alpha_1\right)\frac{L}{2}\right]. \qquad (5)$$

Further are presented the expressions of spectrum of amplitudes of dynamic braking current density in the form of the relative units, when in the inductor there is a different number of excited zones:

a) when the number of excited zones is even

$$I_{de}=\left|2\left(-1\right)^p\frac{\sin\left(\pi p\,\alpha/\alpha_1\right)}{\pi\left(1+\alpha/\alpha_1\right)}\right|; \qquad (6)$$

b) when the number of zones is uneven

$$I_{dun}=\left|2\left(-1\right)^p\frac{\cos\left[\alpha/\alpha_1\left(2p+1\right)\pi/2\right]}{\pi\left(1+\alpha/\alpha_1\right)}\right|; \qquad (7)$$

c) when the number of excited zones is fractional

$$I_{dfr}=\left|\frac{2(-1)^p}{\pi(1+\alpha/\alpha_1)}\{\cos(r\pi/2)\times\sin[\alpha/\alpha_1(2p-r)\pi/2]-\right.$$

$$\left.-\sin(r\pi/2)\times\cos[\alpha/\alpha_1(2p-r)\pi/2]\}\right|; \qquad (8)$$

where *p* – is the whole number of the pairs poles of inductor; α/α_1 – is the relative space frequency of elementary components; *r* – is a fractional part indicating the shortened pole pitch τ .

When $\alpha/\alpha_1\to-1$, there are obtained expressions (6) – (8) which have become undetermined. However, these uncertainties are easily eliminated after having applied the rule of G. H. de L'Hopital:

$$\begin{cases}\lim\limits_{\alpha/\alpha_1\to-1}I_{de}=2p\,,\\ \lim\limits_{\alpha/\alpha_1\to-1}I_{dun}=2p+1\,,\\ \lim\limits_{\alpha/\alpha_1\to-1}I_{dfr}=2p-r\,.\end{cases} \qquad (9)$$

