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# Simulation of Linear Asynchronous Motors of Electric Drive of Quiet Mechanisms

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**Abstract.** The analysis of the drive characteristics of technological units in the agro-industrial complex showed that for some working bodies of machines performing translational and oscillatory movements, as well as rotary movement with a rotational speed of up to 500 $min^{-1}$, special electric drives with an induction motor with an open magnetic circuit are promising. They make it possible to obtain the necessary technologically specified drive characteristics, achieve integration with the working body while excluding mechanical converters, reduce material and energy consumption, and increase the reliability of agricultural machines in general. When simulating by the method of detailed equivalent circuits of linear asynchronous motors having a primary winding with a small number of slots per pole and phase, an increase in the accuracy of numerical differentiation is achieved by decreasing the step of dividing along the coordinate, which corresponds to a conditional increase in the number of slots in the model. The analysis of the influence of the improved algorithm in the numerical study of various designs and operating modes of electric motors is carried out.

## INTRODUCTION

The electric drive consumes the bulk of the world's electricity. The correct solution to the main problems of electric drive development is of great importance for the country's economy. Each new constructive solution should increase the efficiency of the technological equipment - for production plants, particularly for a special electric drive that fully provides the drive characteristics of an agricultural technological plant [1-4].

A rational electric drive is selected based on a detailed analysis of the drive characteristics (technological, kinematic, energy, mechanical, load, inertial) of the working bodies of machines of technological processes in the production of the agro-industrial complex. Considering some of the main driving characteristics of stationary machines of the agro-industrial complex, in particular, 279 crop and 116 livestock machines, showed that they have, respectively, 385 and 260 working bodies and drive electric motors – 325 and 230. The distribution of the working bodies of all machines according to the type of movement showed that 56.3% of their total number have rotational movement (up to 500 $m^{-1}$ – 39.7%, more than 500 $m^{-1}$ – 16.4%); the translational motion – 43.7% (up to 1 m/s – 27.3%, 1-2 m/s – 6.8%, more than 2 m/s – 9.6%) [2-6].

The drive of the working bodies with a rotational speed of up to 500 rpm, a translational movement, and those without an individual drive motor, is carried out using mechanical converters. Consideration of the kinematic diagrams of the above 395 agricultural machines showed that 944 different mechanical converters are used in the drive of 645 working bodies. Their distribution is as follows: cylindrical, bevel and worm gearboxes – 30.6%; belt drives – 37.2%; chain drives – 12.4%; gear drives – 5.1%; geared motors – 4.3%; direct connection – 3.9%; other connections and transmissions – 6.5% [2-6].

The above analysis shows that for several working bodies of agricultural machines performing translational and oscillatory movements and rotary movement with a rotation frequency of up to 500 $m^{-1}$, special electromechanical and electromagnetic converters are promising, incl. an electric drive with an induction motor with an open magnetic circuit. Such drives make it possible to obtain the necessary technologically specified drive characteristics to

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integrate the working body with the exclusion of mechanical converters. The material and energy consumption decreases, and the reliability of agricultural machines as whole increases [5-9].

With a rational choice of the parameters of the motor and the laws of its control, the linear electric drive has some advantages over the classical one, made based on a rotary action motor. These are the constructive integration of the drive into the transport system, the distribution of tractive effort along the length of the path or the feed dispenser, the use of power losses in the secondary element, which is useful in some cases. At the same time, the use of such a drive carries with it several features associated with the disadvantages of a linear induction motor: the presence of edge and thickness effects, an increased non-magnetic gap, the appearance of unbalanced normal forces [10-14].

When studying an electric drive for transport systems based on a linear asynchronous motor (LAM), a very urgent task is to analyze the influence of structural changes and operating modes on traction forces. Moreover, the need for such an analysis may arise both during the engine's design and during operation (when changing the operating mode, making changes to the electric drive elements, etc.). For example, strict requirements are often imposed on the geometric dimensions of traction motors when designing transport systems. As a result, it may turn out that the engine does not develop the required tractive effort in a given range of speeds, which must be provided for the start of a movement. With any method for solving this problem, it is necessary to study the effect of engine parameters on traction forces. Similar problems are encountered not only in transport systems; in some cases, it is necessary to determine and limit the range of changes made to the parameters of individual nodes of the LAM [7-12].

