Calculation of the Braking Force Transitional Processes for Linear Induction Motor

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Introduction

Modern technologies and mechatronic systems not only widely apply rotational electrical motors but also operating devices of linear motion, namely linear induction and arc electric motors. When compiling new systems based on the mentioned above motors, it is required to take into consideration that the moving parts of these systems have to undergo frequent braking. By using mechanical, hydraulic, pneumatic and electromechanical devices or by switching the motor of the drive into the mode of electric braking, it is possible to generate the braking force. The mentioned above method is the one to be most widely applied in practice, because of the efficient performance of an electric motor.

Automatic systems with linear induction motors (LIM) are most commonly realised through the non stationary braking modes: dynamic, regenerative (generator), single – phase, capacitor, frequency (inverter), opposite connection braking and braking by pulsating current. During the moment of braking in the moving part (secondary element), in some cases in the inductor there appear rather complicated interrelated electromagnetic and electromechanical transitional processes. That is why, recently there have been published several scientific articles, dealing with the non stationary modes of braking of LIM [1, 2].

One of the most promising methods of the analysis of the non stationary braking modes is spectrum mode [3]. By applying it the spectrum characteristics of the braking current of LIM are presented in article [4]. In article [5] there are presented the results of the calculations of the braking force and the dynamic characteristics of the braking mode of LIM are analysed.

The review of the similar publications indicate that so far the number of substantially justified methodologies haven’t been enough which could allow the research of the non stationary processes of braking of LIM and would let calculate their dynamic characteristics taking into account the specific characteristics typical for the majority of such type motors. Due to the longitudinal edge effect of the open magnetic circuit and finite length of the active zone, LIM is specified by possessing the internal magnetic and electric asymmetry [6]. The mentioned above asymmetry is not available for rotational electric motors. That is why the known mathematical models of the rotational motors and methods of analysis are considered not to be applicable for the research of such type non symmetric LIM. It is required not only to search for new models but scientifically to justify them as well.

The purpose of the work is to calculate and analyse the transitional processes of the braking force of LIM.

Braking force calculation patterns

For the calculation of the transitional processes of the braking force, in this work there is applied the theoretical simulation model of [4, 5]. According to the model the spectrum method was applied for the analysis of all the braking modes of LIM, based on the theory of electromagnetic field and Fourier integral transformations.

It is considered that during the moment of braking there isn’t any saturation of the magnetic circuit of LIM that is why in such a linear system there validates the principal of the super-position of the magnetic fields. Because of that principal, the total magnetic field $H$ of LIM in the air gap is compiled of two components [4]:

$$H = H_1 + H_2;$$  (1)

where $H_1$ – the complex amplitude of the primary or inductor generated magnetic field; $H_2$ – the complex amplitude of the secondary magnetic field or the field of the induced currents in the secondary element.

When the spectrum method is applied with the expressions of the theory of residuum it is possible to calculate by analytic method the magnetic fields $H_1$ and $H_2$ of any mode of braking. Then the force of braking is possible to be calculated by several ways. The force, conditioning the elementary volume $dx, dy, dz$ of the secondary element, is calculated in the following way:
\[ dF_{elm} = -\frac{\mu_0}{2} \text{Re} H_2 j(x,t) dx dy dz; \]  

(2)

where \( \mu_0 = 4\pi 10^{-7} \ H/m \) – magnetic permeability of the secondary element; \( \text{Re} \) – the real part of the complex number; \( j(x,t) \) – the integrated complex of volume density of the braking current.

Total force operating within the boundaries of the active zone of the analysed model is expressed by the volume integral:

\[ F_{elm} = -\frac{\mu_0}{2} \text{Re} \int V H_2 j(x,t) dV, \]  

(3)

where \( V \) – the volume of the secondary element, in which there is generated the braking force and according to which the expression (3) is integrated.

For the calculation of the force it is possible to use and the equality of Parseval determining the relationship between the elementary component of the force and the complex amplitudes of its spectrum characteristics:

\[ \int_{-\infty}^{\infty} H_{2x} j_x dx = \frac{1}{2\pi} \int_{-\infty}^{\infty} H_{2x} I(i\alpha) d\alpha, \]  

(4)

where \( H_{2x} \) – the elementary component of the continuous spectrum of the secondary magnetic field; \( H_{2x} \) – the spectrum characteristic of the secondary magnetic field; \( j_x \) – the integrated complex of the elementary component of the continuous spectrum of the braking current; \( I(i\alpha) \) – the integrated complex of the spectrum characteristics of the volume density of the braking current; \( \alpha \) – spatial frequency of the braking current and elementary component of the magnetic field; \( i = \sqrt{-1} \).

Based on Parseval equality (4), instead of (3) it is possible to write the following:

\[ F_{elm} = -\frac{\mu_0}{4\pi} \text{Re} \int_{-\infty}^{\infty} H_{2x} I(i\alpha) d\alpha. \]  

(5)

The expression (5) results into the simpler calculation of the braking force because there is no need to search for \( H_{2x} \) expressions according to the reverse change of Fourier, for each mode of braking.

