Linear electric actuator of a sectional plane shut-off of hydrotechnical structures

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Abstract. The sectional design of a flat shutter with an electric drive has lower energy characteristics and improved operational and technological indicators compared to the existing ones for hydraulic structures and channels. The use of linear asynchronous electric motors in linear electric drives allows to simplify the design and reduce material consumption. Modeling of linear induction motors with various designs of the secondary element is carried out on the basis of detailed equivalent circuits for electric and magnetic circuits. Coating a massive or serrated secondary element with a layer of non-magnetic material can increase the traction performance of a linear motor. Comparison of the results of numerical modeling and physical experiments of linear induction motors with various secondary element designs for a sectional flat shutter is the most effective shielded ferromagnetic secondary element.

1. Introduction

A hydraulic structure (HTS) refers to engineering structures that allow for various water management measures, as well as use water resources and prevent the harmful effects of water and liquid waste. This is a whole complex of facilities that ensure the use of water for household, industrial and agricultural purposes. Water supply to agro-industrial facilities (farms, enterprises, industries, etc.) has specific features – the need for water supply of vast territories with unevenly distributed water consumers, water supply over long distances, uneven water consumption during the day, month, quarter and year [1]. Reliable supply of drinking and industrial water to settlements, livestock farms, industrial processing enterprises contributes to the improvement of cultural, living and environmental and economic conditions of the rural population and the development of the agricultural sector in general [2].

Mechanical equipment (gates, movable structures, trash grids and other barriers, lifting and transport mechanisms, assembly and dismantling equipment, devices and systems for maneuvering gates and grids, devices for cleaning grids and removing garbage) is an integral part of hydraulic structures for power, transport, land reclamation and other purposes. As the experience of operating hydroelectric complexes shows, the trouble-free operation of the entire structure often depends on the reliability of electromechanical equipment. Various closures, incl. flat gates are part of the mechanical equipment of hydraulic structures, largely determining the reliability and safety of the waterworks as a whole. Many years of operating experience confirms that emergency situations with gates can be associated with material, environmental and social damage [3].
Research is underway on the development and manufacture of sectional flat doors [4]. Such closures consist of several horizontal flat elements, each section being opened separately if necessary. In this case, the sectional flat gate has the corresponding technological functions: water drainage, collection of debris from the surface or bottom of the water, water discharge and others. In addition, the sectional design of the blinds reduces energy consumption by 30-50%, depending on the technological processes performed.

Despite a fairly large number of studies on the issues of resource and energy saving in hydraulic mechanical installations, this problem has not been fully developed. This is due to the variety and improvement of designs, respectively, the change in the requirements for the electric drive of mechanical installations. On the other hand, the object of research itself - mechanical installations (sectional flat gate) - is a complex system with its inherent properties (increased wear of rubbing and rotating parts, structural breakdowns under dynamic modes and forces, specific operating conditions of the gate, etc.). Therefore, the formulation and solution of scientific and technical problems in this area are relevant and are of great national economic importance [4-6].

For flat sectional gates, it is proposed to improve by replacing the gear electric drive with a resource-saving linear asynchronous electric drive. The use of a linear asynchronous motor makes it possible to simplify the kinematics, reduce electromechanical losses, increase the reliability and speed of the electric drive as a whole.

Figure 1 shows the design of the used electric drive with a mechanical gearbox and a gearless linear asynchronous electric drive. In the cylindrical linear induction motor being developed, the secondary element is a disc or a screw shaft of the shutter.

![Figure 1](image)

**Figure 1.** Structural schemes of gear and linear electric drive flat shutter: 1 - shutter; 2 - shutter rod; 3 - frame; 4 - inductor of a linear cylindrical induction motor; 5 - fixing mechanism

From the literature, the use of various electromechanical and electromagnetic systems of direct action (linear asynchronous motors, induction pumps, trays for pumping liquid media, electromagnetic devices for their mixing, operational control and management of various parameters, etc.) for the implementation of technological processes in the production of the agro-industrial complex [5-12]. Simplified and refined calculations of the electrodynamic forces of an inductor acting on a secondary body of various geometrical shapes, structures, and materials are based. In computational models, both an infinitely extended body and a body of finite length and width with a different cross-sectional shape are considered.
2. Research Methods
The design model allows you to analyze electromagnetic devices with closed and open inductors. In the case of a finite length of the inductor, it is necessary to take into account the effects caused by the non-sinusoidal wave of the traveling magnetic field, the influence of its spatial and temporal harmonics associated with the features of modeling the surfaces of the inductor and the secondary body.

