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SELECTION OF THICKNESS OF MASSIVE STEEL SECONDARY PART OF LINEAR ASYNCHRONOUS MOTOR FOR ELECTRIC DRIVE OF FLAT SHUTTER OF HYDRAULIC STRUCTURES

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Abstract

In the agro-industrial complex, one of the main sectors is water management, which determines production processes in other sectors. In the production processes of hydraulic structures, canals and pumping stations, flat valves are the main water supply equipment. To drive flat gates electrically, it is proposed to use a resource-saving linear disk asynchronous electric motor. A method is outlined for determining the complex electrical resistance of a section of a steel mass of limited thickness. An analysis of the influence of steel thickness on the parameters of the section is presented, and a complex coefficient is proposed that takes this influence into account in calculations. The criteria parameters of the massive steel secondary part of a linear asynchronous motor are determined when choosing its minimum thickness used for a gearless electric drive of a flat valve.

Keywords: *Agro-industrial complex, industry, production, electrical equipment, electric drive, linear motor, secondary element, calculation method.*

Introduction. The agro-industrial complex (AIC), with the possibility of reforming its industries and productions, in particular attracting investments into the industry, introducing resource-saving technologies, as well as providing agricultural producers with modern equipment, is an important part of the country's economy, and includes a large number of industries with production enterprises agricultural products, their processing and delivery to the consumer, as well as providing agriculture and the processing industry with means of production [1-3].

In the structure of the agro-industrial complex there are three main areas, or groups of industries and productions. 1. Agriculture (farming and animal husbandry), forestry and fisheries [4-6]. 2. Industries that process agricultural raw materials (food industry, light industry related to the primary processing of flax, cotton, wool, leather, etc.) [7-9]. 3. Industries that produce means of production for agriculture and industries that process agricultural products (agricultural engineering, tractor manufacturing, mechanical engineering that produces equipment for the food and light industries, land reclamation equipment, mineral fertilizers, etc.). This area includes service industries that provide procurement, storage, transportation and sale of agricultural products [10-12].

Reasonable implementation of reforms for the efficient use of land and water resources, improvement of the water resources management system, modernization and development of water management facilities is a solution to environmental problems. One of the priority areas in the Concept [3] is defined as "modernization and development of water management facilities, automation of management of large water management facilities based on digital technologies, widespread introduction of modern technologies that allow saving energy and other resources, widespread attraction of foreign investment in the field, as well as ensuring targeted and effective use of allocated funds.

Figure 1 shows the relationship between some of the main branches of the agro-industrial complex, production and electrical equipment used with the formulation of problematic measures to save electricity. At the same time, a significant share of the electricity used by the agro-industrial complex is made up of costs aimed at operating electric drives of various mechanisms and machines of the agro-industrial complex [1-12].

In the water management sector of the agro-industrial complex, the strategic directions are the improvement of the water resources management system, the introduction of water-saving technologies for irrigation and cultivation of crops, and the use of effective energy-saving electrical technologies.

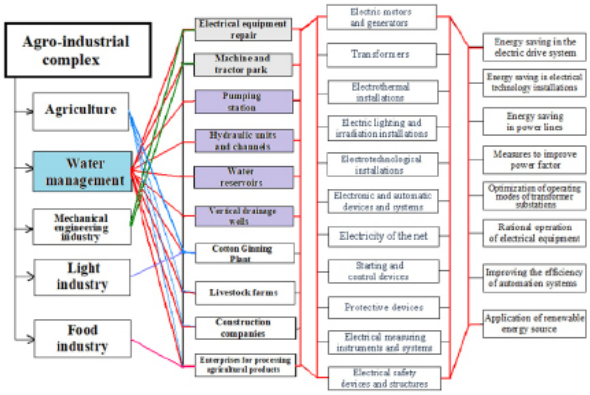


Figure 1. The relationship between industries and enterprises of the agro-industrial complex with electrical technological equipment and the main future problems.

Various mechanical equipment are used in canals, hydraulic structures and pumping stations. One of the main ones are flat metal uniaxial and biaxial valves.

Flat metal gates are produced in widths up to 40 m. The gates are manufactured with manual or electric drives. Motorized valves have a vertically located electric drive shaft. Type of electric drive used: worm gearbox-electric motor [13].

