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Simulation of linear asynchronous electric drive of slow-speed mechanisms of agricultural complex

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Abstract. The agro-industrial complex includes a system of enterprises - the production of means of production for agricultural enterprises and various industries, as well as the sphere of processing, transportation and marketing of raw materials and finished products. The development of rational electric drives corresponding to the drive characteristics of production machines solves the problem of energy and resource saving. The methods are determined by the tasks to be solved in the study of an asynchronous electric drive motor.

1. Introduction

1.1 The urgency of the problem

The agro-industrial complex is one of the largest intersectoral complexes. It includes diverse areas of the economy, including agriculture and certain industries related to agricultural production. At the same time, the Agro-Industrial Complex (AIC) is one of the largest consumers of electricity. Therefore, accurate accounting of the used electricity, as well as its maximum savings in various sectors of the agro-industrial complex, is an important task of modern science. The main works aimed at energy saving are: analysis of the structure and volume of energy consumption, identification of energy losses, establishing the causes of their occurrence and determining ways to eliminate or reduce them; development of energy saving measures; introduction of energy-saving technological processes and equipment; performance of work on forecasting the demand for agricultural products that require less energy; bringing the calculations of the norms of production fuel reserves; collection of information on the availability of local and secondary energy resources and the development of proposals for their use; determination of the list of energy-intensive machinery and equipment to be written off as irrational; application of accounting for consumed energy resources on farms, plots, at each workplace; accounting for excessive consumption of energy resources caused by the inadequate quality of the raw materials, materials and other products received, as well as the low quality of industrial products. The application of measures to eliminate these shortcomings; study and implementation of best practices for the implementation of the energy saving regime; holding incentives for saving energy resources, introducing inventions and rationalization proposals. Figure 1 shows the relationship between some of the main branches of the agro-industrial complex, industries and used electrical equipment with the development of measures to save electricity. At the same time, a significant share in the electricity used by the agro-industrial complex is the cost of operating electric drives of various mechanisms and machines of the agro-industrial complex [1-5].

Features of the development of the domestic agro-industrial complex (AIC) are caused by the close connection of the entire complex with the state of agriculture as its largest and most significant sphere. In turn, the volumes of production of agricultural sectors have an impact on the performance of the agro-industrial complex as a whole. The decline in production in the livestock sector, agricultural engineering is caused by financial problems - the lack of funds does not always allow timely re-equipment and updating of the technical base of economic entities.

1.2 Statement of the purpose and objectives

The use of a large number of different electrified working machines in the technological processes of the agro-industrial complex requires constant improvement of their electric drive (Figure 1).

A rational electric drive is selected on the basis of a detailed analysis of the drive characteristics (technological, kinematic, energy, mechanical, load, inertial) of the working bodies of machines and installations of agricultural production.

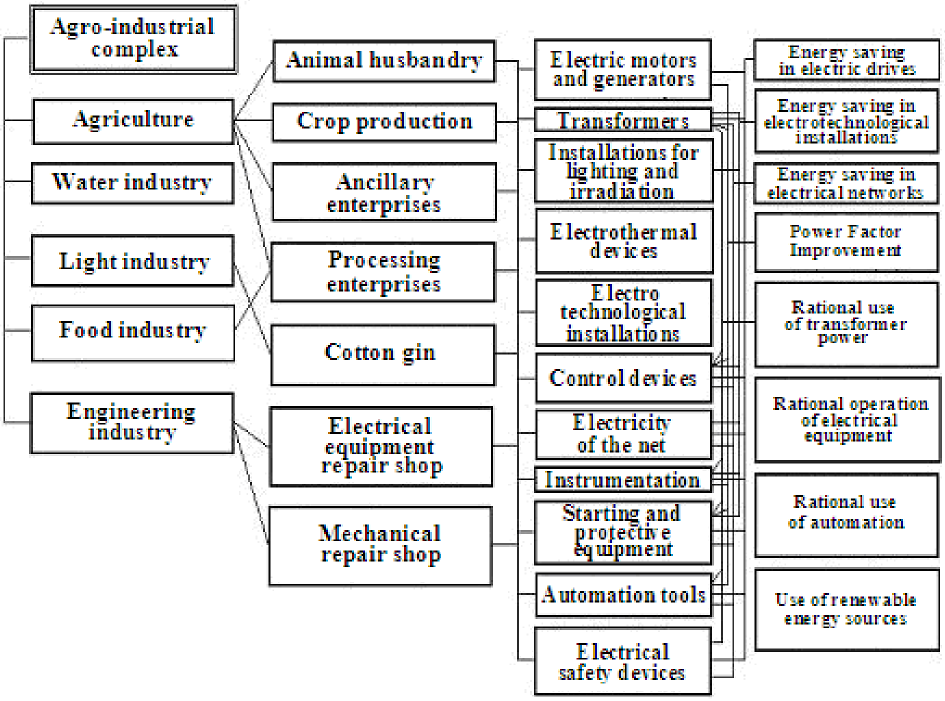

Figure 1. The relationship between the branches of the agro-industrial complex and electrical equipment

