Electromagnetic quality of a linear asynchronous motor with different designs of the secondary element

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Abstract. Linear asynchronous electric motors drive the working bodies of the mechanisms directly and quite fully fulfill their drive characteristics, allow eliminating mechanical converters and increase performance. This solves the problem of maximum articulation, splicing of a source of mechanical energy - an electric motor and an executive technological mechanism. Linear electric motors with a massive ferromagnetic secondary are the most cost-effective, taking into account the operating modes - when operating in starting modes and on stop, therefore, in practice, it often becomes necessary to calculate them in a short circuit mode. With a simplified calculation, it is convenient to use correction factors for increasing magnetic fluxes in the yoke, secondary losses and efforts of linear induction motors compared to the same values in a circular analogue. The dependences of such coefficients on the quality factor, the number of pairs of poles and the relative magnetic resistance of shunting. In the general case, the comparison and selection of the design of a linear induction motor is carried out at the stage of preliminary design using the optimality criteria - the quality factor.

1. Introduction

The electric drive consumes the bulk of the electricity produced in the world. The correct solution of the main problems of the development of the electric drive is important for the country's economy. At present, the traditional solution used to provide low rotational speeds of working mechanisms is a high-speed motor with a gearbox. A systematic approach, analysis from the standpoint of the greatest efficiency for the entire national economy leads to the conclusion that the total mass, overall dimensions and cost with the indicated traditional solution of the electric motor and gearbox in a fairly large class of applications differ very significantly from the corresponding parameters of the electric motors themselves. Consideration of the main alternative - gearless electric drives (ie electric motors directly connected to the working mechanism) is of significant interest [1-4].

The task of creating a gearless electric drive can be solved while maintaining the principle of «movement of the driving and driven element in the same coordinate». These are multi-pole machines powered by an industrial network or a low-frequency source, machines with a rolling rotor, machines powered by a rotor and stator from sources with different frequencies, gear motors, machines operating on magnetic field subharmonics. The same characteristics have been widely developed in recent years induction motors with an open magnetic circuit (linear, arc and end motors) [1-6].

2. Problems and solutions

The design of a linear induction motor (LIM), as well as the design of any electrical machine, begins with a preliminary assessment of the technical and economic indicators of the options under consideration. For rotating electrical machines at this stage, the experience of designing and operating previously created machines is widely used. There is no such experience for LIM, besides, it is difficult to obtain universal recommendations and assessments of the level of technical and economic indicators depending, for example, on the main dimensions of LIM, taking into account the close connection of their parameters with the design features of the driven machines and mechanisms, as well as in connection with variety of LIM designs [6-8].

These difficulties explain the appearance in the works devoted to the study and calculation of LIM, such a generalized indicator as the electromagnetic quality factor, which was not previously used in the practice of designing electrical machines [5-9].

3. Method and Discussion

The electromagnetic quality factor characterizes the quality of the secondary electrical and magnetic circuits of the LIM, i.e. reflects the ability of a machine to convert energy from one type to another [7, 8]. There are various interpretations of this indicator in the literature. One of the first to use the concept of electromagnetic quality factor was professor E.R. Laithwaite [9], who defined it as the ratio of electromagnetic power to the power expended to create a magnetic field in a machine:

$$\varepsilon' = P_{\text{ЭМ}} / Q_m = \frac{Re(\dot{E}\bar{I}'_2)}{Jm(\dot{E}\bar{I}_m)} \; . \tag{1}$$

In the literature, an indicator similar in meaning - the magnetic Reynolds number - was introduced in the studies and calculations of induction MHD machines [8] as a characteristic of the intensity of MHD processes in a liquid metal working medium. The expression for the magnetic Reynolds number in [8] was obtained from the solution of a field problem. For example, in the case when a non-magnetic conducting medium fills the entire gap $\Delta = \delta$, it has the form [10]

$$\varepsilon = \mu_o \gamma_2 s \omega_1 \tau^2 / \pi^2 \; . \tag{2}$$

Taking into account the gearing of the inductor, the saturation of the magnetic circuit and the inequality $\Delta \neq \delta$, we obtain following:

$$\varepsilon = \frac{\mu_o \gamma_2 s \omega_1 \tau^2 \Delta}{\pi^2 k_\delta k_\mu \delta} = \varepsilon_o s \; , \tag{3}$$

where ε_o is the magnetic Reynolds number (electromagnetic quality factor) at sliding $s = 1$. For a double-sided LIM with a non-magnetic secondary element (SE), hereinafter Δ and δ are half the thickness of the SE and half the non-magnetic gap.