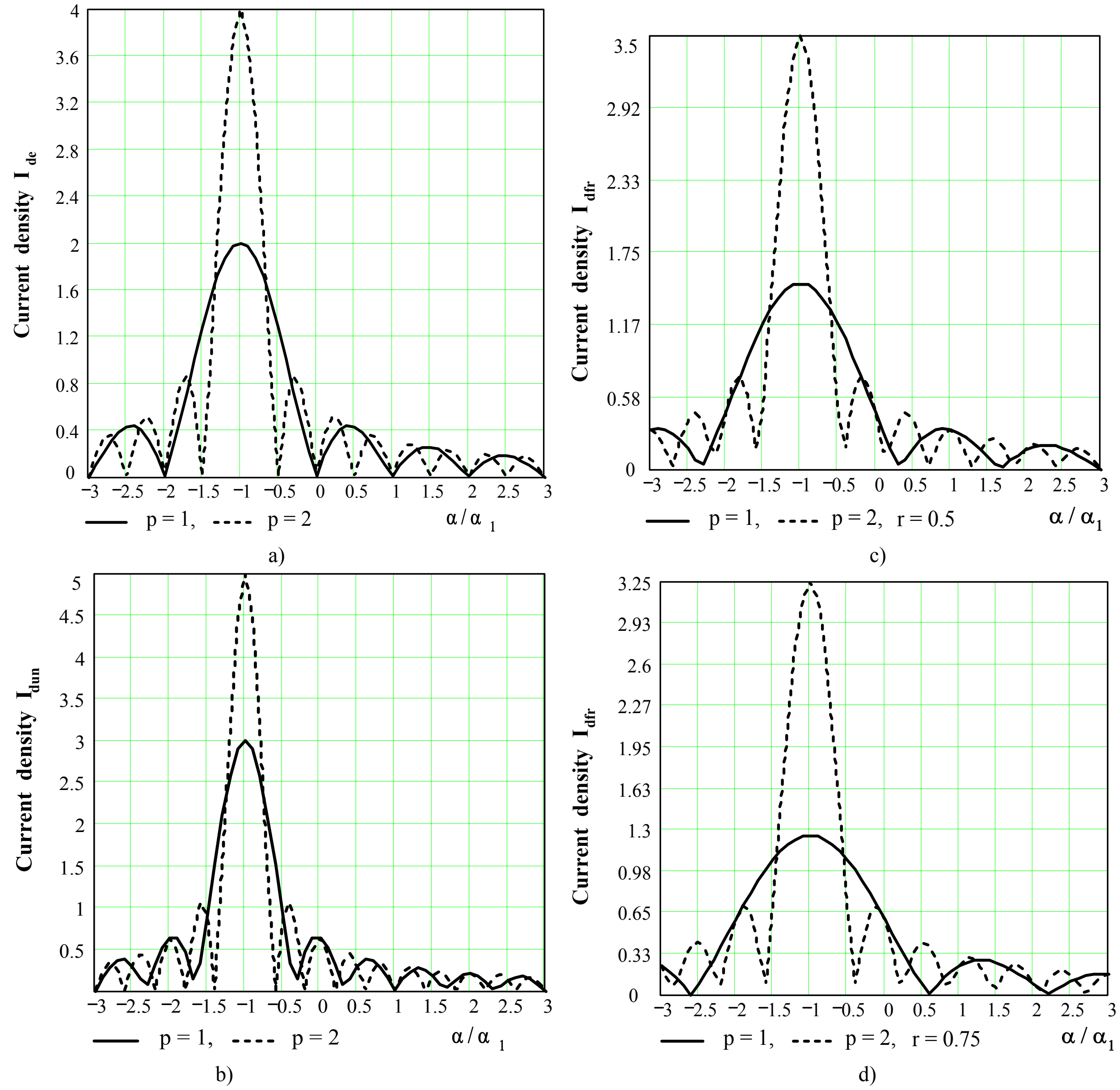

Fig. 1. Relative continuous spatial spectra of dynamic braking current density when $p = 1$ and $p = 2$ and the number of excited zones is: a) – even; b) – uneven; c) and d) – fractional

Results of calculations

In accordance with the obtained expressions (6–9) the software Mathcad 2001 Profesional has been applied to calculate relative spectra of amplitudes of dynamic braking current volumetric density. The results for calculations are presented in Fig. 1 a, b, c and d.

The results of the calculations indicate that the spectra of amplitudes are continuous and similar in their shape. The maximum density of amplitudes of braking current is formed in the point where $\alpha/\alpha_1 \to -1$. By increasing the number of inductor pairs poles p the density of the amplitudes increases as well, but the width of spectra reduces. The greatest amplitudes of current density are received when the number of the excited zones is uneven, i.e. when $L = (2p+1)\tau$. The greatest influence on to the continuous spectrum has the components of the main frequency ($\alpha = \alpha_1$).

Conclusions

The analysis of the literature indicates that at present the braking modes of the linear induction motors haven't been extensively analyzed yet although such motors are successfully applied in various mechatronic systems and in separate installations of the manufacturing processes. In the scientific literature there are no data received on the research of braking mode under the conditions when in the inductor there are induced the fractional number of excited zones. Such a number of zones may be applied to increase the efficiency of the braking.

The received results indicate that the spectra of amplitudes of dynamic braking current volumetric density due to the finite length L of the magnetic core and the active zone of the motor are continuous. However, in marginal case when $L \to \infty$, the spectra of amplitudes become discrete in which there are formed the harmonic components of discrete frequencies α/α_1 . In this case for the analysis of braking processes it is more suitable to have not the Fourier integral method, but the method of Fourier complex series.

References

1. **Budig P. – K.** The application of linear motors // Proc. of 9 – th Int. Conf. on Power Electronics and Motion Control. – Kosice, Slovak Republik. – 2000. – Vol. 3. – P. 1336 – 1341.
2. **Karaliūnas B., Matkevičius E.** Spectral Characteristics of the Braking Current of Induction Motor // Proc. of the fifth Int. Congress Mechanical Engineering Technologies'06. – Varna, Bulgaria. – 2006. – Vol. 5/88. – P. 3 – 6.
3. **Torri S., Mori Y. and Efihara D.** Fundamental Investigations on Analysis of Linear Induction Motor using the Wavelet Transform Technique // Proc. of Int. Conf. on Electrical Machines. – Helsinki, Finland. – 2000. – Vol. 1. – P. 99 – 102.
4. **Nonaka S.** Analysis of Single – Sided Linear Induction Motor by simplified Fourier Transform Method // Proc. of Int. Conf. on Electrical Machines. – Helsinki, Finland. – 2000. – Vol. 1. – P. 247 – 251.
5. **Morizane T., Kimura V., Taniguchi K.** Simultaneous Control of Propulsion and Levitation of Linear Induction Motor in a Novel Maglev System // Proc. of 9 – th Int. Conf. on Power Electronics and Motion Control. – Kosice, Slovak Republik. – 2000. – Vol. 5. – P. 55 – 60.
6. **Karaliūnas B.** Non stationary processes in the electric machine converters of energy // Proc. of Electrotechnical Institute. – Warszawa, Poland. – 1999. – Vol. 200/99. – P. 99 – 112.
7. **Darulienė O., Karaliūnas B.** Mathematical Model of Non–Stationary Braking Processes of Electro-mechanical Power Converters // Proc. of 11 – th Int. Conf. on Power Electronics and Motion Control. EPE – PEMC 2004. – Riga, Latvia. – 2004. – Vol. 3. – P. 415 – 419.