The object of research is linear asynchronous motors, the subject is the specific nature of the flow of electromagnetic processes in them. The main differences from circular induction motors are as follows: there are edge effects; the inductor and the secondary element of LIM, as a rule, operate in short-term and intermittent modes; forces are distributed unevenly along the length of the secondary element (SE). At the same time, the use of well-known calculation methods used in rotary actuators is incorrect since they are based on several assumptions that do not hold for linear machines and lead to imprecise results. The purpose of the study is to develop mathematical models and software that take into account the specified features of the LAM and provide research of traction forces in linear asynchronous motors [7-12]. The research objectives are: analysis and comparison of a numerical model with various details in the pole division of the inductor; determination of the adequacy of the calculation results for different designs and operating modes of asynchronous electric motors.

## METHODS

A mathematical model based on detailed equivalent circuits is used mainly to study asynchronous motors (AM) with an open magnetic circuit. These usually include motors with a translational motion of the secondary element (linear asynchronous motors – LAM), arc-stator and rotary disk motors. Some induction electrotechnical installations are similar in the principle of operation.

The applied mathematical model is built following the following approach: the computational model of an induction motor is divided into a model (submodel) of an inductor electric circuit, a magnetic circuit model, and an armature electric circuit model. For the mathematical description of electromagnetic processes, several assumptions are made [12]. Each of the three circuits (the electric circuit of the inductor, the magnetic circuit, the electric circuit of the armature) is assigned an equivalent circuit, for which matrix (algebraic or differential) equilibrium equations are then compiled based on Kirchhoff's laws. One of the assumptions is that the active zone of the machine is divided into sections with a pitch equal to the toothed division. A uniform distribution of magnetic fluxes and currents is assumed in each section. Their change occurs abruptly when moving to another section. To demonstrate the approach, we will consider a simpler static model that does not consider electromagnetic transients.

The equivalent circuit of the secondary electrical circuit is a cascade connection of the equivalent circuits of the circuit sections (four-pole networks) corresponding to the toothed divisions (Fig. 1). Various degrees of idealization of the real design of the secondary element electrical circuit leads to equivalent circuits and mathematical models of varying degrees of complexity.

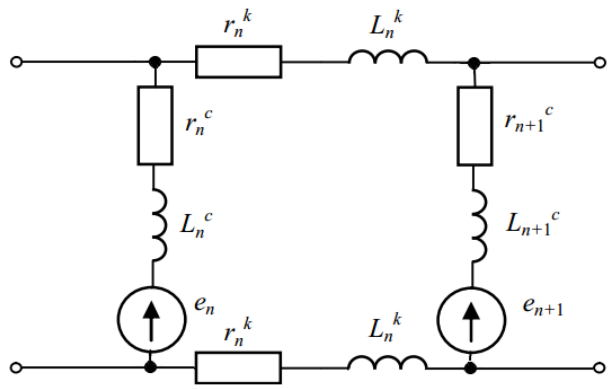


**FIGURE 1.** Equivalent circuit of a section of the electrical circuit of a secondary element.

Let us consider the simplest model obtained under the assumption that the side buses are ideal (in Fig. 1, their resistances and inductances are denoted by *k*), the independence of the parameters of the rods from the frequency, and the equality of the parameters of all the rods (although in the general case they may differ). In this case, we can assume that each rod (in Fig. 1, their resistances and inductances are denoted by the index *c*) is short-circuited (to an infinite number of other rods). For the *n*-th rod of this equivalent circuit, the Ohm's law equation has the form

$$r_n^c i_n^c + L_n^c \frac{di_n^c}{dt} = -\frac{d\Phi_n}{dt} \tag{1}$$

where: $r_n^c$, $L_n^c$, $i_n^c$ is the resistance, leakage inductance and current of the *n*-th reduced bar, respectively; $\Phi_n$ is the magnetic flux of the *n*-th section of the yoke back.

