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Methodology for calculating the characteristics of linear induction motors for low-speed process equipment

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Abstract. An analysis of the drive characteristics of technological machines and mechanisms of agricultural production showed that their working bodies in 56.3% of cases have rotational motion, and in 43.7% they have translational motion. Special electromechanical and electromagnetic converters - an electric drive with a linear asynchronous motor - are very promising for driving the working bodies of technological equipment that perform translational and oscillatory motion, as well as rotational motion with a rotation speed of up to 500 min^{-1}. A linear asynchronous electric drive makes it possible to implement technologically specified drive characteristics, integrate the power parts of an electric motor with a working body with the exception of mechanical converters, while reducing material and energy consumption, increasing operational reliability of process equipment as a whole. The choice of the optimal winding scheme and the design of the magnetic circuit of the inductor, the material of the secondary element increases the energy and traction performance of the linear induction motor. The study and modeling of electromagnetic processes and the optimization of geometric dimensions, winding data of the inductor and electrical parameters can be effectively carried out on a mathematical model of a linear induction motor by a numerical method, represented by a system of three matrix equations describing the states of the magnetic and electrical circuits of the machine, detailed to the level of tooth division and winding section.

1. Introduction

Agricultural production (ACP) is determined by rather broad specific performance indicators and properties for a variety of technological equipment and mechanisms, which are determined by the technologies of agricultural products and the specific conditions of their operation. The most used electrical equipment in the technological processes of ACP, consuming electrical energy, are electric motors. The use and renewal of a large number of different electrified technological equipment and mechanisms in the technological processes of ACP determines the corresponding improvement of their electric drives. A rational electric drive is selected on the basis of a detailed study and determination of drive characteristics (technological, kinematic, energy, mechanical, load, inertial) of the working bodies of technological equipment and mechanisms of ACP [1-4].

Consideration of some drive characteristics of stationary agricultural machines, in particular, 279 crop and 116 livestock machines, showed that they have, respectively, 385 and 260 working bodies and drive 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 motion, incl. up to 500 rpm - 39.7%, more than 500 rpm - 16.4%; progressive movement - 43.7%, incl. up to 1 m/s - 27.3%, 1-2 m/s - 6.8%, more than 2 m/s - 9.6%.

The drive of working bodies with a rotation speed of up to 500 rpm, translational movement, as well as those that do not have an individual drive electric motor, is carried out by means of 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 gears - 30.6%; belt drives - 37.2%; chain transmissions - 12.4%; gears - 5.1%; geared motors - 4.3%; direct connection - 3.9%; other connections and transmissions - 6.5% [1-8].

The analysis of a number of basic drive characteristics of technological equipment of agricultural production showed that the drive of a number of working bodies that perform translational and oscillatory movements, as well as rotational movement with a rotation speed of up to 500 rpm, is effectively, from the point of view of energy and resource saving, carried out using special electromechanical and electromagnetic converters - induction electric drives with a motor with an open magnetic circuit. The optimal choice of an induction motor with an open magnetic circuit makes it possible to obtain the necessary technologically specified drive characteristics, to achieve the integration of the elements of the electric motor with the working body with the complete exclusion of mechanical converters, as a result of which material and energy consumption are reduced, and the performance of technological equipment of agricultural production as a whole is increased [3-11].

2. Problems and methods

The main disadvantage of linear asynchronous electric motors is low energy performance due to the openness of the magnetic circuit of the inductor along the longitudinal axis [8-13]. Also, in this regard, the analysis of electromagnetic processes in linear induction motors (LIM) due to a number of their features is quite complicated [8-17].

A universal tool for studying LIM is the methods of mathematical modeling, which allow considering its mathematical model instead of the original. Due to the complexity and cumbersomeness of the latter, numerical methods of calculation are becoming more widespread.

To date, a wide variety of numerical mathematical models of LIM are known, however, they are poorly suited for studying the dynamics of a machine, taking into account the modes characteristic of industrial drives with LIM (asymmetric switching on of inductor windings, relay transmission of a secondary element from one inductor to another, etc.) . In addition, the available models are weakly focused on the synthesis of drive control systems, in particular, within the framework of classical approaches to solving this problem. In addition, when developing electric drive systems using LIM, much attention should be paid to the formation of channels for monitoring and measuring the main controlled coordinates, as well as a number of integral characteristics of the engine, both in static and dynamic modes of operation [14-17].