Consideration of the main drive characteristics of stationary machines of agricultural production, in particular, 279 crop and 116 livestock machines, showed that they have, respectively, 385 and 260 working bodies and drive motors - 325 and 230 [2-12]. 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, incl. up to 500 min^{-1} – 39.7%, more than 500 min^{-1} – 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, and also without 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%.

The above analysis shows that for a number of working bodies of agricultural machines that perform translational and oscillatory motion, as well as rotational motion with a rotation speed of up to 500 rpm, special electromechanical and electromagnetic converters are promising, incl. an electric drive with an induction motor with an open magnetic circuit (IMOMC) (Figure 2). Such drives make it possible to obtain the necessary technologically specified drive characteristics, to achieve integration with the working body while excluding mechanical converters, as a result of which material and energy consumption is reduced, and the operational reliability of agricultural machines as a whole is increased [2–18].

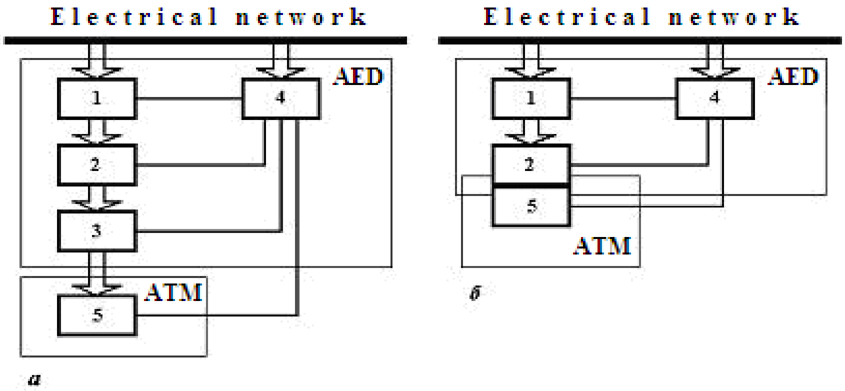

Figure 2. Structural diagrams of traditional (*a*) and linear asynchronous (*b*) automated electric drives (AED): ATM – an actuating technological mechanism; 1 – converting device; 2 – electromagnetic transducer; 3 – mechanical converter; 4 – control system; 5 – working technological body.

Currently, along with the development and widespread use of induction motors with an open magnetic circuit in various areas of the national economy (metallurgy, transport, robotics, textile industry and others), they are increasingly used in agriculture, taking into account its production features and their working conditions. In [13-18], drives based on induction motors with an open magnetic circuit, developed for agricultural machines, are quite diverse in terms of power, speed, operating modes, and designs.

The main disadvantage of electric drives based on induction motors with an open magnetic circuit, which prevents their widespread introduction into production, is low energy performance due to their design features [13-18].

The set of phenomena associated with the finite length of the primary magnetic circuit and the winding zone of an induction machine with an open magnetic circuit ultimately lead to distortion of the traveling magnetic and electric field wave and have a significant impact on its characteristics [13-19].

In the study of induction motors with an open magnetic circuit, researchers use various optimization criteria for their evaluation (specific, energy, traction performance, etc.). Nevertheless, most researchers consider energy (efficiency, power factor or their product) and traction performance to be the main dominant criteria.

Researchers use various methods to improve the energy and traction performance of electric drives based on induction motors with an open magnetic circuit [13-19]. Based on the analysis of publications, ways to improve the energy and traction performance of electric drives based on induction motors with an open magnetic circuit were determined (Figure 3).

2. Methods

The modern practice of designing electrical machines involves the use of mathematical models of varying degrees of complexity at different stages of design. Simpler models that facilitate multivariate calculations are used in machine optimization. In the future, in verification calculations, complex mathematical models are used to refine the parameters and characteristics, which allow taking into account the real operating conditions of the active parts of the machine in various modes [13-19].