In equation (1), the EMF of self-and mutual induction induced in the rods are functions of time and functions of the coordinate of displacement. Let us express the total time derivative in terms of partial derivatives with respect to the time coordinate *t* and the displacement coordinate *x* (which is also a function of time). For differentiation by the coordinate of movement, the formula of numerical differentiation of the second order of accuracy (central finite differences) is used, taking into account the fact that all values are unchanged within the tooth division. Thus, the movement of the rods in the magnetic field of the inductor is modeled by introducing the EMF of the motion into the equations

$$\left.\begin{aligned} L_n^c \frac{di_n^c}{dt} &= L_n^c\left(\frac{\partial i_n^c}{\partial t} + \frac{\partial i_n^c}{\partial x}\frac{\partial x}{\partial t}\right) = L_n^c \frac{\partial i_n^c}{\partial t} + L_n^c \frac{(i_{n+1} - i_{n-1})}{2t_z}\upsilon\ , \\ \frac{d\Phi_n}{dt} &= \frac{\partial \Phi_n}{\partial t} + \frac{\partial \Phi_n}{\partial x}\frac{\partial x}{\partial t} = \frac{\partial \Phi_n}{\partial t} + \frac{\Phi_{n+1} - \Phi_{n-1}}{2t_z}\upsilon\ , \end{aligned}\right\} \tag{2}$$

where: $\upsilon = \dfrac{dx}{dt}$ is the speed of movement of the secondary element; $t_z$ is the tooth division.

Substituting (2) into (1) and performing algebraization by a complex method, we can go to the following expression:

$$z_n^c i_n^c - L_n^c \frac{\upsilon}{2t_z} i_{n-1}^c + L_n^c \frac{\upsilon}{2t_z} i_{n+1}^c = -j\omega\Phi_n - \frac{\upsilon}{2t_z}(\Phi_{n+1} - \Phi_{n-1}) \tag{3}$$

The entire set of equations (3) for the rods lying in the grooves of the secondary element can be written in one matrix equation:

$$Z^c I^c = -V^c \Phi \tag{4}$$

where: $Z^c$ is the matrix of the resistances of the short-circuited cell of the secondary element; $I^c$ is the vector of the currents of the rods reduced to the number of teeth of the inductor of the short-circuited cell of the secondary element; $V^c$ is the matrix of EMF formation in the contours (in the rods) of the secondary element; $\Phi$ is the vector of the magnetic fluxes of the secondary element (for a one-dimensional equivalent circuit of the magnetic circuit, it coincides with the vector of the magnetic fluxes of the inductor). The structure of the circuit and the assumptions adopted when drawing up the equivalent circuit determine, respectively, the dimensions and the elemental composition of the matrix coefficients.

It should also be noted that numerical differentiation along the coordinate is used in calculating the tractive effort.

Following the accepted assumptions, it is possible to calculate the elementary force acting on the conductor in the *n*-th tooth division:

$$f_n = B_n \ell w_n I_n^c \tag{5}$$

where: $B_n$ is the magnetic induction in the n-th section of the air gap; $\ell$ is the length of the active part of the conductor of the secondary element of the machine; $w_n$ is the number of turns of the coil, the side of which is located in the *n*-th slot.

The magnetic induction in the *n*-th section of the gap is written in the form

$$B_n = \frac{d\Phi_n}{dx} \frac{1}{\ell} \tag{6}$$

Substitute (5) into (6), use a second-order finite-difference approximation and sum up the elementary efforts at each tooth division. At the same time, the number of turns is taken for a cell (or strip) $w_n = 1$:

$$F_T = \sum_n f_n = \sum_n \left[ \frac{\Phi_{n+1} - \Phi_{n-1}}{2t_z} I_n^c \right] \tag{7}$$

From the practice of modeling various linear induction motors by the method of detailed equivalent circuits, it is known that with a small number of slots per pole and phase (especially in the case *q=1*), a significant error is introduced when calculating the derivative of the magnetic flux with respect to the coordinate using central finite differences of the second-order [13 ]. This is because the detail step along the coordinate in the model is fixed and equal to the tooth division [13, 14].