Therefore, the task of further development of static and dynamic models and the creation of detailed structures of elements and linear induction motors in order to expand their capabilities is relevant.

These methods include a numerical method for calculating the electromagnetic processes of LIM based on detailed equivalent circuits for electric and magnetic circuits [8, 15-19]. This method allows optimizing the characteristics of an electric drive with LIM in the study of any of its elements. One of the most acceptable and effective, from an economic point of view, ways to improve the characteristics of agricultural electric drives with LIM is to improve their inductor winding connection scheme.

The mathematical model of LIM, given in [8, 15-19] and implemented in computer programs, allows you to determine the distribution of instantaneous electromagnetic indicators (current, magnetic induction, flux, etc.) over the slots of the inductor magnetic circuit, taking into account the discreteness of the structure of various winding circuits. In addition, the parameters and indicators of the power source are taken into account.

3. Results and discussion

The mathematical model of an asynchronous motor is a system of complex matrix features that describe the state of the magnetic and standard circuits of the machine, detailed to the level of tooth division and winding section [8, 19-22]. The solution of this system is possible only by numerical methods on a computer.

The steady state mode of operation of an induction motor (IM) is described by algebraic equations, which, by means of matrix transformations, are reduced to a system of linear algebraic equations with respect to the yoke magnetic flux vector with a dimension equal to the number of inductor slots. The elements of the magnetic flux vector are the fluxes of the inductor yoke at each tooth division. The current vectors are calculated from the flux vector, the elements of the inductor current vector are the currents of the inductor electric circuit branches, the elements of the armature current vector are the currents of the short-circuited cage rods reduced to the tooth division of the inductor. Thus, the mathematical model includes a refined account of the actual current and flow distribution of the machine.

Electromagnetic processes in the engine are described by the following equations in matrix form

$$\left.\begin{aligned} U &= Z_{\phi} \cdot I_{\phi} + j \cdot \omega \cdot K_{\phi} \cdot \Phi, \\ R_M \cdot \Phi &= I_c + K_{red} \cdot I_{\phi}, \\ Z_c \cdot I_c &= V_c \cdot \Phi, \end{aligned}\right\} \qquad (1)$$

where U is the supply voltage vector; I_{ϕ} – vector of independent phase currents; Φ is the vector of magnetic fluxes of the inductor yoke; I_c – vector of currents of reduced cage rods; Z_{ϕ} is the matrix of complex phase resistances; $Z_{\phi}=R_{\phi}+j\omega L_{\phi}$; R_{ϕ} and L_{ϕ} are the active resistance and inductance of the phase, not taken into account in the equivalent circuit of the magnetic circuit; K_{ϕ} is the reduction matrix of slot emfs. to phase; R_M is the matrix of magnetic resistances; K_{red} – matrix of bringing phase currents to slot currents; Z_c is the resistance matrix of the cell of the secondary element; V_c is the emf formation matrix. in the contours of the secondary element.

The first and third equations of system (1) describe the state of the electrical circuits of the inductor and armature, the second – the state of the magnetic circuit. The elemental composition of the matrices Z_f, K_f, K_{pr} depends on the parameters of the branches, the method of laying and connecting the winding sections. To numerically study the influence of winding design features, it is necessary to automate the process of forming these matrices. The first equation of system (1) is the voltage balance equation for independent winding circuits. Let us construct a unified algorithm for the formation of this equation using the topological concepts of a chain.

For a chain containing p branches and q nodes, one can compose $(q-1)$ equations based on the first Kirchhoff law and $n=p-(q-1)$ equations based on the second Kirchhoff law. We form these equations, guided by the following rules. Let's make a directed graph of the electric circuit of the inductor and select its tree. We number the branches of the graph in such a way that the branches of the tree correspond to numbers from the first to $q-1$, and to the links, the numbers from q to p. Based on Kirchhoff's first law, we compose equations for sets of nodes enclosed by closed surfaces, each of which cuts only one branch of the graph tree and is identified by the number of this branch. This possibility follows from the continuity of electric current lines

$$\int_s (J \cdot n) ds = 0 \qquad (2)$$

where J is the current density through the surface element ds, and n is the unit vector normal to the element ds.

Obviously, the number of such surfaces and, accordingly, equations is equal to $q-1$. In addition, we choose the direction and (inward or outward) so that the current of the cut branch of the graph tree is positive.

Let us consider an inductor winding with two parallel branches as an example. The electrical circuit of the inductor is represented by an equivalent circuit (Figure 1) or a graph (Figure 2).