In most cases, the linear asynchronous motor (LAM) design task contains: the required traction force F (starting or in operation), the nominal speed of the moving part $\boldsymbol{v_2}$, the voltage U_1 and the frequency f_1 of the supply network. Sometimes the optimal frequency f_1 is subject to choose. One of the main dimensions of the LAM is set or limited: the length ℓ or the width $2b$ of the active zone. Operating conditions determine the minimum non-magnetic gap δ. The overload capacity of the motor and the multiplicity of the starting force, the load curve, the conjugation of the phases of the inductor winding, the design type according to the method of protection from environmental influences and the proposed method of cooling are also set. The terms of reference for the design of the LAM should also contain requirements for the performance of the machine, allowing you to select the criteria for optimality and limitations for optimizing the engine.

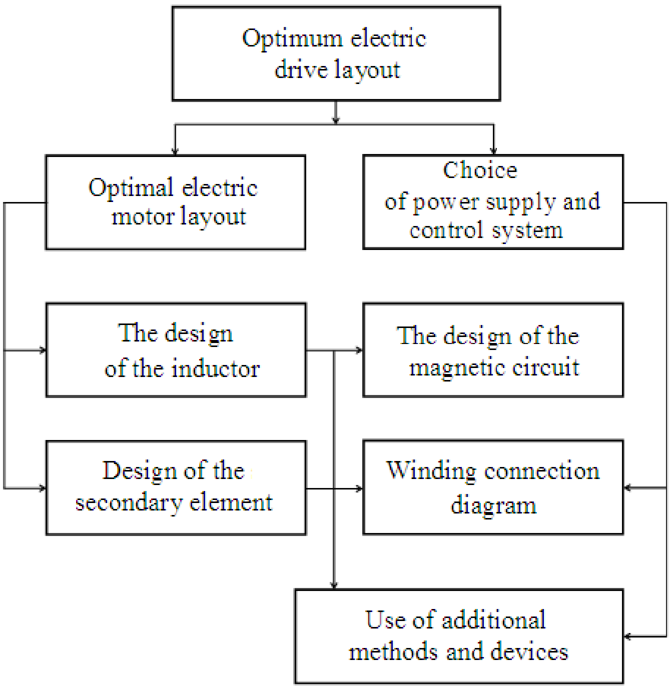

Figure 3. Methods for improving the traction and energy characteristics of an electric drive with an induction motor with an open magnetic circuit (IMOMC)

At the first design stage, during the search calculations, electromagnetic loads *(A_1, B_δ)*, the main dimensions of the machine *(δ, τ, ℓ, 2b)* and the dimensions of the tooth zone of the inductor *(t_z, b_z, b_p, h_n, k_{11}, k_{12})* . The optimization calculation methodology is based on the expressions given in [15-19]. The coefficients included in these expressions can be specified or calculated in advance. The coefficients k_{11} and $k_{12\ that}$ determine the geometry of the tooth zone of the inductor can be taken equal to those recommended for rotating machines: k_{11} = *2.5 ... 4* and k_{12} = *0.4 ... 0.6*. For LAM with relatively large air gaps, the values of the coefficients can be increased: k_{11} =*3 ... 5* and k_{12} = *0.50 ... 0.65*. Filling factor of the magnetic core package with steel k'_c = *0.95…0.97*. The fill factor of the groove with copper $k_{z.m}$ = *0.32 ... 0.36* (for loose windings). Saturation coefficient of the magnetic circuit k_μ = *1.03…1.05*. Winding coefficient k_{rf} = *0.94 ... 0.96*. The air gap coefficient is determined by the expression

$$k\delta = k'_\delta k''_\delta \tag{1}$$

where *k* is the Carter coefficient

$$k'_\delta = t_z \Big/ \left(t_z - \frac{b_n^2}{5\delta + b_n}\right) \tag{2}$$

and the coefficient taking into account the scattering of the main magnetic flux in the air gap [18],

$$k''_\delta = sha\delta/(a\delta) \tag{3}$$

Coefficient k_n, which determines the weakening of the magnetic field on the surface of the secondary element (SE) in comparison with its value on the surface of the inductor, is calculated by the formula [18]

$$k_n = ch a\delta \tag{4}$$

For a bilateral LAM with a non-magnetic highly conductive SE in expressions (2)-(4) δ is half of the total non-magnetic gap.