Similar expressions (2) and (3), relating the electromagnetic quality factor with the physical parameters of the machine, were obtained in [9] through the parameters of the simplified LIM equivalent circuit (without taking into account the leakage inductance of the SE):

$$\varepsilon' = \frac{x_m s}{r_2'} = \frac{\mu_o \gamma_2 s \omega_1 \tau^2 \Delta}{\pi^2 k_\delta k_\mu \delta} \; . \tag{4}$$

The coincidence of expressions (3) and (4) has led to the fact that in many publications the electromagnetic quality factor has become synonymous with the magnetic Reynolds number, although, as shown above, these concepts have different physical meanings. In fact, the magnetic Reynolds number or electromagnetic quality factor ε, determined by (2), (3), takes into account not the electromagnetic power of the LIM, but the amount of the active material of the SE. In the study and calculation of LIM, which are distinguished by a wide variety of SE designs, in which the leakage inductance L_2 cannot be neglected, the difference between ε' and ε should be taken into account. It is easy to get the expression

$$\varepsilon' = \varepsilon \cdot \cos^2 \varphi_2 \; . \tag{5}$$

As follows from (1), the electromagnetic quality factor ε' is organically associated with the currents of the T-shaped equivalent circuit LIM [11], shown in Figure 1,*a*:

$$\varepsilon' = I'_{2a} / I_m \ . \tag{6}$$

Therefore, the use of ε' is more convenient when analyzing LIM with a complex SE (combined – a steel array with a highly conductive screen, a short-circuited cage in a massive magnetic circuit, a double cage, etc.). As can be seen from the vector diagram in Figure 1,*b*, corresponding to the LIM with a combined SE, taking into account (6), the total electromagnetic quality factor of the engine is the sum of the electromagnetic quality factors of the massive steel magnetic circuit ε'_c and the highly conductive screen $\varepsilon'_{\ni}$:

$$\varepsilon' = \varepsilon'_c + \varepsilon'_{\ni} \ . \tag{7}$$

For the electromagnetic quality factor ε, determined by (2) - (3), a similar expression takes the form:

$$\varepsilon \cos^2 \psi_2 = \varepsilon_c \cos^2 \psi_c + \varepsilon_{\ni} \cos^2 \psi_{\ni} \ . \tag{8}$$

For an LIM with a complex CE, when using the electromagnetic quality factor ε', taking into account (7), more compact and convenient expressions are obtained that relate the technical and economic indicators of the LIM with the electromagnetic quality factor. Despite this, the authors of this paper prefer the generalized exponent ε, which makes it possible to organically use the results of numerous studies on the study of LIM and MHD machines in which the magnetic Reynolds number was used in the design.

