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The braking service of the linear induction motors with a compound-equalized magnetic flux for magnetic-levitation transport

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Abstract. In recent years, more and more attention has been paid to the development of new promising high-speed modes of the transport, especially, magnetic and vacuum pipelines. The linear induction motors will be used as traction machines in the early stages of the development of the magnetic-levitation and vacuum transport. The linear induction motors with compound-equalized magnetic flux for lines of the force, which, in addition to traction, can create lateral stabilization forces of high-speed carriages on a magnetic suspension, will be used in a magnetic vehicle in the nearest future. The effective and safe braking issues are of particular importance for high-speed magnetic-levitation transport. To reduce the speed and stop high-speed transport carriages on a magnetic suspension, the linear traction motors can operate as eddy current principle of the brakes. The article discusses the braking modes of a linear induction motor with a compound-equalized magnetic flux for lines based on the equivalent circuit of the machine. The analytical relationships are obtained for the calculation of the braking forces.

1. Introduction

The development of the world economy requires the improvement of the transport communications. The increase of the passenger traffic speed and cargo movement involves usage of the new types of the rolling stock, in particular, the use of the high-speed magnetic-levitation transport (MLT). The scientists and engineers from different countries are working to create the high-speed MLT systems for both passenger and freight traffic. In the Russian Federation, the scientists from transport universities and research organizations are working on the problems developing MLT systems. The contribution of the scholar staff of the Petersburg State Transport University to the development of new transport systems is noticeable [1-7]. Various types of the linear induction motors, which convert electricity directly into the forward movement of a transport carriage, are considered as traction machines of a magnetic-levitation transport. The linear motors can be DC machines, synchronous or induction-based. At the present time of the MLT systems` development, the traction linear induction motors (LIM) seem to be the most promising. The linear induction motors because of their design can be made with compound, equalizing and compound-equalized magnetic flux for lines of a force. The main range of the movement speeds of the mass transport vehicles is in the range from 350 to 500 km/h and the study of braking conditions is of particular importance and relevance. The traction LIM

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can be able to work in the brake mode. The article discusses the braking modes of the linear induction motors with compound-equalized magnetic flux for lines, the LIM with compound-equalized magnetic flux for lines are multifunctional and are able to create, in addition to traction and side stabilization efforts, which increase the safety of the MLT movement. The linear induction motors of this type will develop the efforts of the lateral stabilization when it stops the high-speed carriages suspended in a magnetic field.

2. The purpose of the research

We investigated the brake modes of a linear induction motor with compound-equalized magnetic flux for lines of the force.

3. The diagram of the replacement of the LIM phase with compound-equalized magnetic flux

The use of the equivalent circuits for characterizing and analyzing modes of the induction machines is widespread in electrical engineering [8, 9]. The use of the detailed equivalent circuits allows increasing the accuracy of the calculation of linear induction engines [10-12]. To analyze the processes in the LIM, to determine the parameters and characteristics of the engine, equivalent circuits and a number of other researchers are used [13-16]. In the systems of the magnetic-levitation transport, when studying processes in traction linear induction motors, the influence of the magnetic fields of the carriage's suspension on the characteristics of the LIM should be taken into account [17–20].