The coefficient k_{fp}, which determines the length of the frontal part of the inductor winding, depends on the size of the groove and the method of laying the winding. If we characterize the dimensions of the groove by the product of the coefficients $k_{11}\, k_{12} = 0.16 \ldots 0.36$, then we can approximately accept: for grooves of a relatively small area $(k_{11}\, k_{12} = 0.16 \ldots 0.26)$ $k_{fp} = 1.9 \ldots 2.0$ (single-layer winding) and $k_{fp} = 1.6 \ldots 1.7$ (two-layer winding), and for grooves of a relatively large area $(k_{11}\, k_{12} = 0.26 \ldots 0.36)$ – respectively $k_{fp} = 2.0 \ldots 2.1$ and $1.7 \ldots 1.8$.

The rest of the quantities in the expressions relating the parameters of LAM with electromagnetic loads and dimensions are specified in the design task or are to be determined in the course of LAM optimization. Calculations can be carried out in one of the following ways: 1) initial value – heating factor AJ; 2) the initial value is the maximum allowable magnetic field induction at the base of the tooth $B_{z\,max}$. In the first case, the value AJ is set and the linear current load A_1 is determined by the formula

$$A_1 = k_{12}\sqrt{AJk_{3.M}}\,k_{11}t_z \tag{5}$$

Then, according to [15], the magnetic field induction in the air gap B_δ is found and the magnetic field induction at the base of the tooth B_{zmax} is checked. For example, for LAM with rectangular open slots of the inductor B_{zmax} is calculated by the formula:

$$B_{zmax} = \frac{B_\delta k_n}{k_c(1-k_{12})}\left(\frac{1{,}05k_\delta \delta k_{11}}{k_{o\delta}\tau I_{m*}} + 1\right) \tag{6}$$

If $B_{zmax} < B_{z\,add} = 1.7 \ldots 1.9$ Tl, then you can increase the values of the coefficients k_{11} and k_{12}. If Bzmax > $B_{z\,add}$, then it is necessary to reduce the value of AJ or reduce the coefficients k_{11} and k_{12}.

In the second approach, according to the given value B_{zmax} from expression (6), B_δ is found and further according to [15] and (5) the values A_1 and AJ. The heating factor AJ is compared with the maximum allowable value for a given thermal insulation class. If necessary, the values of k_{11} and k_{12} or $B_{z\,max}$ are corrected.

After specifying the electromagnetic loads, the technical and economic indicators of the LAM are calculated, the required number of inductor poles and correction factors are determined to take into account the longitudinal edge effect. The LAM preliminary calculation form is given in [15]. The simplicity of the described calculation algorithm makes it possible to use it both with manual calculation to evaluate a specific LAM variant, and with the use of a computer for optimization calculations. At the same time, the calculation does not require large amounts of computer time even when using the simplest methods of nonlinear programming.

After the completion of the optimization calculations, the winding data of the LAM inductor are found. Number of turns per phase

$$w_1 = \frac{k_E U_{ном}}{4\sqrt{3}k_{o\delta}k_B\alpha_\delta f_1 B_\delta \tau 2b} \tag{7}$$

number of conductors per slot

$$u_n = aw_1/(pq) \tag{8}$$

inductor current

$$I_1 = A_1 t_{za}/u_n \tag{9}$$

current density

$$J = AJ/A \tag{10}$$

rated cross section of effective conductors

$$S_{np} = I_1/J \tag{11}$$

After determining the actual cross section of the conductors of the inductor winding, the fill factor of the groove with copper is specified:

$$k_{з.м} = S_{пр} u_n \big/ (b_n h_n) \quad (12)$$

and, if necessary, the calculation is repeated from formula (5).

Upon completion of preliminary calculations, the refinement of the characteristics and indicators of the LAM, and in some cases the adjustment of some of their parameters, can be carried out using more complex mathematical models, which allow taking into account both the design features of the LAM and the features of their operating modes.

For the verification calculation of multipole LAMs, in which the influence of longitudinal edge effects is small, the analog modeling method described in [15] may turn out to be rational. At the same time, it becomes possible to analyze the characteristics of the LAM with a complex secondary element, to specify the dimensions of the toothed zone of the inductor with different slot configurations, to investigate motors of non-traditional designs, including those with a crushed tooth-slot structure, with magnetic cores obtained using waste-free technology, etc.

The method that uses detailed equivalent circuits of electric and magnetic circuits has the greatest potential in the analysis, which makes it possible to calculate motors with an arbitrary scheme of inductor windings and various power supply circuits (for example, power supply from a thyristor converter), taking into account the discreteness of the SE, including in non-stationary operating modes.

