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The Edge Effects Influence on the Braking Characteristics of the Linear Induction Motor

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***Abstract*—The article presents the spectral analysis method of the magnetic fields to be able to evaluate transversal and longitudinal effects, based on Fourier integral transformations. It has been determined that the expressions of the relative spectral characteristics of the braking force and power coincide. In accordance with the derived expressions, the software program Mathcad 2001 Professional was used for the calculation of the dependencies of the transversal effect on the relative spatial frequency and under different Reynolds's numbers. The results of the calculation indicate that when increasing the width of the secondary element, the influence of the transversal effect on the braking characteristics tend to be reduced.**

***Index Terms*—Apparent power, braking force, calculation, edge effects, Fourier transformations, linear motor, spectral method.**

I. INTRODUCTION

The controlled linear induction drives are used in the modern mechatronic systems for generation of direct motion. They allow the simplifying of the system itself because the mechanical chains of the movement replacement are not required. The most significant fields for the practical application of the linear induction motors (LIM) are the following [1]:

1) Devices of magnetic hydrodynamics, liquid metals pumps, electromagnetic equipment for mixing and transportation;

2) The systems of the high–speed arterial transportation;

3) Internal transport devices of the industrial enterprises as well as the other manufacturing installations with linear induction motors;

4) Devices and appliances of automation.

Certain technological appliances and processes require accurate positioning of the movable part of the enforcement element. The braking of the linear induction motor plays a very significant role for positioning. The electric braking of LIM comprises a separate specific scientific and technical problem. The scientists from various countries investigated separate modes of LIM braking [2]–[4]. However, the electrical modes of braking are analysed the most extensively, presuming that the velocity of the motor during the moment of braking is constant. Therefore, there are received the static characteristics of braking which are different from the dynamic characteristics. Furthermore, LIM distinguishes itself by the specific characteristics, which are missing in the rotary motors of the usually practiced design. As regards the open magnetic circuit and finite length and width of the active zone of the inductor in the LIM, there tend to appear the magnetic field deformations. They form the transversal and longitudinal edge effects and the internal electrical as well as the magnetic asymmetry is formed in the motor. Rotary electric motors do not have such type of asymmetry. Therefore, when investigating the LIM braking modes it is necessary to solve the following essential problems:

1) The compiling of the mathematical model for LIM meant for calculating of the braking mode;

2) The description and computation of the magnetic fields created by means of the inductor and the current of the secondary element, presenting the evaluation of the transversal and longitudinal edge effects;

3) The calculation of the power and braking force for different designs of the linear induction motors;

4) The calculation of the non – stationary braking modes, taking into account the variations of the velocity as well as the influence of the acceleration on the characteristics of braking;

5) The comparison of the efficiency of various braking modes as well as the compiling of the new modes and diagrams of braking.

When trying to solve these mentioned above issues it is appropriate to analyse the dynamic modes of braking of LIM by means of the methods of computer modelling.

The objective of the work is to calculate the force of braking as well as power and analyse the influence of the edge effects.

II. CALCULATION OF THE BRAKING FORCE

The theoretical computational model for LIM, which is very extensively described in works [5], [6], is applied for calculation the braking force and power. In accordance with the model the electromagnetic processes of braking are analyzed in Descartes rectangular system of coordinates x, *y*, *z*, *0*.

To appraise the transversal and longitudinal edge effects, are applied the spectral analysis method of the magnetic fields and Fourier integral changes [7], [8]. From the

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amplitudes of the continuous spectrum were derived the braking currents $\underline{j}_e$ and the expressions of the elementary components of the secondary magnetic field $\underline{H}_{2e}$. Thus, the elementary component of the braking force could be calculated in the following way

$$f_e = -\mu_0 \operatorname{Re} \underline{j}_e^* \underline{H}_{2e}, \tag{1}$$

where $\mu_0 = 4\pi 10^{-7}$, H/m – is the magnetic permeability of the secondary element; Re – is the real part of the complex number.