For flat valves, instead of an electric drive with a worm gearbox and bevel gears, it is proposed to use a resource-saving electric drive with a disk linear asynchronous motor (DLAM). Such an electric drive makes it possible to simplify the kinematic circuit, reduce electromechanical losses, and increase the reliability and speed of the electric drive as a whole. Design diagrams of existing geared and gearless linear disk electric drives are shown in Figure 2. In a disk linear induction motor, the secondary element is a metal flat steel disk rigidly attached to the gate nut.

2. Statement of the problem. The secondary part of a linear induction motor (LIM) is often a steel mass of limited thickness. An example of this is a linear motor with a steel reaction bus for the electric drive of a platform feed dispenser and various ground transport systems, a LIM for transporting steel products, a linear electric drive for flat metal gates of hydraulic structures, etc. [4, 14,15].

To study such motors, it is effective to use the method of magnetic equivalent circuits. In this case, it is necessary to know the electrical resistance of the section of the secondary part corresponding to the division interval in the magnetic circuit [4, 14,15].

To determine the parameters of such a section, when the steel thickness is sufficiently large (greater than the penetration depth), simple analytical solutions are known [16,17]. The limited thickness of the steel mass leads to redistribution of the field and changes in parameters. This requires special consideration and consideration when determining the electrical resistance of the secondary element.

The purpose of the study is to analyze the influence of the limited thickness of the massive steel secondary part on its parameters and to develop a method for taking this influence into account.

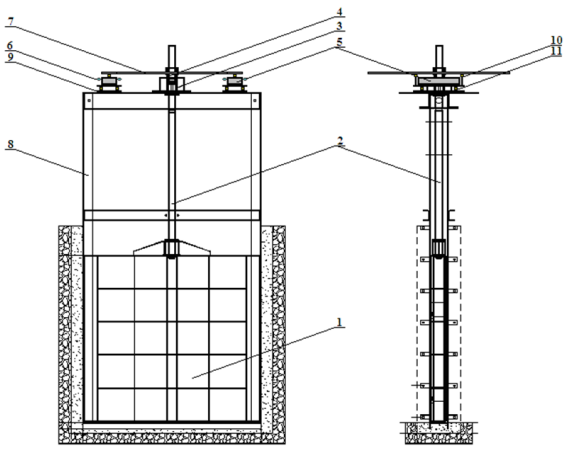


Figure 2. Electric drive of a flat valve with a disk linear asynchronous motor:
1 – flat metal shutter; 2 – cargo screw; 3 – nut; 4 – nut body; 5 – inductor DLAM;
6 – inductor winding DLAM; 7 – secondary element DLAM; 8 – flat shutter frame;
9 – base of the DLAM inductor; 10 – fixing roller; 11 – flexible element.

3. Research method. Analysis of the electromagnetic field in the section of the secondary part and determination of its parameters can be carried out using the numerical finite element method [18]. In this case, it is necessary to take into account a number of features. Since the parameters of the medium do not change in the direction of the x axis, the field is also constant in this direction, i.e. we can consider the region under study as a parallelepiped cut out of an infinite (in the x and z direction) medium, into which a plane wave penetrates, created by a current layer on the surface with a current density $\boldsymbol{J}$. In this case, the division of the region into elements is simplified (Figure 3). As shown in [18,19], the problem is reduced to solving a system of algebraic equations that determine the values of the vector magnetic potential at nodal points, taking into account boundary conditions.

For a plate thickness greater than the penetration depth, the boundary conditions are similar to those adopted in [16,18]:

1. The magnetic induction component $\boldsymbol{B_u}$ is zero;
2. The electric field strength on the outer surface is zero. $\left(\dot{E}_{/y=\Delta_s} = -j\omega\dot{A}_{/y=\Delta_s} = 0\right)$

