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Calculation of the Braking Force Transitional Processes for Linear Induction Motor

B. Karaliūnas, E. Matkevičius
Department of Automation, Vilnius Gediminas Technical University, Naugarduko str. 41, LT-03227 Vilnius, Lithuania,
phone: +370 274 50 63, e-mail: Bronius.karaliunas@el.vgtu.lt, Edvardas.matkevicius@el.vgtu.lt

Introduction

Modern technologies and mechatronic systems not only widely apply rotational electrical motors but also operating devises 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 $\underline{H}$ of LIM in the air gap is compiled of two components [4]:

$$\underline{H} = \underline{H}_1 + \underline{H}_2 ; \qquad (1)$$

where $\underline{H}_1$ – the complex amplitude of the primary or inductor generated magnetic field; $\underline{H}_2$ – 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 $\underline{H}_1$ and $\underline{H}_2$ .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*:*

$$dF_{elm} = -\frac{\mu_0}{2}\operatorname{Re}\underline{H}_2\,\underline{\dot{j}}(x,t)dxdydz\,; \qquad (2)$$

where $\mu_0 = 4\pi 10^{-7}$, *H/m* – magnetic permeability of the secondary element; Re – the real part of the complex number; $\underline{\dot{j}}(x,t)$ – 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:

$$F_{elm} = -\frac{\mu_0}{2}\operatorname{Re}\int\limits_{(V)}\underline{H}_2\,\underline{\dot{j}}(x,.t)dV\ , \qquad (3)$$

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:

$$\int\limits_{-\infty}^{\infty}\underline{H}_{2e}\,\underline{\dot{j}}_e dx = \frac{1}{2\pi}\int\limits_{-\infty}^{\infty}\underline{H}_{2\alpha}\,\underline{\dot{I}}(i\alpha)d\alpha\ , \qquad (4)$$

where $\underline{H}_{2e}$ – the elementary component of the continuous spectrum of the secondary magnetic field; $\underline{H}_{2\alpha}$ – the spectrum characteristic of the secondary magnetic field; $\underline{\dot{j}}_e$ – the integrated complex of the elementary component of the continuous spectrum of the braking current; $\underline{\dot{I}}(i\alpha)$ – the integrated complex of the spectrum characteristics of the volume density of the braking current; α – 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:

$$F_{elm} = -\frac{\mu_0}{4\pi}\operatorname{Re}\int\limits_{-\infty}^{\infty}\underline{H}_{2\alpha}\,\underline{\dot{I}}(i\alpha)d\alpha\ . \qquad (5)$$

The expression (5) results into the simpler calculation of the braking force because there is no need to search for $\underline{H}_2$ 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 $\underline{H}_2$. 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:

$$F_{elm} = F_1 + F_2 + F_3\,; \qquad (6)$$

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:

$$F_1 = F_0\operatorname{Re}h_s\left[\frac{i}{\varepsilon_0} + \frac{\sin\beta_n - i\cos\beta_n}{\varepsilon_0 T_e}(K_c - iK_s)\right]; ..(7)$$

where F_0 – the braking force of the ideal motor without the edge effects; h_s –the coefficient evaluating the transversal edge effect; ε_0 – magnetic number of Reynolds, T_e – an electromagnetic constant of time; K_c and K_s – integral functions dependent to the Fresnel's integrals.

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

$$\beta_n = \omega v_{0n}\left(t - \frac{v_k}{v_{0n}^2 + v_k^2}\frac{t^2}{T_m}\right); \qquad (8)$$

where ω – the angular frequency of the induced currents in the secondary element; v_{0n} 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:

$$F_2 = F_0\operatorname{Re}h_s\frac{\sin\beta_n - i\cos\beta_n}{1 - i\varepsilon_0 v_{0n}}\exp\left(-{}^{t}\!/_{T_e}\right). \qquad (9)$$

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:

$$h_s = \operatorname{Re}\left\{1 - \frac{sh(\pi\,{}^{c}\!/_{\tau}\sqrt{1 - i\varepsilon_0 v})}{\pi\,{}^{c}\!/_{\tau}\sqrt{1 - i\varepsilon_0 v}}\times\right.$$

$$\left.\times\frac{ch\left[\pi\,{}^{c}\!/_{\tau}(\xi - 1)\sqrt{1 - i\varepsilon_0 v}\right]}{ch\pi({}^{c}\!/_{\tau}\,\xi\sqrt{1 - i\varepsilon_0 v})}\right\}; \qquad (10)$$

where ${}^{c}\!/_{\tau}$ – a relative width of the active zone; $\xi = {}^{b}\!/_{c}$ – a relative width of the secondary element; v – the velocity of the secondary element at the time of braking.