It should be noted that the electromagnetic figure of merit ε, determined by (2), (3), strictly corresponds only to a cylindrical LIM with a highly conductive non-magnetic SE. When determining ε for other versions of the LIM, one should take into account certain design features of the SE that affect the active resistance r'_2, and hence the electromagnetic quality factor.
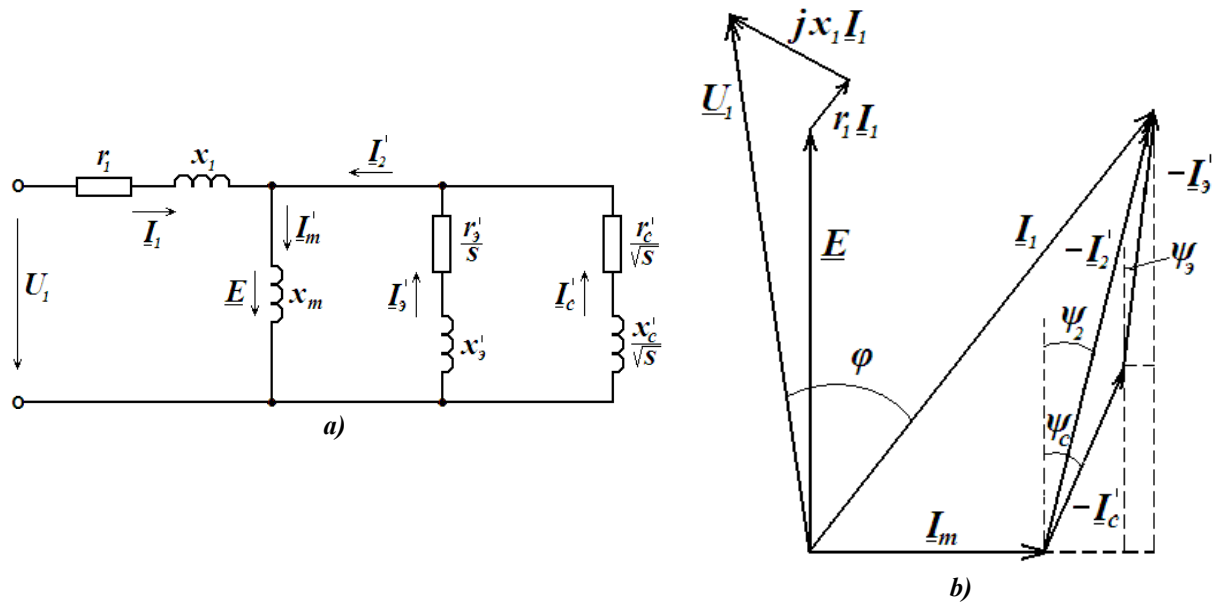

Fig. 1. Equivalent circuit *(a)* and vector diagram *(b)* LIM.

The transverse edge effect in planar LIMs with non-magnetic SE increases the resistance r'_2 and reduces the electromagnetic quality factor ε. This decrease can be taken into account by introducing the coefficient k_q into (3):

$$\varepsilon = \frac{\mu_o \gamma_2 k_q s \omega_1 \tau^2 \Delta}{\pi^2 k_\mu k_\delta \delta} \quad , \tag{9}$$

where k_q according to [8] is determined from the expression

$$k_q = 1 - \frac{1}{\alpha b[cth(\alpha b)+th(\alpha t)]} \quad , \tag{10}$$

here t is the unilateral departure of the SE to the limits of the inductor. As shown in [10], an increase in the SE width is effective only up to the value $t = 0.4\,\tau$.

A flat LIM with a short-circuited SE and a laminated magnetic circuit can also be characterized by the electromagnetic quality factor ε according to (9), if the equivalent thickness of the highly conductive screen is determined through the total cross section of the rods of the short-circuited cage, similarly to how it was done in [8, 12], and the effect of the resistance of short-circuiting tires is taken into account coefficient k_γ [13, 14], substituting it into (9) instead of k_q:

$$k_\gamma = \frac{r_c}{r_2} \cdot \frac{1}{1 + \dfrac{r_k}{2r_c \cdot sin^2(\alpha t_{z2})}} \quad . \tag{11}$$

For a flat LIM with a massive steel SE, both the transverse edge effect and the pronounced surface effect should be taken into account. In this case, to determine the electromagnetic figure of merit, expression (9) can be used if, instead of the thickness Δ, we substitute the depth of penetration of the electromagnetic field into the steel mass $\sqrt{1/(\omega_1 s \mu_e \gamma_c)}$. Taking this into account, we get

$$\varepsilon_c = \frac{\mu_o k_q \tau^2 \sqrt{\omega_1 s}}{\pi^2 k_\mu k_\delta \delta} \cdot \sqrt{\frac{\gamma_c}{\mu_e}} \quad . \tag{12}$$