A linear asynchronous motor (LAM) is used in the mechanisms of translational or reciprocal motion and performs not only the conversion of electrical energy into mechanical energy, but also other functions [5-12]. The secondary element (SE) of the engine can be massive and have limited dimensions. To select the parameters of LAM, calculation methods are needed that take into account the peculiarities of its design. Obviously, the degree of complexity of the methods used at different stages of the calculation can be different. So, at the stage of evaluative calculations, simple techniques are needed that take into account the design features of the LAM by means of correction factors based on the well-known T-shaped equivalent circuit. As the accuracy of the description of the electromagnetic processes of such machines increases, their mathematical models become more complicated. The most accurate mathematical model of LAM with various designs of a massive secondary element can be obtained using finite difference methods and finite elements. However, this approach unduly complicates the calculations [12-14].

A sufficiently high degree of accuracy with relative simplicity of calculation can be obtained using equivalent circuits of the magnetic and electrical circuits of a machine detailed to the level of tooth division [12-15]. In this case, the main features of the machine are taken into account at the stage of determining the parameters of equivalent circuits, the elements of which correspond to sections of the design of the value of the tooth division.

At the first stage, the parameters and characteristics of the circular analog of LAM are calculated for a given heating factor \( A_j \). Specific force per unit of active surface

\[
F_{sp} = B_j^2 (\alpha \nu / 2 \mu_0) J_m (Z_{2s}^M) ,
\]

where \( \alpha = \pi / \tau \), \( B_j \) is the induction in the air gap \( \delta \).

The magnetic resistance of a non-magnetic continuous SE in fractions of the magnetic resistance of the gap

\[
Z_{2s}^M = j \varepsilon_0 \delta ,
\]

where \( \varepsilon_0 \) is the electromagnetic Q factor of the machine [16], \( \delta \) is slip.

In the case of ferromagnetic secondary element

\[
Z_{2s}^M = (0.52 + j0.85) \varepsilon_M ,
\]

where \( Z_{(i)}^M \) and \( K_L \) are determined according to [17, 18], and \( Z_{(i)}^M \) depends on the magnetic field strength on the surface \( H_0 = \alpha F_2 / 2 \sqrt{2} \), and the magnetomotive force \( F_2 = \varepsilon_M 2 \delta \delta / \mu_0 \).

Gap induction

\[
B_j^2 = (A_j / I_2^2) \cdot (\mu_0^2 \tau^3 / (10 \delta^2 (q / 2))) ,
\]

where \( I_2 = 1 + Z_{2s}^M \), \( q \) is the number of grooves per pole and phase.

The electrical parameters of the secondary circuit are as follows:

\[
Z_z = j K_z / Z_{2s}^M ,
\]

where \( K_z \) binds electrical and magnetic resistances [17,18].

Incomplete overlap of the inductor by the secondary element is taken into account when determining the \( \varepsilon \)-parameters of the primary circuit in the T-shaped equivalent circuit [12,16,19,20]. At the secondary stage of numerical research, engine equivalent circuits detailed before tooth division are used. Within the framework of the same approach, the degree of approximation can be different, since the model can be either dynamic or static. In the first case, the displacement of the edge of the
secondary element is taken into account by recalculating the parameters of equivalent circuits at each step of integration of the differential equations describing the electromechanical transient, and in the second, this displacement is modeled by a sequence of states, in each of which the electromagnetic process is considered established, and only the equation of motion is integrated.