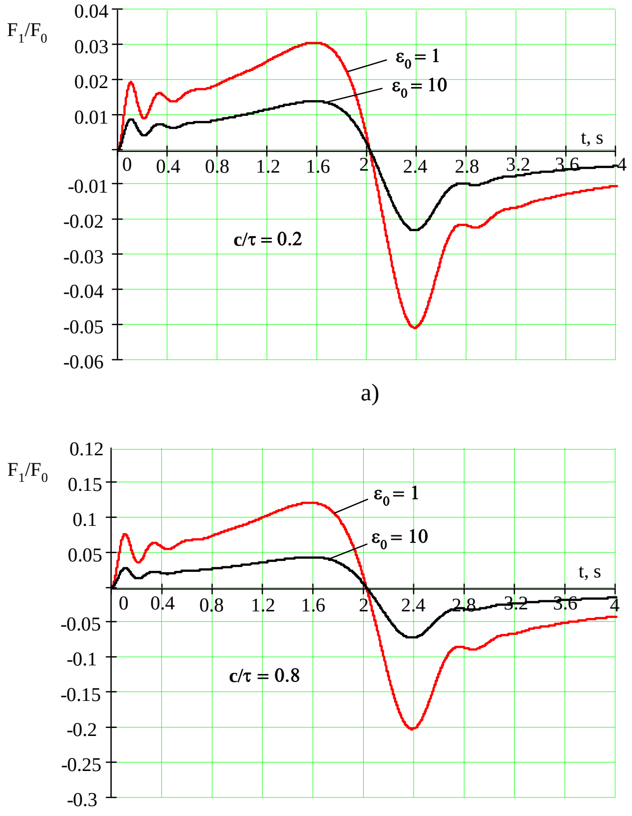
The expressions of the integral functions K_c and K_s are the following:

$$K_c = \exp\left(-{}^{t}\!/_{T_e}\right)\int_0^t \exp\left({}^{t}\!/_{T_e}\right)\cos\beta_n dt\,; \tag{11}$$

$$K_s = \exp\left(-{}^{t}\!/_{T_e}\right)\int_0^t \exp\left({}^{t}\!/_{T_e}\right)\sin\beta_n dt\,. \tag{12}$$

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 Profesional. There are presented the transitional processes of the relative braking force F_1/F_0 in Fig.1, a) and b).



a)

b)

Fig. 1. The transitional processes of the relative braking force F_1/F_0, when Reynolds's numbers ε_0 and the widths of the active zones c/τ are diverse

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/τ 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.

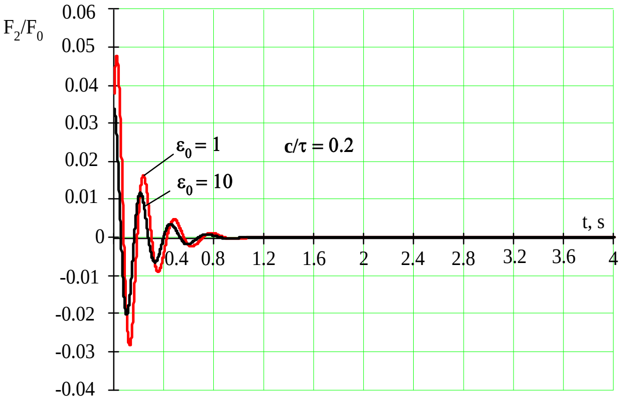


Fig. 2. Transitional process of the free braking force

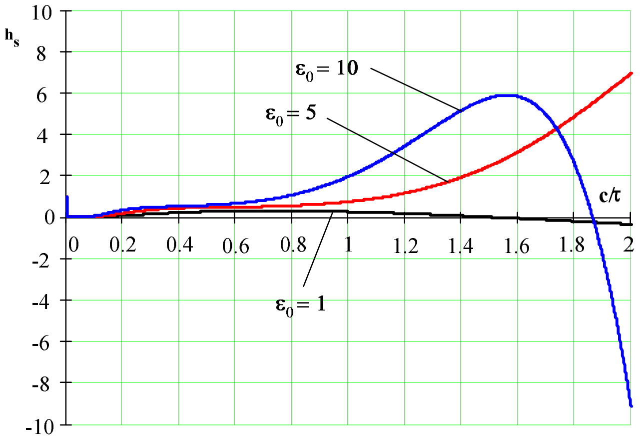


Fig. 3. Dependencies of coefficient h_s on the width c/τ of the active zone under diverse Reynolds's numbers