Whereas $\underline{j}_e$ and $\underline{H}_{2e}$ is the sine function of coordinate *x*, that is why to the expression (1) it is possible to apply the inverse Fourier replacement

$$f_e = \frac{1}{2\pi} F_\alpha e^{i2\alpha x} d(2\alpha), \tag{2}$$

where α – is a variable spatial frequency from the infinite band ($-\infty ... +\infty$); F_α – is the spectral characteristic of the braking force; $i = \sqrt{-1}$.

To calculate F_α it is convenient to use the expression in relative units

$$F_\alpha = \operatorname{Re} \frac{i\left|I_\alpha\right|^2}{\pi k} K_F A_{kv}, \tag{3}$$

where K_F and A_{kv} – is the coefficient of the transversal effect and the function of velocity and acceleration; $\left|I_\alpha\right|^2$ – is the square of the module of the relative spectral characteristics of the braking current; $k = \alpha / \alpha_1$ – is the relative spatial frequency; $\alpha_1 = \pi / \tau$; τ – is pole pitch of the inductor.

The coefficient K_F in the expression (3) evaluates not only the transversal edge effect, but also the demagnetizing effect of the secondary currents. For the model, where the secondary element is wider than the inductor ($b > c$), was derived the following expression of K_F

$$K_F = 1 - \frac{\operatorname{ch}\left[\pi \, y/\tau \, \sqrt{k^2 + ik\varepsilon_0 v}\right]}{\operatorname{ch}\left[\pi \xi \, c/\tau \, \sqrt{k^2 + ik\varepsilon_0 v}\right]} \times$$
$$\times \operatorname{ch}\left[\pi(\xi - 1) \, c/\tau \, \sqrt{k^2 + i\varepsilon_0 v}\right], \tag{4}$$

where ε_0 – is the magnetic Reynold's number; c/τ – is the relative width of the active zone; $\xi = b/c$ – is the relative width of the secondary element; v – is the velocity of the secondary element during the moment of braking.

When the margin is determined in the expression (4) under $\xi \to 1$, is derived the coefficient value of the transversal effect for the model, where $b = c$

$$K_{1F} = 1 - \frac{\operatorname{ch}\left[\pi \, y/\tau \, \sqrt{k^2 + ik\varepsilon_0 v}\right]}{\operatorname{ch}\left[\pi \, c/\tau \, \sqrt{k^2 + ik\varepsilon_0 v}\right]}. \tag{5}$$

For the model of the infinite width, when $c \to \infty$, from (5) we derive

$$K_{2F} = \frac{1}{1 + k^2 \varepsilon_0^2 v^2}. \tag{6}$$

The total force operating within the boundaries of the active zone of the investigated model, there is nothing less than the integral sum (1) of the elementary components. The calculations indicate that the electromagnetic force of braking has three components

$$F_{elm} = F_1 + F_2 + F_3, \tag{7}$$

where F_1 – is the component of the braking force, where there is evaluated only the transversal edge effect F_2 – is the free component of force existing only during the moment of the transitional process; F_3 – is the component, estimating the longitudinal and transversal edge effects and their reciprocity.

The analytical expressions of the components F_1, F_2 and F_3 and the diagrams of their changes are presented in part [8].

III. THE CALCULATION OF THE BRAKING POWER

During the process of braking, the kinetic energy of the moving parts is replaced by the electric one, one part of which is converted into heat in the internal resistances of the secondary element, but the other part is used to create the braking power. Each elementary component $\underline{H}_{2e}$ of the secondary magnetic field from the point of view of the inductor moves within the velocity $v(t)$ of the secondary element. Therefore, the elementary components of the electromotive force is induced in the windings of the inductor, due to which there is created the electric field of the following strength

$$\underline{E}_{12e} = \mu_0 v(t) \underline{H}_{2e}. \tag{8}$$

Then in the secondary element, the derived elementary component of the apparent power of the continuous spectrum could be calculated as the result of the interaction of $\underline{E}_{12e}$ and $\underline{j}_e$

$$\underline{S}_e = -\underline{E}_{12e} \dot{\underline{j}}_e. \tag{9}$$

This expression indicates that the continuous spectrum of the electric field in the secondary element creates the continuous spectrum of the apparent power. Following the inverse Fourier replacement from equation (9) in the form of the relative units was derived the following expression of the spectral characteristics of the apparent power