**The main expressions of the braking force**

Following the expressions (3) and (5) the braking force is considered to be the integral sum of elementary components. In this work the braking force is calculated following the expression (3), after determining the complex amplitude of the secondary magnetic field \( H_{2x} \). In this case, for all the modes of braking, there are derived rather complicated expressions of force, indicating that the transitional process \( F_{elm} \) is characterized by three components:

\[ F_{elm} = F_1 + F_2 + F_3; \]  

(6)

where \( F_1 \) – the component of the braking force, evaluating only the transversal edge effect as well as the velocity change and is validated for the motor with an infinitely long active zone; \( F_2 \) – a free component of the braking force, existing only during the transitional process; \( F_3 \) – the component which evaluates longitudinal and transversal edge effects and their interrelation.

In the case of dynamic braking, when the direct current flows via the inductor windings, the following expression are derived to calculate component \( F_1 \):

\[ F_1 = F_0 \text{Re} h_s \left[ \frac{i}{\varepsilon_0} + \frac{\sin \beta_n - i \cos \beta_n}{\varepsilon_0 T_e} (K_e - i K_s) \right], \]  

(7)

where \( F_0 \) – the braking force of the ideal motor without the edge effects; \( h_s \) – the coefficient evaluating the transversal edge effect; \( \varepsilon_0 \) – magnetic number of Reynold, \( T_e \) – an electromagnetic constant of time; \( K_e \) and \( K_s \) – integral functions dependent to the Fresnel’s integrals.

The argument \( \beta_n \) of the trigonometry functions in expression (7) is the function of time. The following expression was derived to calculate it:

\[ \beta_n = \omega v_{0m} \left( t - \frac{v_k}{v_0 + v_k} \frac{t^2}{T_m} \right); \]  

(8)

where \( \omega \) – the angular frequency of the induced currents in the secondary element; \( v_0 \) and \( v_k \) – the initial and critical velocities of braking of the secondary element; \( T_m \) – an electromechanical constant of time.

Free component of the transitional process of the braking force is calculated in the following way:

\[ F_2 = F_0 \text{Re} h_s \frac{\sin \beta_n - i \cos \beta_n}{1 - i \varepsilon_0 v_0} \exp \left( -\frac{t}{T_e} \right). \]  

(9)

For LIM model in which the secondary element is wider than the active zone of the inductor (b>c), there is derived such an expression for the coefficient of transversal edge effect:

\[ h_s = \text{Re} \left[ 1 - \frac{sh(\frac{c}{\xi} \sqrt{1 - i \varepsilon_0 v})}{\frac{c}{\xi} \sqrt{1 - i \varepsilon_0 v}} \times \frac{ch[\frac{c}{\xi} (\xi - 1) \sqrt{1 - i \varepsilon_0 v}]}{ch(\frac{c}{\xi} \sqrt{1 - i \varepsilon_0 v})} \right]; \]  

(10)

where \( \frac{c}{\xi} \) – a relative width of the active zone; \( \xi = \frac{b}{c} \) – a relative width of the secondary element; \( v \) – the velocity of the secondary element at the time of braking.
The expressions of the integral functions $K_c$ and $K_s$ are the following:

$$K_c = \exp\left(-\frac{1}{T_c}\right)\int_0^T \exp\left(-\frac{t}{T_c}\right) \cos \beta_0 dt;$$  \hspace{1cm} (11)

$$K_s = \exp\left(-\frac{1}{T_s}\right)\int_0^T \exp\left(-\frac{t}{T_s}\right) \sin \beta_0 dt. \hspace{1cm} (12)$$

The results of calculations

Following the derived expressions (7 - 12) there are calculated the dynamic characteristics of braking and transitional processes of force by means of software Mathcad 2001 Professional. There are presented the transitional processes of the relative braking force $F_1/F_0$ in Fig.1, a) and b).

![Fig. 1. The transitional processes of the relative braking force $F_1/F_0$, when Reynolds’s numbers $\varepsilon_0$ and the widths of the active zones $c/\tau$ are diverse](image)

The change of the free braking force $F_2/F_0$ within the time is presented in Fig. 2. The dependencies of the coefficient $h_s$ on the relative width $c/\tau$ of the active zone are presented in Fig.3. The diagrams of the change of the integral functions $K_c$ and $K_s$ are presented in Fig.4.

From expression (7) there is possible to derive that component $F_1$ doesn’t depend on the number $p$ of the pole pairs of the motor, and the same time on length $L$ of the inductor’s active zone. Because of that the force $F_1$ don’t estimate the longitudinal edge effect and validates for the model of the motor with infinitely long active zone. In such a model braking force $F_1$ doesn’t generate braking at the initial moment while free component $F_2$ of the force...
quickly fades. From the point of view of the efficiency of the braking, the model of the motor with an infinitely long active zone is insufficiently correct.

Conclusions

1. It has been determined that the transitional processes $F_{elm} = f(t)$ of the braking force of LIM are characterized by three components of the force evaluating the change of the secondary element, the transversal edge effect and interrelated interaction of the transversal and longitudinal edge effects.

2. In the model of the motor with infinitely long active zone there isn’t generated braking force during the initial moment that is why such sort of a model is insufficiently correct.

3. The results of the calculations indicate that the type of the transitional processes of the dynamic braking of the force as well as duration are characterized by two time constants: electromechanical $T_m$ and electromagnetic $T_e$. The intensity of the transitional processes depends on the ratio of the time constants $T_m/T_e$.

References


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