The value $\sqrt{\gamma_c/\mu_e}$ included in (12) is a non-linear function of the magnetic field strength on the steel surface, so its determination at the stage of preliminary calculation is difficult. It is more convenient to determine ε_c through the relative values of the currents I'_{2*} and I_{m*}

$$\varepsilon_c = 1,167(I'_{2*}/I_{m*}) \quad , \tag{13}$$

where I'_{2*}, I_{m*} and ε_c can be found from Figure 2 depending on the value of the coefficient k_I [10]:

$$k_I = 10^3 \frac{k_\mu k_\delta \delta}{k_q \tau^2 \sqrt{f_1 s}(k_{o\delta} A)^{0,428}} \quad , \tag{14}$$

For computer calculations, the dependences I'_{2*} and $I_{m*} = f(k_I)$ are approximated by expressions of the form

$$I'_{2*} = exp\left(\frac{-k_I}{1,1121 + 0,226k_I - 0,8281 \cdot lg(k_I)}\right) \quad (15)$$

$$I_{m*} = 1 - exp\left(\frac{-k_I}{0,6847 + 0,2325k_I - 0,5315 \cdot lg(k_I)}\right) . \quad (16)$$
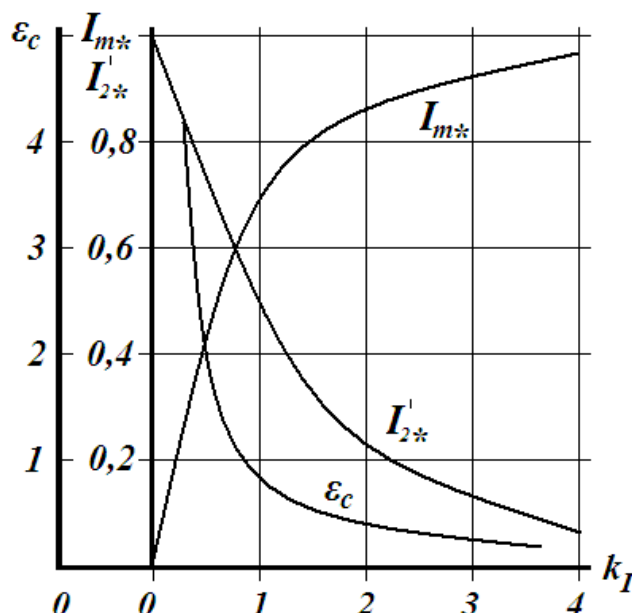

Fig. 2. To the definition of currents and electromagnetic quality factor LIM with steel SE.

As follows from (1) and (5), the electromagnetic power of the LIM depends both on the electromagnetic quality factor and on the phase angle between the secondary EMF and the current - ψ_2. For the LIM versions discussed above, the angle ψ_2 can be determined as follows. For a cylindrical LIM with a nonmagnetic SE, $tg\,\psi_2 = 0$. For a flat LIM with a nonmagnetic SE, taking into account the transverse edge effect, we obtain

$$tg\,\psi_2 = (K^2 - K_p)/K_a) , \quad (17)$$

where for a SE having a width equal to the width of the inductor, the coefficients K_a and K_P can be determined according to [8]; $K = \sqrt{K_a^2 + K_p^2}$. There are also ways to determine the coefficients K_a and K_P in the presence of departures of SE outside the inductor.

For a short-circuited secondary winding, we obtain

$$tg\,\psi_2 = x_2/r_2 , \quad (18)$$

where x_2 and r_2 are the parameters of the short-circuited winding, determined by known methods [13-18].

For LIM with massive steel SE $tg\psi_2 = 0,6$ [11]. In this case, the influence of the transverse edge effect on the active and reactive components of the SE resistance is assumed to be the same.