One of this manifestations is the presence of torque (pulling force) at zero slip. For LIM, this is partly due to the longitudinal edge effect [12]. Physically, this is explained as follows: with an increase in speed (i.e., at small slips), the contribution of the EMF of motion (proportional to the speed of movement of the rods of the secondary element) becomes more noticeable. This leads to errors in determining secondary currents, efforts and powers, especially at low slip [13].

Since numerical differentiation is also used in calculating force, another manifestation is some additional error at all slip values. The absolute error in differentiating magnetic fluxes along with the coordinate decreases slightly with increasing slip, since in this case, the magnetic LAM decreases by a factor of 1.5–3. The secondary currents of LAM, on the contrary, increase 3–5 times in the slip range from 0 to 1. Therefore, the error in calculating the force becomes larger with increasing slip.

Thus, both described manifestations of the error in the model are due to the same reason. Following the general approach, the accuracy of numerical differentiation can be increased to certain limits in two ways: using a more complex finite-difference scheme or decreasing the step of partitioning along the coordinate. Since decreasing the step along the coordinate (equal to the toothed division) is possible, it is fraught with some difficulties [13], as described below, let us first consider the first method. For a more accurate account of the EMF of the movement and the calculation of the effort, it is proposed to complicate the differentiation algorithm, i.e. apply formulas of higher orders of accuracy [15-16].

Having carried out transformations (1) using the formula of the fourth order of accuracy, we obtain the expression:

$$z_n^c i_n^c + L_n^c \upsilon \frac{-i_{n+2} + 8i_{n+1} - 8i_{n-1} + i_{n-2}}{12t_z} = -j\omega\Phi_n - \upsilon \frac{-\Phi_{n+2} + 8\Phi_{n+1} - 8\Phi_{n-1} + \Phi_{n-2}}{12t_z} \quad (8)$$

A similar expression can be written using a formula of the sixth order of accuracy:

$$z_n^c i_n^c + L_n^c \upsilon \frac{i_{n+3} - 9i_{n+2} + 45i_{n+1} - 45i_{n-1} + 9i_{n-2} - i_{n-3}}{60t_z} =$$
$$= -j\omega\Phi_n - \upsilon \frac{\Phi_{n+3} - 9\Phi_{n+2} + 45\Phi_{n+1} - 45\Phi_{n-1} + 9\Phi_{n-2} - \Phi_{n-3}}{60t_z} \quad (9)$$

A system consisting of equations similar to (8) or (9) for all rods can also be written by matrix equation (4). Thus, when passing to the refined algorithm, only the elemental composition of the matrix coefficients of the mathematical model of the secondary element (the number of filled diagonals) changes. In the existing software package for modeling blood pressure, this led to the creation of additional subroutines [15-20].

To calculate the effort by expression (7), you can also use any finite-difference scheme for calculating the derivative with respect to the coordinate from those considered above:

$$F_T = \sum_n \left[ \frac{-\Phi_{n+2} + 8\Phi_{n+1} - 8\Phi_{n-1} + \Phi_{n+2}}{12t_z} I_n^c \right];$$
$$F_T = \sum_n \left[ \frac{\Phi_{n+3} - 9\Phi_{n+2} + 45\Phi_{n+1} - 45\Phi_{n-1} + 9\Phi_{n-2} - \Phi_{n-3}}{60t_z} I_n^c \right]$$

As already noted, increasing the accuracy of numerical differentiation is also possible by decreasing the step of dividing along the coordinate, which corresponds to a conditional increase in the number of slots in the model. It is this approach that was previously used to study LAM with *q=1*. In this case, the toothed pitch (model pitch along the longitudinal coordinate) equals one-third of the pole pitch. When simulating according to this approach, windings with q=2 were considered the main options when one groove of a real structure is replaced in the model by two, twice as narrow [13, 14, 21]. Sections with half the number of turns are laid out into two "new" slots, i.e. all grooves are filled. There are also options to layout real (full) sections in new grooves but through the groove [13]. From a mathematical point of view, this corresponds to a decrease in the differentiation step, which leads to an increase in accuracy.

## RESULTS AND DISCUSSION

Comparison of different approaches and different differentiation algorithms will be considered on the example of a flat one-sided LAM *SL5-100*. Technical data are given in [13]. A real *SL5-100* motor has a winding with several slots per pole and phase *q=1* and represents the most difficult case from the standpoint of numerical differentiation.