The first condition is realized by combining the corresponding rows and columns of the system of equations [16,18]. The second means that the values of the vector magnetic potential ($\boldsymbol{A'}$) at nodal points on the outer surface are equal to zero. With a limited plate thickness, less than the depth of field penetration into the array, the electric and magnetic field strengths at the outer boundary of the region under consideration ($\boldsymbol{E_0}$) are not equal to zero. Let us denote the electric field strength at the boundary and the vector magnetic potential as . In this case, the vector magnetic potential at any point can be represented as the sum of two components:

$$\dot{A} = \dot{A}' + \dot{A}_0 \qquad ,(1)$$

where $\boldsymbol{A_0}$ is a constant component (independent of coordinates) throughout the entire region; $\boldsymbol{A}$, $\boldsymbol{A'}$ – component depending on coordinates , determined by the finite element method in the form

$$\dot{A}' = \dot{A}'_l L_l + \dot{A}'_m L_m + \dot{A}'_n L_n \qquad ,(2)$$

where $\boldsymbol{A'_l}$, $\boldsymbol{A'_m}$, $\boldsymbol{A'_n}$ – values $\boldsymbol{A'}$ at nodal points; $\boldsymbol{L_i}$ – geometric coefficient determined by the coordinates of nodal points; $\boldsymbol{i = l, m, n}$ – numbers of the vertices of the triangular element.

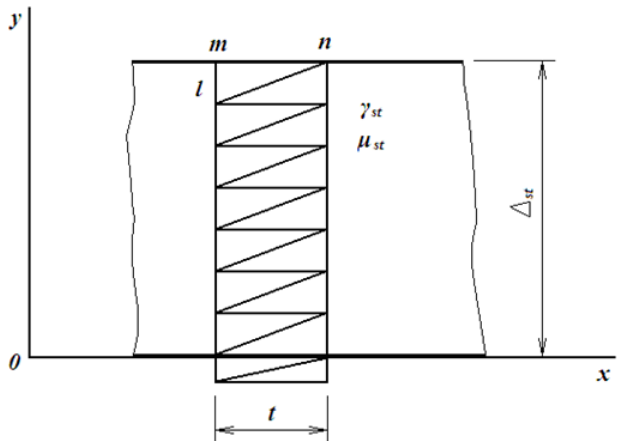


Figure 3. Division of a section of a massive steel secondary part into triangular elements: $\mu_{st} = f(H)$.

Then the expression for the vector potential inside the elementary region can be written as

$$A = A'_l L_l + A'_m L_m + A'_n L_n + A'_0 L_0, \qquad (3)$$

where $\boldsymbol{L_0 = 1}$.

Taking the derivative of the functional with respect to each nodal value Ai in the same way as was done in [19], and equating it to zero taking into account (3), we obtain for each triangular element a system of four algebraic equations, in which one unknown value has been added $\boldsymbol{A_0}$:

$$[\dot{P}]\cdot[\dot{A}]+[\dot{Q}]\cdot[\dot{A}]=[\dot{J}] \quad (4)$$

where

$$[\dot{P}]=\frac{\nu}{4\Delta}\begin{bmatrix} k_1 & k_{12} & k_{13} & 0 \\ k_{12} & k_2 & k_{23} & 0 \\ k_{13} & k_{23} & k_3 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

$$[\dot{Q}]=\frac{j\gamma\omega\Delta}{12}\begin{bmatrix} 2 & 1 & 1 & 4 \\ 1 & 2 & 1 & 4 \\ 1 & 1 & 2 & 4 \\ 4 & 4 & 4 & 12 \end{bmatrix} \quad (6)$$

$$[\dot{A}]=\begin{bmatrix} \dot{A}_1 \\ \dot{A}_2 \\ \dot{A}_3 \\ \dot{A}_0 \end{bmatrix} \qquad [\dot{J}]=\frac{\dot{J}\Delta}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 3 \end{bmatrix} \quad (7)$$

where k_{ij} – coefficients determined by the coordinates of the vertices of the triangular element; Δ – area of the elementary part; ω – angular frequency; γ – electrical conductivity of steel; ν – reciprocal of magnetic permeability $\nu = 1/\mu$.

Combining the equations for each element, we obtain a system of equations that determines the values of the vector magnetic potential at all nodal points, including the value. In this case, instead of the second boundary condition, we write $\dot{A}_{/y=\Delta_3} = \dot{A}_0$, then

$$\dot{A}'_{/y=\Delta_3} = 0, \quad (8)$$

which means that the values A'_i at the nodal points on the outer surface of the secondary part are equal to zero.