$$S_\alpha = \frac{i|I_\alpha|^2}{\pi k} K_F A_{kv}. \tag{10}$$

The obtained result indicates that expressions (10) and (3) of the relative spectral characteristics of the apparent power and braking force tend to coincide. But when calculating F_α, from expression (3) only the real part of the complex function is taken, but when calculating S_α according to expression (10), there are used both parts, namely the real part and the imaginary part. It is easy to see that the real part of expression (10) produces the continuous spectrum P_α of the active power, and the imaginary part creates the spectrum Q_α of the reactive braking power. Thus, it is possible to present the following

$$S_\alpha = P_\alpha + iQ_\alpha. \tag{11}$$

Then the spectrum of the amplitudes of the apparent power is equal to

$$|S(\alpha)| = \sqrt{P^2(\alpha) + Q^2(\alpha)}. \tag{12}$$

IV. THE RESULTS OF CALCULATIONS

The diagrams of the changes of the coefficient of the transversal effect were calculated following expressions (4)–(6) and by replacing various parameters of the motor. The software Mathcad 2001 Professional was used for the calculations.

Fig. 1 presents the diagrams of the changes of coefficient K_F under the different numbers of Reynolds.

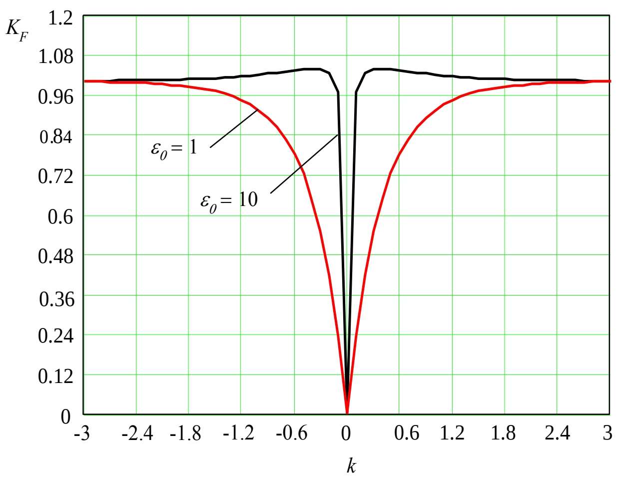

Fig. 1. The dependence of the transversal edge effect coefficient on the relative spatial frequency, when Reynold's numbers are different.

Fig. 2 presents the diagrams of the changes of coefficients K_{1F} and K_{2F} when the parameters of the motor are the following: $v = 0.4$; $y/\tau = 0.2$; $c/\tau = 0.8$; $\varepsilon_0 = 1.0$ and $\varepsilon_0 = 10$.

There were analyzed the dependencies of the coefficients on the relative width c/τ. Fig. 3 presents such diagrams, when $k = -1.0$; $v = 0.4$; $\xi = 1.5$; $y/\tau = 0.5$.

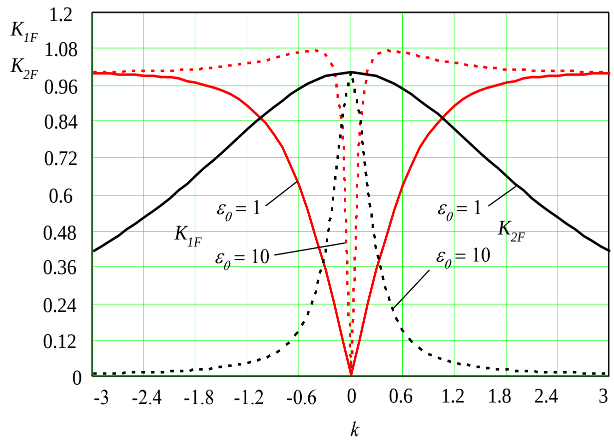

Fig. 2. The diagrams of the changes of coefficients K_{1F} and K_{2F} when $\varepsilon_0 = 1.0$ and $\varepsilon_0 = 10$.