For one-sided LIMs, the most common is the combined SE (a highly conductive screen allows you to raise the technical and economic indicators of the LIM, a massive steel magnetic circuit is much cheaper, more

technologically advanced and stronger than a laminated one). In some cases, a short-circuited SE with a massive steel magnetic circuit is used. When determining the electromagnetic figure of merit ε and the angle ψ_2 for such LIMs, one should take into account the joint contribution of the highly conductive screen and the massive steel magnetic circuit. From the vector diagram in Figure 1,*b* can be obtained

$$\varepsilon\,cos^2\,\psi_2 = \varepsilon_{_э}\,cos^2\,\psi_{_э} + \varepsilon_c\,cos^2\,\psi_c \;; \qquad (19)$$

$$tg\,\psi_2 = \frac{\varepsilon_{_э}\cdot tg\,\psi_{_э}\cdot cos^2\,\psi_{_э} + \varepsilon_c\cdot tg\,\psi_c\cdot cos^2\,\psi_c}{\varepsilon_{_э}\cdot cos^2\,\psi_{_э} + \varepsilon_c\cdot cos^2\,\psi_c} \;. \qquad (20)$$

The values of $\varepsilon_{_э}$, ε_c, $tg\psi_{_э}$ and $tg\psi_c$ are found using the above expressions. When determining the electromagnetic quality factor ε_c, it is necessary to take into account the demagnetizing effect of a highly conductive screen, since the parameters of the steel massive SE layer depend nonlinearly on the magnetic field strength on its surface. In the first approximation, such an account can be made using the formulas obtained from a comparison of the vector diagrams in Figure 3:

$$\varepsilon_c = \varepsilon_{co}(1+D)^{-0,214} \;; \qquad (21)$$

$$D = \frac{\varepsilon_{_э}^2 + 1,468\varepsilon_{_э}\varepsilon_{co}}{1+0,734\varepsilon_{co}^2 + 0,88\varepsilon_{co}} \;. \qquad (22)$$
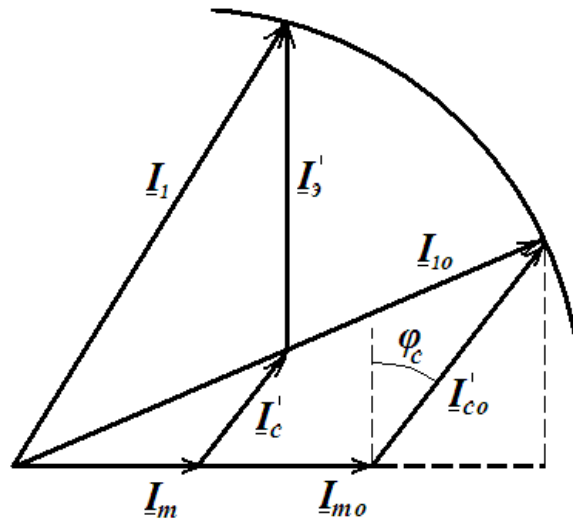

Fig. 3. To the calculation of the demagnetizing effect of the screen in the LIM with a combined SE.

The index *«o»* marks the currents and electromagnetic quality factor of the massive steel SE, obtained in the absence of a highly conductive screen, but with the same linear load of the inductor as in the case of the combined SE *(I_1 = I_{1o})*. As calculations show, with subsequent refinement, the value of ε_c, calculated according to (21), changes by no more than 10% [10, 12-18].

Using (19) - (22), one can estimate the mutual influence of a highly conductive screen and a steel mass, as well as determine the screen thickness and linear current load, at which the effect of one of the layers of the combined SE can be neglected. On Figure 4 shows the dependences $\Delta_{_э} = f(\varepsilon_{co})$, corresponding to the fulfillment of the condition:

$$\varepsilon_c \, cos^2 \, \psi_c = 0{,}05\varepsilon_{_9} \, cos^2 \, \psi_{_9} \; . \tag{23}$$