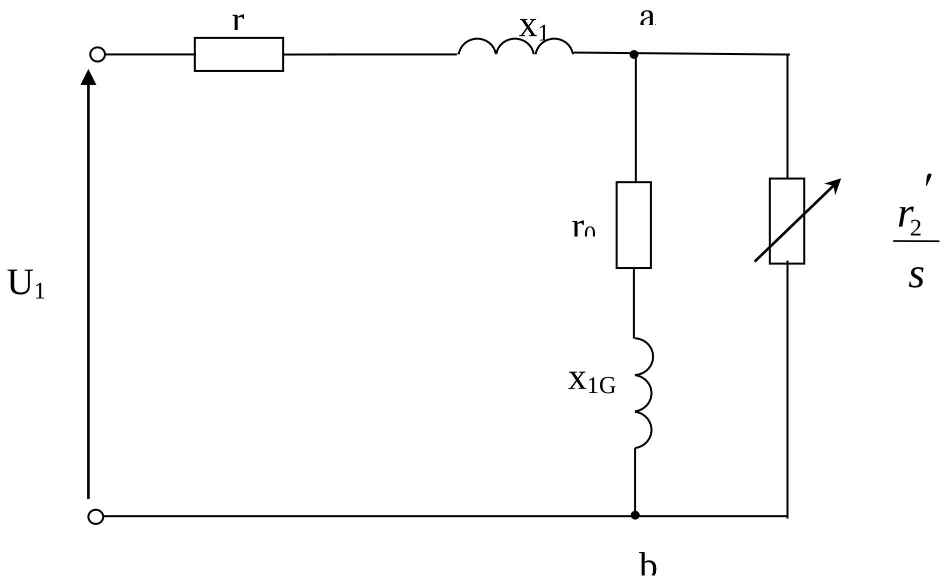

Figure 1. The LIM replacement circuit with compound-equalized magnetic flux for lines of the force

The equivalent circuit of a linear induction motor with a compound-equalized magnetic flux for lines of the force contains a branch with active r_1 and inductive x_1 inductor resistances, a branch with active resistance of the secondary element (SE) r'_2/s (the electrically conductive part of the secondary element is a bus-bar, therefore we ignore the inductive resistance) and a magnetizing branch with resistances r_0 (it takes into account the power loss in steel) and x_{1G}. On the basis of the LIM replacement scheme with compound-equalized magnetic flux for lines of the force (Figure 1), we consider the braking modes of the operation.

4. The braking modes of the LIM operation with compound-equalized magnetic flux for lines of the force

In the braking mode of the opposition LIM with compound-equalized magnetic, flux for lines of the force passes without the use of the special equipment. The LIM control circuit must contain a device for reversing the phase order. The braking force of the LIM with a compound-equalized magnetic flux for lines of the force in the opposition mode depends on the amount of the slip that exceeds one. At large slips, the frequency of the electromotive force (EMF) and current in the secondary element, induced by a running magnetic flux, increases to such values that it becomes necessary to take into account the influence of the surface effect (current displacement) when determining the active resistance of the SE. Therefore, when it determines the mechanical braking force, the effect of the current displacement in the secondary element should be taken into account by calculating the depth of penetration of an electromagnetic wave of a running magnetic field into a flat conducting bus-bar based on relation (1):

$$Z_0 = \sqrt{\frac{2}{\omega\mu\mu_0\gamma}}, \tag{1}$$

where Z_0 is the depth of the penetration of the electromagnetic wave (current) into the secondary element;

ω is the angular frequency of the EMF and current in the electrically conductive element;

μ - the relative magnetic permeability;

μ_0 - the absolute magnetic permeability of the vacuum;

γ - a conductivity of the material of the secondary element.

The need to take into account the effect of the current displacement is determined by the condition $Z_0 < \Delta_2$, where Δ_2 is the thickness of the secondary element, m.

To determine the braking effort, the reduced active resistance value of the secondary element is introduced into the calculation, taking into account current displacement:

$$r_2'' = r_2' \cdot k_r, \tag{2}$$

where $k_r = \Delta_2 / Z_0$ is the coefficient of the increase in the active resistance of the secondary element of the LIM due to the displacement of the current in the braking mode.

Since the angular frequency of the EMF and current in the secondary element of a linear induction motor with a compound-equalized magnetic flux for lines of the force depends on the slip, the k_r value is determined for the entire slip range actually possible in the deceleration mode by inhibition. The determination of these factors precedes the calculation of the brake characteristics of the LIM.

The braking with opposite connection can be considered as a logical continuation of the motor mode in the area of the slips exceeding one. In this regard, to calculate the braking characteristics of a linear electric motor, a replacement circuit with the same parameters is used as for the motor operation mode (Figure 1).