The calculation was carried out using a static model; the electromagnetic processes were assumed to be steady. Let's introduce the notation: $d_E$ is the number of points taken into account when calculating the EMF of the motion induced in the rods (corresponds to the order of accuracy of the differentiation formula); $d_F$ is the number of points taken into account when calculating the tractive effort [12-17].

In fig. 2 shows the mechanical characteristics of the investigated LAM with different differentiation algorithms when calculating the EMF of movement and effort.

From these graphs, it follows that when calculating (especially when *q=1*), it is necessary to simultaneously apply a more accurate algorithm when calculating the EMF of motion and when calculating the effort. This is because separate application leads to significant errors either in the zone of small (Fig. 2, curve 3) or in the zone of large slips (Fig. 2, curve 2).

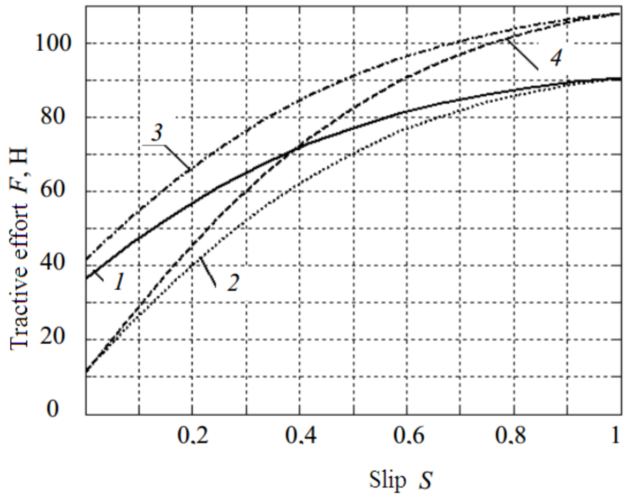


**FIGURE 2.** Mechanical characteristics with separate application of algorithms: *1* – initial characteristic ($q=1$, $d_E=2$, $d_F=2$); *2* – $q=1$, $d_E=6$, $d_F=2$; *3* – $q=1$, $d_E=2$, $d_F=6$; *4* – $q=1$, $d_E=6$, $d_F=6$.

As a result, the following conclusions can be drawn from the static model.

Studies have shown that the qualitative nature of the phenomena in the transition to the proposed algorithms is approximately the same for the models of all considered engines. From a mathematical standpoint, algorithms of the fourth and sixth orders allow, with the same accuracy, to work with a large step, i.e. get more adequate results in the study of blood pressure with a lower q.

The traction force at zero slip is due to both the differentiation error and the longitudinal edge effect that the LAM takes place. However, it is possible to reduce the component due to the error by applying a more accurate algorithm for calculating the EMF of the motion (Fig. 3, curve 2).

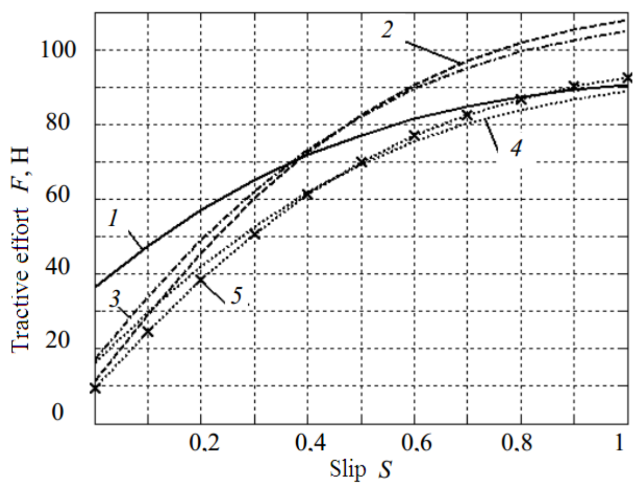


**FIGURE 3.** Mechanical characteristics for different approaches and algorithms: *1* is initial characteristic ($q=1$, $d_E=2$, $d_F=2$); *2* is $q=1$, $d_E=6$, $d_F=6$; *3* is $q=2$, $d_E=4$, $d_F=4$; *4* is $q=2$, $d_E=2$, $d_F=2$; *5* is $q=1$, $d_E=4$, $d_F=4$.