We write the equations based on the first Kirchhoff law in accordance with the accepted rules, given that $p=9$ and $q=6$:

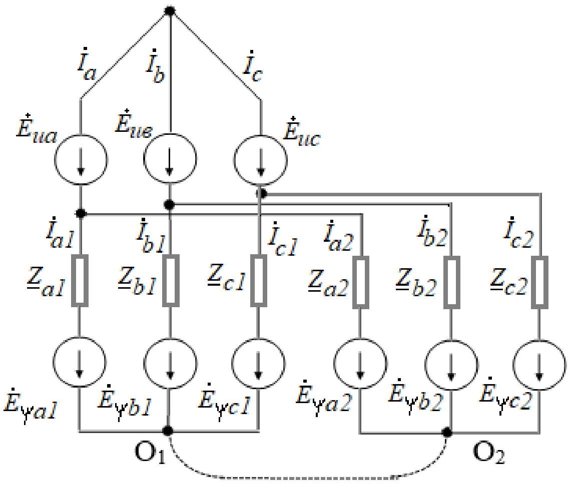

Figure 1. The equivalent circuit of the inductor winding.

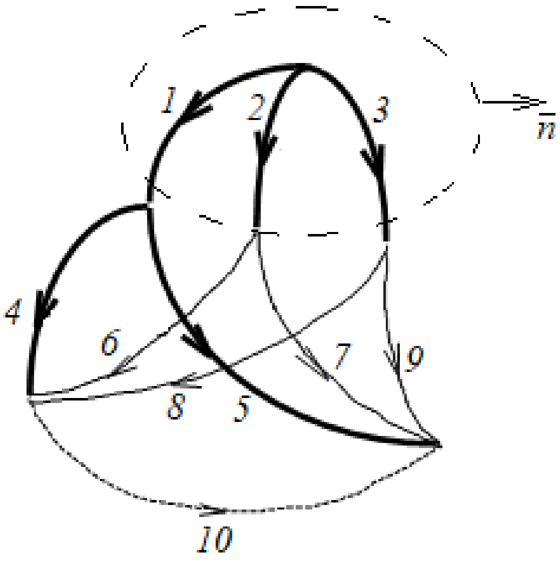

Figure 2. Graph of the electric circuit of the inductor: n – external normal to a closed surface that cuts branch 1.

$$\left.\begin{array}{l} I_1 + I_2 + I_3 + I_4 + I_5 = 0, \\ I_2 - I_7 - I_6 = 0, \\ I_3 - I_8 - I_9 = 0, \\ I_4 + I_8 + I_6 = 0, \\ I_5 + I_7 + I_9 = 0. \end{array}\right\} \tag{3}$$

It is convenient to write the entire set of equations in one matrix

$$A \cdot I_o = 0, \tag{4}$$

where A is a matrix of sections of dimension $(q-1, p)$; I_o – branch current vector, $I_o^T = (I_1, I_2,..., I_p)$, O – zero vector; the index T denotes the transposition of the vector.

Each row of the matrix A corresponds to an equation for a closed surface with the same number, and each element of the row corresponds to the branch number. The line element is equal to zero if the branch is not cut by the given surface, equal to +1 or –1 if the branch is cut and the direction of the normal coincides or does not coincide with the direction of the branch. System (3) corresponds to the following elemental composition of the matrix:

$$A = \left(\begin{array}{ccccc|cccc} 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & \multicolumn{4}{c}{\underbrace{0 \quad 1 \quad 0 \quad 1}_{A_2}} \end{array}\right) \tag{5}$$

It is easy to see that this matrix can be divided into two submatrices – the identity one and some *A=[1, A₂]*.

We will form the contours for compiling equations based on the second Kirchhoff law by supplementing the graph tree with one connection in turn in ascending order of their numbers. In addition, we choose the directions of bypassing the contours to coincide with the connection direction. Then each circuit will include only one connection and some branches of the graph tree.

Let us introduce the vector of voltage drops $U_0^T = (U_1, U_2, \ldots, U_p)$. We express the voltage of the *k*-th branch in terms of components that have different physical meanings:

$$\dot{U}_k = Z_k \cdot \dot{I}_k - \dot{E}_{\psi k}, \tag{6}$$

where I_k is the branch current; $Z_k = R_k + j\omega L_k$ – branch complex resistance; $E_{\psi k} = -U_{\psi k} = -j\omega a\ \Psi_k$ - emf induced by flux linkage Ψ_k; Ψ_k is the total magnetic flux coupled to the branch.