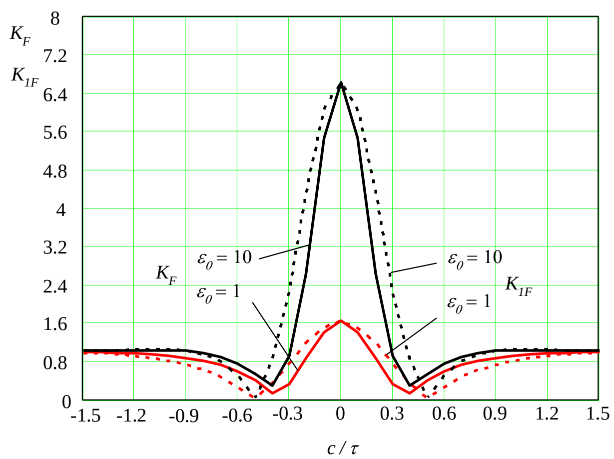

Fig. 3. The dependencies of the coefficients of the transversal edge effect on relative width c/τ, under different Reynolds's numbers.

The continuous spectrums of the amplitudes of the apparent, active and reactive power are calculated according to expressions (10)–(12). Such diagrams are presented in Fig. 4 and Fig. 5.

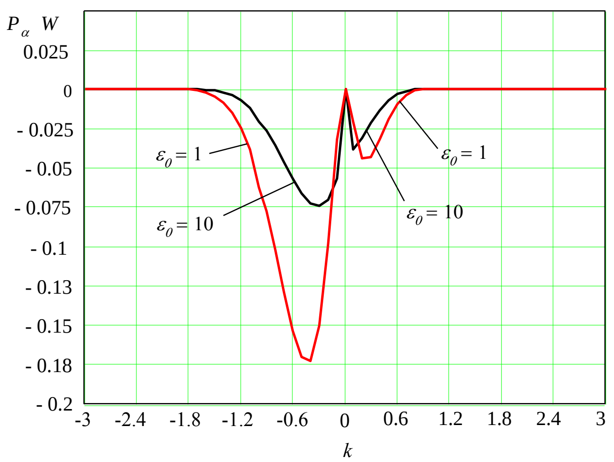

Fig. 4. The continuous spectrums of the amplitudes of the active braking power, when $\varepsilon_0 = 1.0$ and $\varepsilon_0 = 10$.

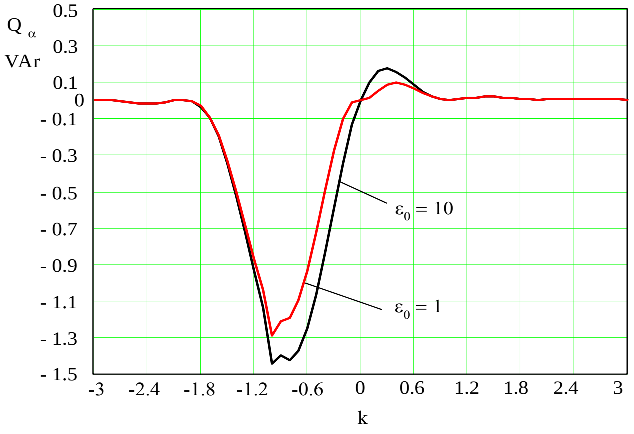

Fig. 5. Continuous spectrums of the amplitudes of the reactive braking power, when $\varepsilon_0 = 1.0$ and $\varepsilon_0 = 10$.

The obtained results indicate that the spectrums of the braking power of the amplitudes are negative. This indicates the fact, that during the moment of braking, the LIM operates as the generator and the kinetic energy of the moving parts is turned into the electric power.

V. Conclusions

1) There has been determined the fact that the braking force and power of the linear induction motor have to be characterized by three components, evaluating the change of the velocity of the secondary element, the transversal edge effect and the reciprocity of the transversal and longitudinal effects.

2) The results of the calculations indicate that the expressions of the relative spectral characteristics of apparent power S_α and braking force F_α coincide (are the same). The real part of the complex function S_α makes the active power, but the imaginary part creates the spectrum of the amplitudes of the reactive power.

3) According to the obtained expressions, it is possible to calculate the characteristics of the braking force and power of the linear induction motor, which appear due to the separate elementary component of the continuous spectrums with any frequency α .

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