Using a more accurate algorithm in calculating the tractive effort has little effect on the region of small slips. In contrast, in the region of large slides, on the contrary, a noticeable effect of the algorithm is observed (Fig. 3, curve 3).

The graphs presented to confirm the assumptions made based on physical considerations earlier.

The adequacy of the modified model was also assessed on the circular analogue model, i.e. a machine with the same parameters but with a closed magnetic circuit. The criterion of adequacy was the closeness to zero of the torque value at zero slip. Naturally, with more accurate algorithms, the mechanical characteristic goes much closer to zero with zero slip [12-15].

In the course of applying a more accurate differentiation algorithm, only a refinement of the existing model is made, and with a conditional increase in the number of slots, new assumptions (and errors) are introduced into the model. Moreover, in the case of a conditional increase in q and the number of grooves twice (and in general for LAM with *q=2*), there is still a significant differentiation error, which is also desirable to reduce (Fig. 3, curves 4 and 5). In this case, a conditional increase in the number of grooves by more than two times does not make sense. In this case, even for engines with small q, the calculation time increases noticeably and the simulation errors introduced when using this method. Comparing both approaches to improving the differentiation accuracy when simulating engines with *q=1*, we can conclude that in the case of a conditional transition to *q=2* (i.e., with a decrease in the differentiation step) and in the case of using another numerical differentiation algorithm, the results are quite close only for small slips. At the same time, applying the differentiation algorithm of the next order of accuracy is much easier; it is only required to change the algorithm for the formation of the differentiation matrices [12-21].

An increase in the number of filled diagonals in the matrix coefficients of the mathematical model of the secondary element and the differentiation matrix when calculating the force does not lead to a noticeable increase in the time for modeling the structure, and the addition of conditional slots to the model (following the second approach) increases the size of the matrices, and, as a consequence, the calculation time, as well as the amount of memory required to store the matrices. But in general, this is not very relevant since the number of slots for motors with small q is, as a rule, not very large, and the calculation is done quickly enough since the matrices are small in any case.

Following the principles described above, the dynamic model of the LAM was modernized. At first glance, such modernization is not relevant specifically for the dynamic model, since the greatest jump in the moment (or effort) occurs at slides close to unity, when the influence of the error of numerical differentiation in the model of any motor has little effect, because the EMF of the motion is small compared to the «transformer» EMF. Only the effect on the steady-state value of the speed (rotation frequency) is noticeable, which, generally speaking, can be determined by a much faster static model [12-17, 21].

However, the impact of the improved algorithm in the dynamic model is advisable to evaluate since, in transport systems based on linear asynchronous motors, the "pick-up" mode is often used, i.e. switching on the inductors at a non-zero initial speed of the secondary element. In this case, the jumps in the thrust and motor current occur at a small slip; the smaller, the closer the initial speed of the moving part is to the nominal speed for the given motor. To study this mode, it is important to have a model that adequately describes it, since, to improve the technical and economic indicators, it is necessary to correctly determine the moment of switching on the next inductor of the transport system, the degree of overlap of the secondary element and the inductor, and the pickup speed.

## CONCLUSIONS

1. A mathematical model has been developed based on detailed equivalent circuits with various degrees of detail within the pole division of the primary part.

2. Based on the analysis of static and dynamic models, the following conclusion can be drawn: the computational experiments have shown that for the study of asynchronous motors with inductor windings with $q > 1$, in most cases, a fourth-order numerical differentiation algorithm is sufficient, and in some cases even a second-order accuracy. To study AM with inductor windings at $q = 1$, it is preferable to use the sixth order of accuracy algorithm. Although for some structures of the AM (with small values of the nominal and critical slip), it turns out to be insufficient.

3. It seems possible to obtain the most approximate values of the characteristic by applying an even more complex finite-difference scheme or a mixed approach based on decreasing the step along the coordinate. It is also possible to use any of the differentiation formulas discussed above with correction factors that consider the differentiated function's specifics.

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