A dynamic model can be represented by the following system of equations:

\[
\begin{align*}
U &= R\text{}_M I\text{}_M + LDI\text{}_M - E_{\phi}; \\
R\text{}_M F_M &= I_1 + I_2; \\
Z\Delta I_1 + Z2I_2' &= V1DF_M + V2F_M; \\
M(du/dt) &= F_T - F_R,
\end{align*}
\]

where \(U\) – is the vector of applied stresses; \(I\text{}_M\) – vector of independent phase currents; \(D = d / dt\) – time differentiation operator; \(R, L\) – matrix of active resistances and inductances of the phases of the inductor winding; \(E_{\phi} = -U_{\phi}\) vector in contours under consideration; \(R\text{}_M\) – matrix of magnetic resistances; \(F_M\) – is the vector of magnetic fluxes of the yoke of the inductor; \(I'\) - is the vector of currents of the equivalent rods of the SE; \(I=K_{giv}I\text{}_M\) – vector of groove currents of the inductor; \(K_{giv}\) – a matrix of reduction of phase currents to groove; \(Z1, Z2\) – matrix of the formation of stresses in the circuits of the electrical circuit of the secondary element; \(V1, V2\) – EMF formation matrix in the circuits of the electrical circuit of the secondary element; \(M, \nu\) – mass and speed of the moving part of the drive; \(F_T, F_R\) – traction and resistance to movement.

The solution of system (6) can be written as

\[
(K_{giv}(I\text{'}_M)^{-1}K_{M}\text{}_M + V1)DF_M = A2; \\
A2 = K_{giv}(I\text{'}_M)^{-1}(U - R\text{}_M I\text{'}_M) + Z2(K_{giv}I\text{'}_M - R\text{}_M F_M) - V2F_M; \\
F_{M1+\Delta M} = F_{M1} + \Delta t(DF_M)_1; \\
I_{t1+\Delta t} = I_{t1} + \Delta t(DI\text{'}_1)_1; \\
I_{t1+\Delta t} = R\text{}_M F_{M1+\Delta t} - K_{giv}I_{t1+\Delta t}; \\
(D\nu)_1 = ((F_1 + F_{t1+\Delta t})/2 - F_R)/M; \\
\nu_{t1+\Delta t} = \nu_1 + \Delta t(D\nu)_1.
\]

It is easy to pass from system (6) to a static model in which it is assumed that all electromagnetic quantities change in time according to a sinusoidal law. The last assumption allows us to go from instantaneous values of quantities to their complex amplitudes and algebraize (6), replacing the differentiation operation by multiplying by \(j\omega\), where \(\omega\) – is the circular frequency. As a result, we get

\[
\begin{align*}
U &= Z\text{'}M I\text{'}_M + j\omega K\text{'}_{MF} F_M, \\
R\text{'}_M F_M &= I_1 + K_{giv}I\text{'}_M, \\
Z\text{'}I_1 &= V\text{'SF}_M, \\
M(du/dt) &= F_T - F_R,
\end{align*}
\]

where

\[
Z\text{'} = R + j\omega L, \quad Z\text{'}_1 = Z1 + j\omega Z2, \quad V\text{'_1} = V1 + j\omega V2.
\]

System (7) can be reduced to

\[
\begin{align*}
AI_F_M &= A2; \\
MD\nu &= F_T - F_R
\end{align*}
\]

where

\[
AI = Z\text{'}(j\omega K_{giv}(Z)^{-1} K_{MF} F_M + R\text{'}_M) + V\text{'}, \quad A2 = Z\text{'}K_{giv}(Z)^{-1} U.
\]
Solution (6) or (8) allows you to find the flow in the yoke, and then the distribution of the currents of the equivalent SE rods for each position relative to the inductor. Then, the asynchronous component of the force is determined as a result of the interaction of the SE currents with the magnetic field in the gap. In the case of magnetic SEs of limited extent, the magnetic force is found using the energy method.

3. Results and Discussion

The main goal of the research is to determine the traction and energy characteristics of a linear asynchronous motor (LAM) for given geometric values. In this case, the traction force largely depends on the design parameters (the number of poles $2p$, air gap $\delta$, thickness $d_2$ and electrical conductivity $\gamma_2$ of non-magnetic material of the secondary element (SE), electrical conductivity $\gamma_3$ and magnetic permeability $\mu_3$ of a massive steel secondary element acting as a magnetic circuit). For specific values of these parameters, the traction force will be uniquely determined by the linear current load of the inductor, which, in turn, at $U = \text{const}$ depends on the layout of the tooth layer: the number of grooves per pole and phase $q$, the number of turns in the coil $w_k$ and parallel branches $a$ [21].