It is known that the choice of one or another calculation method is limited by the capabilities of computer technology, the methods for calculating the LAM proposed in [13-19] in this regard compare favorably with others, since they allow changing the degree of discretization of the mathematical model, and hence changing the complexity of calculations.

3. Results and Discussion

The results of calculating the characteristics of the LAM for various production mechanisms with the corresponding drive characteristics of the production of the agro-industrial complex are given in [1, 4, 8,15-17].

The purpose of the research on mathematical and physical models is to determine the degree of dependence of the traction and energy characteristics of a linear asynchronous motor (LAM) on its design features (shape and material of the magnetic conductors of the inductor and secondary element (SE), their geometric values, the connection scheme of the inductor winding, etc.). According to formulas (5)-(12), the maximum dependence of the traction force of the LAM on its design, the winding data of the inductor and the SE material is visible (the air gap δ, the number of poles of the inductor $2p$, the thickness d_2 and the specific electrical conductivity γ_2 of the non-magnetic SE material, the specific electrical conductivity γ_3 and the magnetic permeability μ_3 of the massive steel SE, which performs the functions magnetic circuit). According to the results, it can be seen that with specific set values of the above criteria (parameters) affecting the traction force, its efficiency is uniquely determined by the winding data of the inductor (the linear current load of the inductor, which, in turn, at $U = const$ depends on the layout of the tooth layer: the number of slots per pole and phase q, the number of turns in coil $w_к$ and parallel branches a) [16, 17, 20].

Naturally, of the above parameters of the inductor (winding data), some take discrete values *(2p, τ, q, wk, a)*. The range of variation of these values is insignificant and structurally limited. For example, the number of poles $2p$ is often made equal to *2, 4* and *6*, and very rarely up to *12* poles. Depending on this, there are quite specific values of the pole division, the number of slots per pole and phase, the number of parallel connected branches-coils of the phase ($\tau = 400/4 = 100$ mm and $400/6 = 66.6$ mm; $q = 1$ or 2; $a = 1, 2$ or 3 and 4).

An increase in the number of poles for a specific accepted length of the inductor magnetic circuit leads to a significant decrease in the starting traction force. The decrease in the value of the traction force of the LAM is associated with a decrease in the length of the pole division τ and magnetic induction in the air gap B_δ. According to the results, it can be seen that the optimal value of the number of poles is $2p = 4$ (Figure 4).

The effect of increasing the air gap is unambiguously known from [13-20], it should be minimal under the conditions of the principle of operation of an asynchronous electric motor. In the calculations, the value of the air gap was assumed to be $\delta = 1$ mm. Regardless of this, Figure 4 shows the dependence of the traction force on the air gap. Naturally, an increase in the value of the air gap leads to a sharp decrease in the traction force of the LAM. This also leads to an increase in the operating current *I* and a decrease in energy indicators (efficiency and power factor).

Of all the above values that effectively increase the traction force of the LAM, the specific electrical conductivity γ_2, γ_3 and the magnetic permeability μ_3 of the SE remain. However, the material of the massive magnetic core of the SE, made of a steel cylinder (specific electrical conductivity γ_3), has an insignificant effect on the traction force of the LAM – up to 5% (Figure 5).

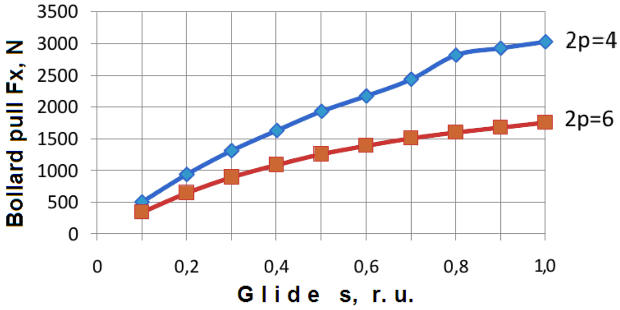

Figure 4. Graph of the dependence of the traction force of the LAM on the number of poles of the inductor

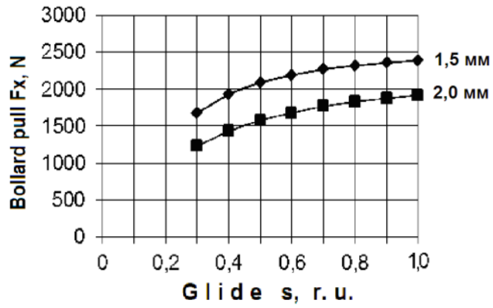

Figure 5. Graph of the dependence of the LAM traction force on the air gap between the inductor and the secondary element (δ = 1.5 mm and δ = 2.0 mm)

The choice and execution of a steel cylinder of a different material (optimization of the magnetic permeability of the steel cylinder μ_3) does not lead to a significant increase in the tractive effort $F_x = f(s)$. The starting tractive effort of the LAM increases within 3 ...4%. Therefore, based on the results of the research, it can be concluded that the values of γ_3 and μ_3 have an insignificant effect on the traction force of the LAM, and a material made of soft magnetic steel can be used to perform the magnetic core of the SE.