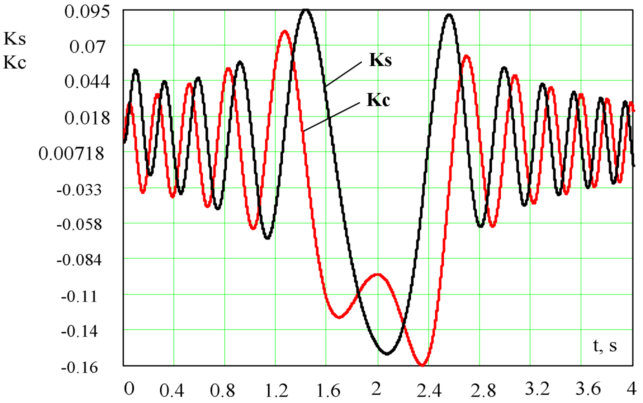


Fig. 4. Diagrams of the integral functions K_c and K_s within the time change

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 dosen'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 dosen'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 .

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B. Karaliūnas, E. Matkevičius. Calculation of the Braking Force Transitional Processes for Linear Induction Motor // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 3(91). – P. 81–84.

Issues on the modes of the electric braking of the linear induction motors (LIM), the patterns for the calculation of the braking force are discussed. There is stated the fact that for the analysis of all modes of braking there is applied the spectrum method, based on the theory of electromagnetic field and Fourier integral transformations. There is determined that the transitional processes of the braking force of LIM $F_{elm} = f(t)$ are characterized by means of three components of the force evaluating the change of the velocity of the secondary element, the transversal edge effect and interrelated interaction of the transversal and longitudinal edge effects. Following the expressions derived, separate components of the force are calculated by means of software Matchad 2001 Professional. The results of the calculation indicate that in the model of the motor with the infinitely long active zone at the initial moment, the braking force is not generated that is why such a model from the point of efficiency of the braking process is insufficiently correct. Il. 4, bibl. 6 (in English; summaries in English, Russian and Lithuanian).

Б. Каралюнас, Э. Маткевичус. Расчет переходных процессов тормозного усилия линейного асинхронного двигателя // Электроника и электротехника. – Каунас: Технология, 2009. – № 3(91). – С. 81–84.

Рассматриваются вопросы электрического торможения линейных асинхронных двигателей (ЛАД), обсуждаются способы расчета тормозного усилия. Показано, что для анализа всех способов торможения применен спектральный метод, основанный на теории электромагнитного поля и итегральных преобразований Фурье. Установлено, что переходные процессы тормозного усилия $F_{elm} = f(t)$ ЛАД характеризуют три составляющие, учитывающие изменение скорости вторичного элемента, поперечный краевой эффект, а также взаимодействие продольного и поперечного краевых эффектов. По полученным выражениям отдельные составляющие силы были рассчитаны с применением компьютерной порграммы Matchad 2001 Professional. Результаты расчетов показывают, что для модели двигателя с бесконечно длинной активной зоной в начальном этапе торможения тормозное усилие не создается, поэтому такая модель с точки зрения эффективности торможения не является вполне корректной. Ил. 4, библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

B. Karaliūnas, E. Matkevičius. Tiesiaeigio asinchroninio variklio stabdymo jėgos pereinamųjų procesų skaičiavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009 – Nr. 3(91). – P. 81–84.

Nagrinėjami tiesiaeigių asinchroninių variklių (TAV) elektrinių stabdymo režimų klausimai, aptarti stabdymo jėgos skaičiavimo būdai. Parodyta, kad visų stabdymo režimų analizei taikomas spektrinis metodas, pagrįstas elektromagnetinio lauko teorija ir Furjė integralinėmis transformacijomis. Nustatyta, kad TAV stabdymo jėgos pereinamuosius procesus $F_{elm} = f(t)$ apibūdina trys jėgos dedamosios, įvertinančios antrinio elemento greičio kitimą, skersinį kraštų efektą ir skersinio bei išilginio kraštų efektų tarpusavio sąveiką. Pagal gautas išraiškas atskiros jėgos dedamosios buvo skaičiuojamos kompiuterine programa Matchad 2001 Professional. Skaičiavimo rezultatai rodo, kad variklio modelyje su be galo ilga aktyviąja zona pradiniu momentu stabdymo jėga nesukuriama, todėl toks modelis stabdymo efektyvumo požiūriu yra nepakankamai korektiškas. Il. 4, bibl. 6 (anglų kalba: santraukos anglų, rusų ir lietuvių k.).