Just as when deriving expressions (21), (22), when calculating the curves in Figure 4, $\psi_{_9} = 0.$ is assumed. The specific electrical conductivity of copper and aluminum screens at 75°C is assumed to be $4.705 \cdot 10^7$ and $1.35 \cdot 10^7$ Sm/m, respectively. For all values of the thickness $\varDelta_{_9}$ lying above the curves shown, the LIM characteristics can be determined without taking into account the effect of the steel layer. In the manufacture of SE from other materials, you can use the dependence $\varepsilon_{_9} = f(\varepsilon_{co})$ in Figure 5, which also corresponds to condition (23). As can be seen from Figure 5, not taking into account the non-linear properties of the steel mass can lead to a significant error.
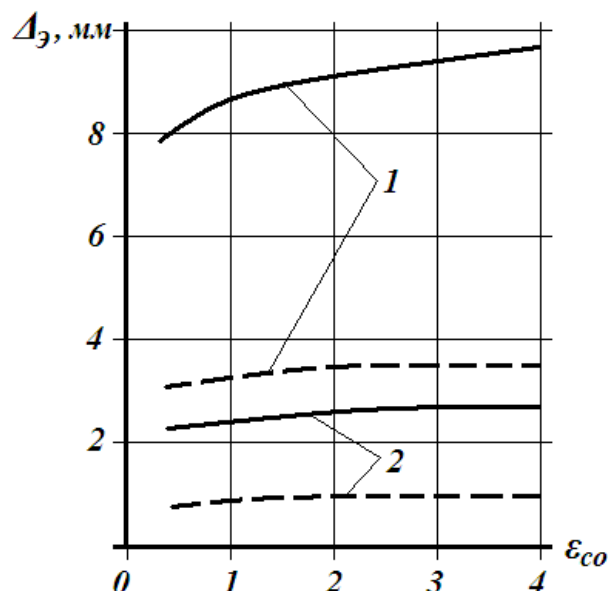

Fig. 4. Dependences of the thickness of the aluminum (1) and copper (2) screens of the combined SE on $\boldsymbol{\varepsilon}_{co}$, corresponding to the condition $\boldsymbol{\varepsilon_c \, cos^2 \, \psi_c = 0{,}05\varepsilon_{_9} \, cos^2 \, \psi_{_9}}$. Inductor linear load: 5×104 A/m (solid lines) and 0.5×104 A/m (dashed lines).
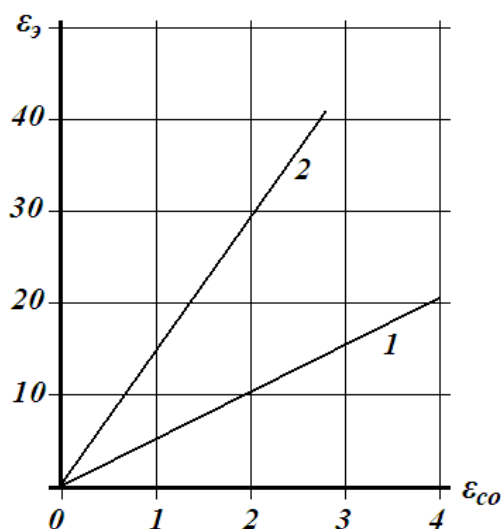

Fig. 5. Dependencies $\boldsymbol{\varepsilon_{_9} = f(\varepsilon_{co})}$ corresponding to the condition $\boldsymbol{\varepsilon_c \, cos^2 \, \psi_c = 0{,}05\varepsilon_{_9} \, cos^2 \, \psi_{_9}}$ with (1) and without (2) nonlinear properties of the steel mass.

4. Conclusion

In many cases, according to the operating conditions, LIMs have relatively large air gaps. In this case, part of the magnetic flux coming out of the pole division of the inductor is closed to adjacent pole divisions through the air gap, without reaching the secondary part. A similar phenomenon in conventional asynchronous motors is relatively rare. In cases where LIMs have a massive secondary part, one should also take into account the transverse effect associated with the uneven distribution of currents across the width of the secondary part and, as a result, the redistribution of the magnetic flux. This phenomenon occurs in circular asynchronous motors with massive rotors.

Often the secondary part of the LIM can be a steel array, or a steel array containing a winding. In this case, one should take into account the sharp manifestation of the surface effect and the nonlinear dependence of the parameters of the secondary part and on the remagnetization frequency, taking into account the uneven distribution of the magnetic field along the length of the LIM. The described phenomena indicate the complexity of electromagnetic processes in the LIM and necessitate the creation of a theory and calculation methods that take into account the specifics of such machines. One of the main optimization criteria is the magnitude of the electromagnetic figure of merit.

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