Submitted for publication 2006 11 30

B. Karaliūnas, E. Matkevičius. Investigation of the Linear Induction Motor Braking Modes by Spectral Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 3(75). – P. 37–40.

The article investigates the issues of electrical braking for induction motors the operation of which is based on the sliding magnetic field. It has been revealed that one of the most progressive analytical research methods of such type modes is considered the method of spectral magnetic fields analysis. To compile mathematical model there have been derived the main assumptions according to which all the measures of electric braking have to be investigated by means of the analysis of one dimensional magnetic field. The braking processes have been analysed in the motionless right – sided Descartes system of coordinates *x, y, z.* There have been presented the expressions of volumetric density of braking current which have been regarded the non – periodic functions of coordinate *x*. Besides that in cases of single – phase and capacitor braking these expressions are also regarded as the non – periodic functions of time. Therefore when compiling the mathematical model there have been applied Laplace and Fourier integral transformations. After having applied Fourier transformation there have been received the expressions of the spectra amplitudes of braking current volumetric density, under the condition that the number of excited zones in the inductor is even, uneven and fractional. The continuous spectra of amplitudes have been calculated by the software Mathcad 2001 Profesional. The results of the calculations indicate that the maximum amplitude density of dynamic braking current is obtained if the number of excited zones is uneven . Il.1, bibl. 7 (in English; summaries in English, Russian and Lithuanian).

Б. Каралюнас, Э. Маткевичюс. Исследование тормозных режимов линейного асинхронного двигателя спектральным методом // Электроника и электротехника. – Каунас: Технология, 2007. – № 3(75). – С. 37–40.

Рассматриваются вопросы электрического торможения индукционных двигателей, принцип действия которых основан на бегующем магнитном поле. Показано, что одним из наиболее перспективных методов исследования таких режимов является спектральный метод анализа магнитных полей. При создании математической модели приняты основные допущения, в итоге которых все электрические способы торможения исследуются на базе одномерной теории магнитного поля. Процессы торможения рассматриваются в неподвижной правовинтовой системе координат Декарта *x, y, z.* Представлены выражения обьемной плотности тормозного тока, которые являются непериодическими функциями продольной координаты *x.* Кроме того, в случае однофазного и конденсаторного торможения эти функции являются непериодическими функциями времени. Поэтому при создании математической модели были прменены интегральные преобразования Лапласа и Фурье. На основании преобразования Фурье получены выражения амплитудных спектров объемной плотности тормозного тока при четном, нечетном и дробном числе возбужденных зон индуктора. Сплошные амплитудные спектры были расчитаны с помощью компьютерной программы Mathcad 2001 Profesional. Результаты расчетов показывают, что наибольшая плотность амплитуд тормозного тока наблюдается при нечетном числе возбужденных зон. Ил. 1, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

B. Karaliūnas, E. Matkevičius. Tiesiaeigio indukcinio variklio stabdymo režimų tyrimas spektriniu metodu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 3(75). – P. 37–40.

Nagrinėjami indukcinių variklių, kurių veikimas pagrįstas slenkamuoju magnetiniu lauku, elektrinio stabdymo klausimai. Parodyta, kad vienas iš perspektyviausių analizinių tokių režimų tyrimo metodų yra spektrinis magnetinių laukų analizės metodas. Matematiniam modeliui sukurti daromos prielaidos, pagal kurias visi elektrinio stabdymo būdai nagrinėjami remiantis vienmačio magnetinio lauko analize. Stabdymo procesai nagrinėjami nejudančioje dešininėje Dekarto koordinačių sistemoje *x, y, z.* Pateiktos stabdymo srovės tūrinio tankio išraiškos, kurios yra neperiodinės koordinatės *x* funkcijos. Be to, vienfazio ir kondensatorinio stabdymo atvejais tos išraiškos yra dar ir neperiodinės laiko funkcijos. Dėl to, sudarant matematinį modelį, buvo taikyti Laplaso ir Furjė integraliniai pakeitimai. Pritaikius Furjė pakeitimą, gautos stabdymo srovės tūrinio tankio amplitudžių spektrų išraiškos, kai induktoriuje sužadintų zonų skaičius yra lyginis, nelyginis ir trupmeninis. Amplitudžių ištisiniai spektrai buvo skaičiuoti kompiuterine programa Mathcad 2001 Profesional. Skaičiavimo rezultatai rodo, kad didžiausias dinaminio stabdymo srovės amplitudžių tankis gaunamas tada, kai sužadintų zonų skaičius yra nelyginis. Il.1, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).