We also introduce the emf vector. sources $E^T=(E_1, E_2,\ldots,E_p)$. E_k is emf. source operating in the *k*-th branch.

For the example under consideration, we write an equation based on the second Kirchhoff law, taking into account that $E_k = 0$ for $k>3$

$$\left.\begin{array}{l} -\dot{U}_1 + \dot{U}_2 - \dot{U}_4 + \dot{U}_6 = -\dot{E}_1 + \dot{E}_2, \\ -\dot{U}_1 + \dot{U}_2 - \dot{U}_5 + \dot{U}_7 = -\dot{E}_1 + \dot{E}_2, \\ -\dot{U}_1 + \dot{U}_3 - \dot{U}_4 + \dot{U}_8 = -\dot{E}_1 + \dot{E}_3, \\ -\dot{U}_1 + \dot{U}_3 - \dot{U}_5 + \dot{U}_9 = -\dot{E}_1 + \dot{E}_3. \end{array}\right\} \tag{7}$$

Let us rewrite (7) in matrix form:

$$C \cdot U_o = C \cdot E, \tag{8}$$

where *C* is the matrix of contours.

Each row of the matrix *C* corresponds to the stress balance equation for the circuit formed according to the rules adopted above, and each element of the row identifies a branch with the corresponding number. The line element is equal to zero if the branch is not included in the given contour, and is equal to +1 or -1 if the branch is included in the contour and the direction of the bypass coincides or does not coincide with the direction of the branch. For the example under consideration, matrix *C* has the following elemental composition:

$$C = \left(\begin{array}{ccccc|cccc} -1 & 1 & 0 & -1 & & 1 & 0 & 0 & 0 \\ -1 & 1 & 0 & & -1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & -1 & & 0 & 0 & 1 & 0 \\ \multicolumn{5}{c|}{\underbrace{-1 \quad 0 \quad 1 \qquad\qquad -1}_{F}} & 0 & 0 & 0 & 1 \end{array}\right) \tag{9}$$

We select two blocks in it – the first *q–1* columns and the next *n* columns – and denote the first submatrix *F*.

It is easy to see that the matrices *C* and *A* are related by the relation

$$\left.\begin{aligned} C &= (F, \quad 1), \\ A &= (1, \quad -F^T \end{aligned}\right\} \tag{10}$$

This relation is satisfied for any circuit if the rules for compiling equations based on Kirchhoff's laws are fulfilled.

The work [23] proposes a structural matrix of the winding, which characterizes the distribution of winding sections over the slots,

$$I_n = w \cdot G \cdot I_{\phi}, \tag{11}$$

where I_n is the vector of slot currents; w is the number of turns of sections; I_f is the vector of currents of the winding branches laid in the grooves; *G* is the structural matrix of the winding.

However, in addition to the branches formed by the sections laid in the slots of the inductor, the winding may contain additional switching branches that do not form the MMF. Therefore, we introduce the modernized structural matrix of the winding G_o:

$$I_n = w \cdot G_o \cdot I_o, \tag{12}$$

where I_o is the vector of currents of all branches of the winding.

Then

$$E_{\psi} = -j \cdot \omega \cdot w \cdot G_o \cdot \Phi, \tag{13}$$

where Φ is the vector of magnetic fluxes of the yoke; E_{ψ} is the emf vector induced by the magnetic flux in the branches of the circuit.

For the stress vector, taking into account (13), we write

$$U_o = Z_o \cdot I_o + j \cdot \omega \cdot w \cdot G_o \cdot \Phi, \tag{14}$$

where Z_o is the diagonal matrix of complex branch resistances.

It should be noted that relations (11) – (13) do not depend on the method of numbering the branches of the electrical circuit of the winding, therefore, we number the branches in accordance with the accepted rules. Let's write the mathematical model of IM taking into account (4), (7), (11), (13):

$$\left.\begin{aligned} & A \cdot I_o = 0, \\ & C \cdot U_o = C \cdot E, \\ & R_M \cdot \Phi = I_c + w \cdot G_o \cdot I_o, \\ & Z_c \cdot I_c = V_c \cdot \Phi, \\ & U_o = Z_o \cdot I + j \cdot \omega \cdot w \cdot G_o \cdot \Phi. \end{aligned}\right\} \tag{15}$$