Solving the resulting system, we determine the field pattern in the area under consideration and calculate its equivalent electrical resistance

$$z = j\omega\frac{\dot{A}_{/y=0}\cdot L}{\dot{J}\cdot t}, \quad (9)$$

where L and t – width and length of the area.

To analyze the accuracy, a comparison was made of the results obtained by the described method and analytically according to [16,17], at a constant magnetic permeability of steel. The distribution of magnetic field induction along the depth of the array and the electrical resistance of its section are calculated. The results coincide, which allows us to judge the high efficiency of the proposed method.

It is known that the parameters of a steel mass are significantly influenced by the nonlinearity of the magnetic properties of steel and the phenomenon of hysteresis. To take into account nonlinearity, it is necessary to introduce into equation (4) the value ν (in all elements), depending on the corresponding value of induction. In this work, the dependence $\nu = f(B)$ is approximated by two segments of parabolas:

at $B \geq 1.4$ Tl $\nu = 312.7\cdot B6$,

at $B < 1.4$ Tl $\nu = 740.5+6722\cdot(B - 0.7)^4$. (10)

In this case, the problem is reduced to solving a system of nonlinear algebraic equations by successive approximations with refinement at each step of the values of ν (in all elements) and solving a linearized system of equations. The iterative formula has the form

$$\nu_{k+1}^i = f(B_k^i), \quad (11)$$

where ν_{k+1}^i – value of ν in the i-th element at the $k+1$st iteration; B_k^i – value of magnetic induction of the i-th element of the k-th iteration.

The convergence of the iterative process depends on the correct choice of the initial approximation. Convergence can be improved and the process accelerated by introducing a convergence coefficient a. In this case, the iteration formula will change

$$\nu_{k+1}^i = \nu_k^i - a\left[\nu_k^i - f(B_k^i)\right], \quad (12)$$

where ν_k^i – value ν of the i-th element in the k-th iteration.

As the calculations showed, the value $a > 1.1$, like simple iterations $(a = 1.0)$, does not lead to stable convergence of the iterative process. At $a = 0.5\text{-}0.10$, the iteration process converges under almost any conditions. However, the desire to reduce calculation time leads to the need to use other methods to determine the value of ν_{k+1}^i, taking into account its change in previous iterations. One of these methods is the Steffensen method with its modifications [20,21]. The iterative formula of the method has the form (12). In this case, the coefficient a is determined taking into account the previous values ν^i and B^i:

$$a = \frac{\nu_{k-1}^i - \nu_k^i}{\nu_{k-1}^i + f(B_k^i) - \nu_k^i - f(B_{k-1}^i)} \quad (13)$$

As calculations have shown, in some cases the value of a, determined by (13), may be less than 0.1, which will lead to an undesirable decrease in the convergence rate. In this regard, it is advisable to limit the value of a from below. The introduction of the minimum permissible value of a_{min} equal to 0.1 made it possible to sharply reduce the number of steps and, consequently, the calculation time.

Thus, the system of nonlinear equations is solved by the method of successive approximations with linearization at each step. The iterative process is applied directly to the changing parameter and is constructed according to formula (12). The values of the convergence coefficient at each step are determined by expression (13) and are limited from below by the value $a_{min}=0.1$.

The influence of hysteresis can be taken into account [16] by introducing complex magnetic permeability

$$\mu = \mu\cdot\mathring{a}^{-j\psi}, \quad (14)$$

where μ – absolute value of magnetic permeability; ψ – loss angle depending on magnetic field strength.

As shown in [16], when analyzing electromagnetic processes in massive steel bodies, the angle ψ, which depends on the field strength, can be replaced with a constant value equal to the average ψ'. In this work, the

value is adopted $\psi' = 12$.

4. Results and Discussion. In Figure 4 shows the calculated dependences of the complex electrical resistance of a massive steel section on its thickness for unit length and width of the section (frequency 50 Hz) for different values of the magnetic field strength on the H_e surface.