The braking forces of the LIM with a compound-equalized magnetic flux for lines of the force in the opposition mode are determined in the following order:

1) by the slip in a given range of the speeds;

2) by the expression (1) for the depth of the current penetration into the secondary element of the linear motor for each value of the angular frequency within a given speed range;

3) the calculated parameters of the equivalent circuit LIM are determined by the resistance values:

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$$r_{emo}=\frac{x_{1G}^2\cdot\frac{r_2''}{s}}{\left(\frac{r_2''}{s}\right)^2+x_{1G}^2};\quad x_{emo}=\frac{x_{1G}\cdot\left(\frac{r_2''}{s}\right)^2}{\left(\frac{r_2''}{s}\right)^2+x_{1G}^2},\tag{3}$$

with connection of which is equivalent to the impedance of the parallel-connected elements of the equivalent circuit x_{1G} and r''_2/s;

4) by the total equivalent resistance of the equivalent circuit of the phase of a linear induction motor with a compound-equalized magnetic flux for lines of the force:

$$Z=\sqrt{\left(r_1+r_{emo}\right)^2+\left(x_1+x_{emo}\right)^2};\tag{4}$$

5) the phase current inductor LIM:

$$I_{1ph}=\frac{U_{1ph}}{Z};\tag{5}$$

6) the current in secondary element connected with inductor:

$$I_2'=I_{1ph}\frac{x_{1G}}{\sqrt{\left(\frac{r_2''}{s}\right)^2+x_{1G}^2}};\tag{6}$$

7) the electromagnetic power transmitted by the magnetic field from the inductor of the linear motor through the air gap to the secondary element:

$$P_{EM}=m_1\left(I_2'\right)^2\cdot\frac{r_2''}{s};\tag{7}$$

8) the braking force in opposition mode:

$$F=\frac{P_{EM}}{V_1},\tag{8}$$

where V_1 is the synchronous speed of the traveling magnetic field of a linear induction motor with a compound-equalized magnetic flux for lines of the force, m / s.

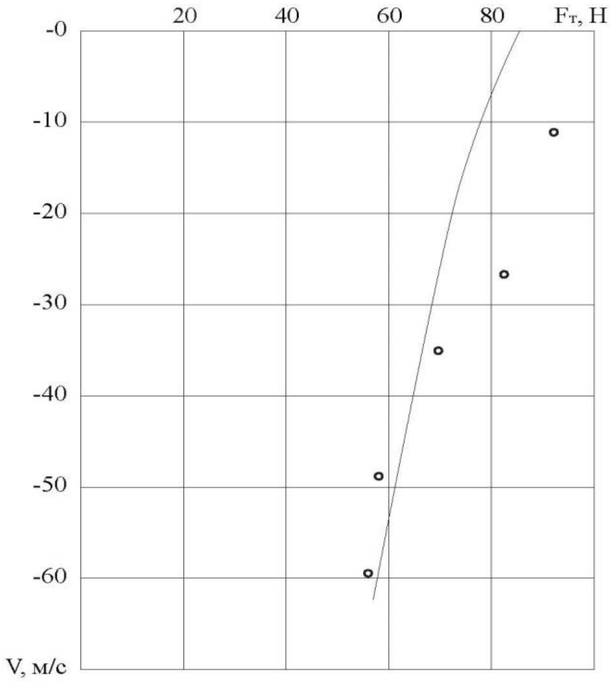

Figure 2. The mechanical characteristics of LIM in mode braking with opposite connection: - calculation; ° - experiment.

In order to test the methodology for calculating the LIM braking forces in the opposition mode and to evaluate the braking properties of the linear machines of this type, the mechanical characteristics of an experimental laboratory engine model were calculated. The mechanical characteristic of a linear induction motor in the mode of the braking with opposite connection, obtained by calculation, is shown in Figure 2. A pilot study of the braking of the LIM with the opposite connection produced a number of the test points, shown in Figure 2 in the form of the circles. The convergence of the calculated and experimental values of the braking forces can be considered quite satisfactory. The maximum discrepancy of the results was 15%.

The regenerative braking is used at high speeds of the carriages for uniformity of motion (for improving dynamic qualities) or for smoothing the transitional regime with significant changes in the speed of movement from higher to lower. In the first case, the wiring diagram of the inductor winding remains unchanged, while in the second, a change in the pole division value of the inductor is required.