Let us reduce the structure of system (15) to the structure of system (1). To do this, from the vectors of currents, voltages and emf. source, we select subvectors of dimensions *q–1* and *n*:

$$\boldsymbol{I_o} = \begin{pmatrix} \dot{\boldsymbol{I}}_{\boldsymbol{1}} \\ \vdots \\ \dot{\boldsymbol{I}}_{\boldsymbol{q-1}} \\ \dot{\boldsymbol{I}}_{\boldsymbol{q}} \\ \vdots \\ \dot{\boldsymbol{I}}_{\boldsymbol{p}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{I1} \\ \boldsymbol{I2} \end{pmatrix}, \qquad \boldsymbol{U_o} = \begin{pmatrix} \dot{\boldsymbol{U}}_{\boldsymbol{1}} \\ \vdots \\ \dot{\boldsymbol{U}}_{\boldsymbol{q-1}} \\ \dot{\boldsymbol{U}}_{\boldsymbol{q}} \\ \vdots \\ \dot{\boldsymbol{U}}_{\boldsymbol{p}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{U1} \\ \boldsymbol{U2} \end{pmatrix}, \qquad \boldsymbol{E} = \begin{pmatrix} \dot{\boldsymbol{E}}_{\boldsymbol{1}} \\ \vdots \\ \dot{\boldsymbol{E}}_{\boldsymbol{q-1}} \\ \dot{\boldsymbol{E}}_{\boldsymbol{q}} \\ \vdots \\ \dot{\boldsymbol{E}}_{\boldsymbol{p}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{E1} \\ \boldsymbol{E2} \end{pmatrix}. \tag{16}$$

We also divide the Z_o and G_o matrices into blocks:

$$Z_o = \left(\begin{array}{ccc|ccc} \underline{Z}_1 & & & & & \\ & \ddots & & & & \\ & & \underline{Z}_{q-1} & \underline{Z}_q & & \\ & & & & \ddots & \\ & & & & & \underline{Z}_p \end{array}\right) = \begin{pmatrix} Z1 & 0 \\ 0 & Z2 \end{pmatrix}, \qquad (17)$$

$$G_o = (G1, \quad G2).$$

The submatrices *G1* and *G2* have the dimensions $N_z{}^{x}$ *(q—1)* and $N_z{}^{x}$ *n*, respectively, where N_z is the number of AM inductor slots.

We rewrite the first equation of system (15) in the form

$$(1, \quad F^T) \times \begin{pmatrix} I1 \\ I2 \end{pmatrix} = I1 - F^T \cdot I2 = 0 \quad \text{or} \quad I1 = F^T \cdot I2, \qquad (18)$$

the second equation, after some transformations of the block matrices, is in the form

$$(F \cdot Z1 \cdot F^T + Z2) \cdot I2 + [F \cdot (G1)^T + (G2)^T] \cdot \Phi = F \cdot E1 + E2. \qquad (19)$$

We also transform the product:

$$G_o \cdot I_o = (G1 \cdot F^T + G2) \cdot I2. \qquad (20)$$

As a result, (15) takes the form

$$\left.\begin{array}{l} F \cdot E_1 + E_2 = Z_{\phi} \cdot I_2 + j \cdot \omega \cdot w \cdot K_{\phi} \cdot \Phi, \\ R_M \cdot \Phi = I_c + K_{np} \cdot I_2, \\ Z_c \cdot I_c = V_c \cdot \Phi, \end{array}\right\} \qquad (21)$$

where $Z_{\text{ф}} = F \cdot Z_1 \cdot F^T + Z_2;$ $K_{\text{ф}} = F \cdot (G_1)^T + (G_2)^T;$ $K_{\text{пр}} = G_1 \cdot F^T + G_2,$ and $\boldsymbol{K_{\phi} = K_{np}^T}$.

For a computational experiment to study the influence of the method of connecting coil groups on the characteristics of the machine, it is necessary to form the matrices *F* and G_o. In this case, the matrix *F* is determined only by the method of connecting the branches of the electric circuit of the inductor, and the matrix G_o is determined by the method of connecting the coil groups of the winding.

4. Conclusion

The necessity of integration of the working bodies of technological machines and mechanisms with elements of linear asynchronous electric motors is substantiated. Analysis of electromagnetic processes and optimization of geometric dimensions, winding data of the inductor and electrical parameters can be effectively carried out on a mathematical model of a linear asynchronous motor, represented by a system of three matrix equations describing the state of the magnetic and electrical circuits of the machine, detailed to the level of tooth division and winding section.

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