Obviously, among these parameters, some accept only discrete values $(2p, \tau, q, w_k, a)$; the range of variation of these values is insignificant. For example, the number of poles can only be considered $2p = 4$ or $2p = 6$; hence the quite specific pole divisions $\tau = 400/4 = 100$ mm and $400/6 = 66.6$ mm; $q$ is 1 or 2; $a = 1, 2$ or 3 and 4.

With an increase in the number of poles, the starting pulling force decreases significantly. The drop in traction is associated with a decrease in the pole division $\tau$ and magnetic induction in the air gap $B_\delta$. Therefore, $2p = 4$ is optimal (Figure 2).

Changing the air gap does not make sense, it should be minimal according to the operating conditions of the electric motor. In our version, $\delta = 1$ mm. However, Figure 3 shows the dependence of traction on the air gap. They clearly show a drop in effort with an increase in clearance.

At the same time, the operating current $I$ increases and the energy indicators decrease. Only the electrical conductivity $\gamma_2$, $\gamma_3$ and the magnetic permeability $\mu_3$ of the secondary element remain relatively freely varying.

The change in the electrical conductivity of the steel cylinder $\gamma_3$ (Figure 4) on the traction force of the LAM has an insignificant value – up to 5%.

![Figure 2. The traction characteristic of LAM depending on the number of poles](image1)

![Figure 3. The traction characteristic of LAM at various values of the air gap ($\delta = 1.5$ mm and $\delta = 2.0$ mm)](image2)

A change in the magnetic permeability $\mu_3$ of the steel cylinder does not lead to significant changes in the traction force $F_x = f(\delta)$. Starting pulling force varies within 3 ... 4%. Therefore, taking into account the insignificant effect of $\gamma_3$ and $\mu_3$ on the traction force of LAM, the steel cylinder can be made of soft magnetic steel.

An analysis of the graphic dependences (Figures 3 and 4) leads to the conclusion: changes in the conductivity and magnetic permeability of the steel secondary element, limitations of the non-
magnetic gap, it is impossible to achieve a significantly visible increase in traction force $F_х$, due to their small influence [21].

The main parameter by which it is possible to achieve an effective increase in traction force $F_х = f(2p, τ, δ, d_2, γ_2, μ_3, q, w_k, A, a)$ LAM is the electrical conductivity $γ_2$ of the secondary element. Figure 5 shows the optimal extreme conductivities. The experiments carried out on a physical model made it possible to determine the most suitable conductivity within $γ = 0.8 \times 10^7 ... 1.2 \times 10^7 \text{Sm/m}$.

Thus, on the basis of the results of a numerical experiment using the calculation method described above, it is possible to determine with a sufficient degree of accuracy the trend of change in traction and energy indicators for various designs of a linear induction motor. The main indicator for increasing traction is shielding a non-magnetic material of the secondary element. By changing its electrical conductivity within $γ = 0.8 \times 10^7 ... 1.2 \times 10^7 \text{Sm/m}$, it is possible to obtain the necessary traction characteristic [21].

Therefore, to increase the traction force of a linear induction motor, it suffices to set the constant values $2p, τ, δ, d_2, γ_2, μ_3, q, A, a$.

Then we obtain the following dependence $F_х = f(K, γ_2, w_k)$, where $K = f(2p, τ, δ, d_2, γ_3, μ_3, q, A, a)$.

4. Conclusions

1. Induction electromechanical converters are the most effective for operational control and automatic regulation of water supply parameters for technological processes in the Agro-industrial complex.

2. The most effective method for calculating electromagnetic processes in linear induction motors is a numerical method based on detailed electrical and magnetic equivalent circuits. The mathematical model allows you to analyze the electromechanical transients of an induction converter when powered from a voltage source of any form, specified analytically or in tabular form.

3. In the mathematical model, the nonlinear elements in the electric circuit of the inductor are formed by the nonlinearity of the parameters of its equivalent circuit, when calculating for each moment of time according to a given algorithm. Various modes, power consumption are modeled by the corresponding formation of the vector of applied voltages. A numerical method for calculating the static characteristics of an induction motor with a ferromassive secondary element, based on detailed primary and secondary electrical and magnetic equivalent circuits using complex amplitudes of sinusoidal values.

4. The results of a numerical experiment allow us to conclude that, with a sufficient degree of accuracy, the tendency for changes in traction and energy indicators is determined for various designs of a linear induction motor. The main indicator for increasing traction is shielding a non-magnetic material of the secondary element.
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