The analysis of the calculation results shows (Figure 5 and 6) that increasing the conductivity and magnetic permeability of the steel secondary element, reducing (limiting) the non-magnetic gap does not allow to achieve a significant increase in the traction force F_x [16, 17, 20].

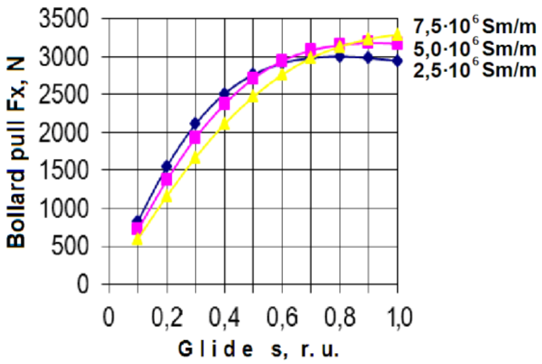

Figure 6. Graph of the dependence of the traction force of the LAM on various values of the electrical conductivity of the magnetic circuit of the secondary element

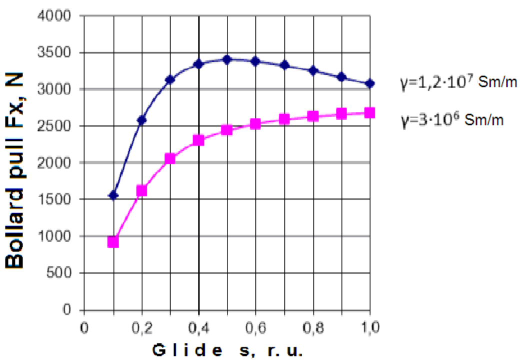

Figure 7. Graph of the dependence of the LAM traction force on the electrical conductivity of the coating material of the magnetic circuit of the secondary element

Summarizing the research, it should be noted that a significant increase in the traction force of the LAM, from the given values $F_x = f\,(2p, \tau, \delta, d_2, \gamma_2, \gamma_3, \mu_3, q, w_k, A, a)$, is determined by the optimal choice of the specific conductivity of γ_2 SE. Figure 5 shows the values of the criterion optimal values of the conductivity of the SE. Experiments carried out on a physical model made it possible to clarify the optimal range of specific conductivity values within $\gamma = 0{,}8\cdot10^7 \ldots 1{,}2\cdot10^7$ *Sм/м*.
Thus, according to the above mathematical model, based on the results of a numerical experiment confirmed by physical models, it is possible to determine with a sufficient degree of accuracy the tendency of the influence of various structures and materials of the inductor and VE, their winding data, on the traction and energy characteristics of the LAM. The main criterion for increasing the traction force of the LAM is the shielding of the SE with a non-magnetic material. By optimizing the electrical conductivity of the SE within $\gamma = 0{,}8\cdot10^7 \ldots 1{,}2\cdot10^7$ Sm/m, it is possible to obtain the necessary traction characteristic of the LAM [16, 17, 20].
Therefore, to increase the traction force of a linear induction motor, it suffices to set the constant values $2p, \tau, \delta, d_2, \gamma_3, \mu_3, q, A, a$. Then we obtain the following dependence $F_x = f\,(K, \gamma_2, w_k)$, where K $= f\,(2p, \tau, \delta, d_2, \gamma_3, \mu_3, q, A, a)$.
The results of the numerical analysis have been verified using physical experiments on special prototype samples and have shown good agreement with the experimental data.

4. Conclusions

The structure of the agro-industrial complex is rather arbitrary and includes various industries and their production, ranging from preparation for production to processing and transportation of raw materials and finished agricultural products. The problems of energy and resource saving are dominant in the most used electrical consumers – asynchronous electric motors in the electric drive system. Linear asynchronous motors meet a set of criteria in the development of electric drives for machines with low-speed and linear movements of working bodies. The proposed calculation method fully defines the features of linear asynchronous motors and allows you to evaluate their energy and traction performance.

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