With the regenerative braking, the linear induction machine goes into the generator mode of the operation. The LIM operates in an asynchronous generator mode connecting in parallel to the network and giving it electrical energy. At the same time, the linear movement speed does not decrease to "0", but at the same time, the linear machine prevents external accelerating factors acting on the carriages and gives the movement a more uniform character smoothing the transition process. It is noted that while it operates in regenerative braking mode, a linear induction machine with a compound-equalized magnetic flux for lines of the force consumes the reactive energy from the network. The equivalent circuit of a linear induction motor with a compound-equalized magnetic flux for lines of the force operating in regenerative braking mode is shown in Figure 3. The main feature of this equivalent circuit is the EMF representation of the secondary element in regenerative braking in the form given to the inductor as follows:

$$E'_{2B} = -I'_2 \cdot r'_2 \frac{1-s}{s}. \qquad (9)$$

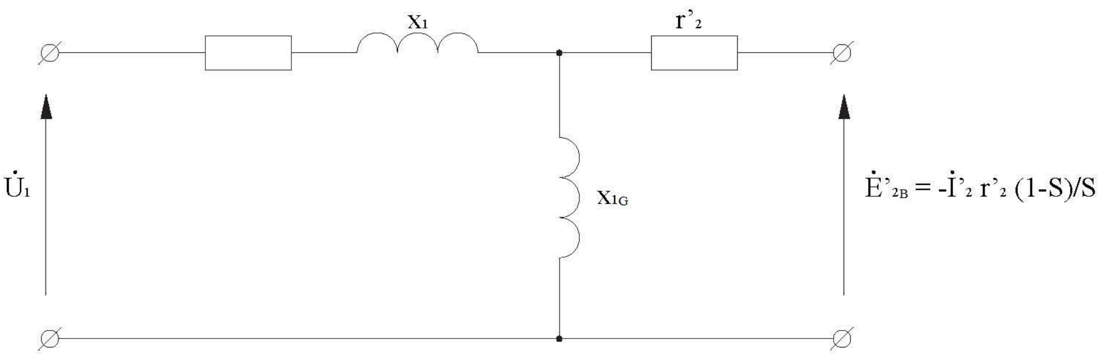

Figure 3. The equivalent circuit of a linear induction motor mode for regenerative braking mode

Given there are directions of the currents of the phase of the inductor LIM and to the inductor with the current of the secondary element that applies the method of the loop currents, we obtain a system of the initial equations for calculating the braking characteristics:

$$\begin{cases} \dot{U}_1 = -\dot{I}_1\left(r_1 + jx_1\right) + \left(\dot{I}_2'' - \dot{I}_1\right) jx_{1G}; \\ \dot{E}_{2B} = \dot{I}_2' r_2' + \left(\dot{I}_2' - \dot{I}_1\right) jx_{1G} = -\dot{I}_2' r_2' \dfrac{1-s}{s}. \end{cases}, \tag{10}$$

Having performed a series of the transformations of the second equation system (10), we obtain:

$$\dot{I}_1 = \dot{I}_2' \cdot \frac{\dfrac{r_2'}{s} + jx_{1G}}{jx_{1G}}. \tag{11}$$

Substituting the result in the first equation of the system (10), we obtain the following expression:

$$U_1 = -\dot{I}_2' \left[\frac{\dfrac{r_2'}{s} + jx_{1G}}{jx_{1G}} \left(r_1 + jx_1\right) + \frac{r_2'}{s} \right]. \tag{12}$$

After a series of simple conversions, we present the reduced current of the secondary element of the LIM operating in regenerative braking mode in the following form:

$$\dot{I}_2' = \frac{\dot{U}_1 jx_{1G} \left[\left(x_{1G}x_1 - \dfrac{r_2' r_1}{s} \right) + j\left(\dfrac{r_2' x_1}{s} + \dfrac{r_2' x_{1G}}{s} + r_1 x_{1G} \right) \right]}{\left(x_{1G}x_1 - \dfrac{r_2' r_1}{s} \right)^2 + j\left(\dfrac{r_2' x_1}{s} + \dfrac{r_2' x_{1G}}{s} + r_1 x_{1G} \right)^2}. \tag{13}$$

Performing a series of transformations, we obtain the modulus of the current value of the current in the secondary element:

$$I_2' = \frac{U_1 x_{1G}}{\sqrt{R^2 + X^2}}, \tag{14}$$

where $R = x_{1G}x_1 - \dfrac{r_2' r_1}{s}$; $X = \dfrac{r_2'}{s}\left(x_1 + x_{1G}\right) + r_1 x_{1G}$.