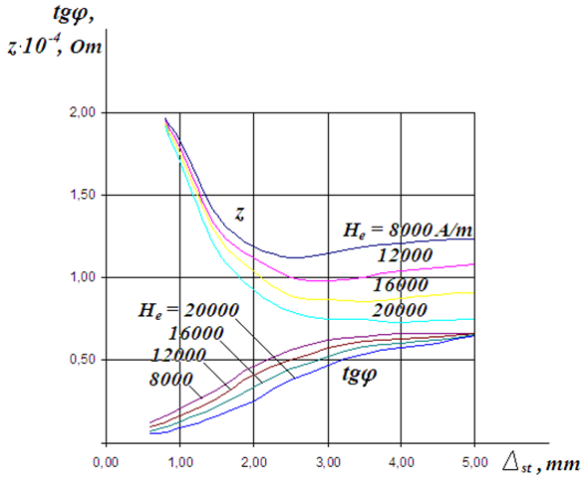


Figure 4. Dependence of parameters of a section of a steel mass on thickness (f = 50 Hz).

From the analysis of the results it is clear that with a plate thickness of $\Delta_{st} > 5$ mm the parameters are the same as with an infinite thickness, but with $\Delta_{st} > 5$ mm they change significantly. As H_e increases, the effect of limited thickness is stronger. This is explained by a decrease in magnetic permeability on the surface of the array μ_e, which leads to an increase in the depth of field penetration into the array. Moreover, even a large thickness is commensurate with the penetration depth, and this leads to a redistribution of the field and a change in parameters. Frequency has a similar effect – as the frequency decreases, the parameters change at a larger plate thickness.

In connection with the above, it is convenient to analyze the dependences of the parameters as a function of the relative thickness of the plate Δ' (the ratio of the plate thickness to the penetration depth Δ_{st}/Δ_{pn}). Figures 5 and 6 show the dependences of the parameters of a section of unit width and length on the frequency and strength of the magnetic field on the surface at different ratios Δ_{st}/Δ_{pn}. The nature of the curves is the same as for an infinite thickness of steel mass. This makes it possible to determine the parameters of an array of limited thickness through the resistance of an infinitely thick array, multiplying it by a complex correction factor k_n, which takes into account the influence of thickness. The modulus and argument of this coefficient are determined by the relative thickness of the plate. In Figure 7 shows the dependences of k_n and $tg\varphi_n$ on the ratio of the plate thickness to the penetration depth. Consequently, the parameters of the array section, taking into account the limited thickness, are determined by the formula

$$z = z_\infty k_n \quad , \qquad (15)$$

where z_∞ - complex resistance of a section of an infinite array, determined taking into account nonlinearity and hysteresis losses.

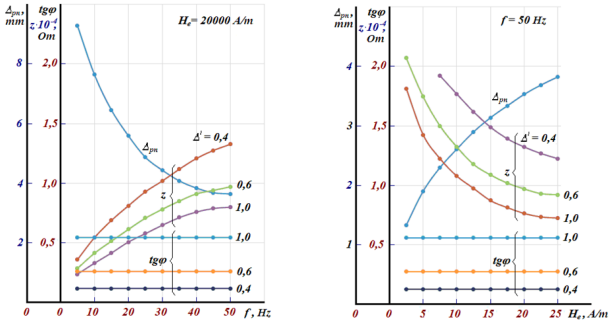


Figure 5. Dependence of the resistance of a section of a steel mass on frequency at different values .

Figure 6. Dependence of the resistance of a section of a steel mass on the magnetic field strength at different values .

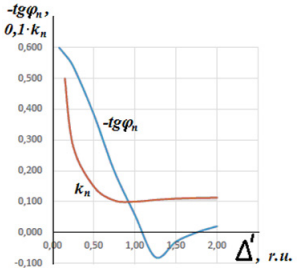


Figure 7. Dependence of kп and t tg⊠п on relative thickness.

5. Conclusions.

1. The agro-industrial complex connects many sectors of the national economy with its products in various forms. Water utilities largely determine production efficiency.

2. A large number of flat valves of various sizes are used in hydraulic structures, canals and pumping stations. The use of a gearless electric drive for them based on a linear asynchronous electric motor with a massive disk secondary element will reduce material consumption by up to 50% and simplify the design of the electric drive.

3. Data were obtained based on the method of magnetic equivalent circuits, indicating a significant influence of limited thickness on the parameters of the steel mass. A complex correction factor has been proposed to take this effect into account in calculations.

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