Substituting I'_2 into the expression that determines the current in the phase of the LIM inductor for the generator operating mode:

$$\dot{I}'_2 = \frac{\dot{U}_1\left(\frac{r'_2}{s} + jx_{1G}\right)\left[\left(x_{1G}x_1 - \frac{r'_2 r_1}{s}\right) + j\left(\frac{r'_2 x_1}{s} + \frac{r'_2 x_{1G}}{s} + r_1 x_{1G}\right)\right]}{\left(x_{1G}x_1 - \frac{r'_2 r_1}{s}\right)^2 + j\left(\frac{r'_2 x_1}{s} + \frac{r'_2 x_{1G}}{s} + r_1 x_{1G}\right)^2}. \tag{15}$$

Having made several transformations, we obtain the module of the current value of the inductor phase current in the form:

$$I'_2 = \frac{U_1\sqrt{\left(\frac{r_2}{s}\right)^2 + x_{1G}^2}}{\sqrt{R^2 + X^2}}; \tag{16}$$

The obtained results made it possible to create a methodology for calculating the LIM braking forces with a compound-equalized magnetic flux for lines of the force in the mode of the energy recovery to the network. The mechanical characteristic of a linear machine in regenerative braking mode is calculated in the following sequence:

1) the range of slides is set, in which the linear machine will be transferred to regenerative braking mode (usually the slip changes from 0 to -1);

2) equivalent resistance values are determined:

$$R = x_{1G}x_1 - \frac{r'_2 r_1}{s}; \quad X = \frac{r'_2}{s}\left(x_1 + x_{1G}\right) + r_1 x_{1G}; \quad Z = \sqrt{R^2 + X^2}; \tag{17}$$

3) reduced current of the secondary element (during regenerative braking, it is actually the primary current):

$$I'_2 = \frac{U_1 x_{1G}}{Z}; \tag{18}$$

4) reduced the phase EMF of the secondary element of the LIM operating in the generator mode:

$$E'_{2B} = -I'_2 \cdot r'_2 \frac{1-s}{s}. \tag{19}$$

5) total power of the linear machine in the brake mode:

$$P_{B1} = m_1 \cdot E'_{2B} \cdot I'_2; \tag{20}$$

6) electrical losses in the secondary element:

$$P_{EL2} = m_1\left(I'_2\right)^2 r'_2; \tag{21}$$

7) electromagnetic braking power transmitted by the electromagnetic field from the secondary element to the inductor:

$$P_{EM} = P_{B1} - P_{EL2}; \tag{22}$$

8) braking force generated by the linear machine:

$$F_B = \frac{P_{EM}}{V_1}; \tag{23}$$

where V_1 is the synchronous speed of the motor mode of the LIM;

9) inductor phase current:

$$I_1 = I_2' \frac{\sqrt{\left(\frac{r_2'}{s}\right)^2 + x_{1G}^2}}{x_{1G}}; \tag{24}$$

10) power delivered to the power supply:

$$P_{B2} = P_{EM} - m_1 I_1' r_1. \tag{25}$$

As for countering braking, the calculation is made for the number of the slips. The results are combined into a regenerative braking system. It is highlighted that this technique does not take into account the magnetic losses in the steel of the inductor core. But as the effective theoretical research showed, if these losses are not taken into account, the error does not exceed 3-5% and in engineering practice the losses in the inductor steel can be neglected.

5. Conclusion

Analytical relations have been obtained for calculating the braking characteristics of a high-speed magnet levitation transport based on the equivalent circuit of a linear induction motor with a compound-equalized magnetic flux for lines of the force. Methods have been developed for calculating the braking modes with opposite connection and recuperative for traction the LIMs with compound-equalized magnetic flux for lines of the force. The results of the effective theoretical studies are confirmed by experimental data. The comparison showed that the discrepancy between the theoretical and experimental data does not exceed 15%.

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