

SHIP'S MECHATRONIC ELECTROHYDRAULIC STEERING ACTUATOR WITH "TRANSVECTOR" CONTROL SYSTEM

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ABSTRACT

Ship's active maneuvering is carried out by the electrohydraulic (EH) drive of the steering gear. The maneuvering properties of the object completely depend on the proper operation of the drive control system. To move the rudder blade, it is necessary to regulate the change of oil flow from the pump to the steering gear, which is carried out by a special controlling device - a servomechanism. In order to obtain structural stability in the controlled and automatic modes of operation, feedback is provided by the servomotor, which in most cases is a short-circuited rotor motor. The main problem in creating an automatic control system/mechatronic system is the optimization of its structure and parameters taking into account certain criteria of the system components. It is possible to provide the regulation accuracy and energy efficiency automated electrical equipment by means of the control system "transvector" which is necessary for controlling the ship's steering drives. The article represents the discussion about the effectiveness of using the "transvector" control system for a short-circuited rotor motor, and as a result it is possible to provide the ship's steering mechatronic system with precise steering in the shortest possible time, which will minimize the ship's deviation from the course.



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1. INTRODUCTION

There are great variety of steering electric drives used on modern ships. This depends on the structural characteristics of the operating body, the operating mode of the main electrical equipment, the connection between the actuator electric motor and the steering gear, the degree of control automation, etc.

The actuator motor continuously turns the pump, which ensures the flow of working fluid corresponding to the steering angle in the electro-hydraulic steering gear drive. Fork Type, Rotary Vane and Swing Cylinder electrohydraulic steering drives are used on modern vessels (Geddavalasa & Mallikarjuna, 2019). According to the principle of regulating the oil supply to the steering gear, constant and variable supply pumps are used. electromechanical servomotors are used in more

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powerful systems. Regulation with special servomotors is characteristics for powerful systems. Relatively simple and inexpensive short-circuited rotor asynchronous motors (Induction Motor) are used as actuators/servomotors. They are operated by remote control.

The maneuverability of the electrohydraulic (EH) steering drive fully depends on the proper operation of the drive control system (Lecomble & Schmitt, 2019). In order to obtain structural stability during the safe operation of the rudder blade, feedback is provided not by the steering gear, but by the servomotor. Figure 1 shows the structural diagram of the EH steering drive (Babaev & Yagodin, 1986).

The main problem of creating an automatic control system is the optimization of its structure and parameters taking into account certain criteria of the components of this system.

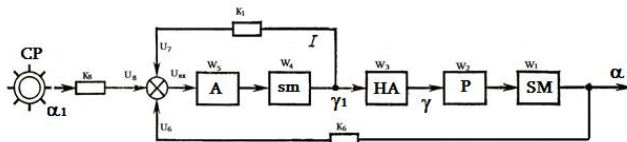


Figure. 1. Structural diagram of the steering gear drive with electrical feedback. CP– control post (ship's wheel); A– amplifier; sm – servomechanism (changing the oil supply to the hydraulic steering machine); HA – hydraulic amplifier; P– pump; SM – steering machine;

2. PREREQUISITION AND MEANS OF SOLVING THE PROBLEM

2.1 Theoretical model

One of the best directions for the development of an automatic ship course control system is the construction of an optimal system, which is described by a system of equations:

$$\left. \begin{aligned} x' &= g(x, f, u, t), \\ x(0) &= x_0 \end{aligned} \right\} \quad (1)$$

Where, g – vector function describing the dynamic properties of the object; x – vector function of the object coordinate; f – vector function of external disturbing influences; u – vector function of control; t – time. Usually, optimum control means the sum of two control types:

$$u_{opt} = u_{sf} + u_c. \quad (2)$$

Where, u_{sf} – software control, which is built according to the data of the g, f functions;

u_c – control, which compensates the random deviations from the optimal trajectory.

When the ship deviates from a given course, a voltage is

generated at the input of the summing element, which is proportional to three parameters:

$$U_\Psi = K_\varphi \Delta\Psi; \quad U_d = K_d \frac{d(\Delta\Psi)}{dt}; \quad U_{in} = K_{in} \int \Delta\Psi dt \quad (3)$$

Where, $\Delta\Psi$ – is the angle of deviation of the ship from the course; $\frac{d(\Delta\Psi)}{dt}$ – the derivative of the deviation angle; $\int \Delta\Psi dt$ –the integral of the deviation angle.

At the same time, the summing element is fed with a control signal corresponding to the rudder angle in the form of a voltage $U_\alpha = K_\alpha \alpha$. The voltage U_α is always in the opposite phase of the main control signal. The speed and accuracy of the control signal formation in the summing element determines the quality of the ship's automatic course control.

2.2 Experimental device

In automatic control units powered by alternating current with a frequency of 50/60 Hz, an asynchronous squirrel-cage motor is most often used as the actuator (Katsman, 1987; Akin et al., 2006; Pyrhonen et al., 2016).

The development of automated electrical equipment, in particular thyristor control drives, allows us to control the existing coordinates of an alternating current machine. With the “transvector” control system, it is possible to provide the regulation accuracy required for controlling ship steering drives.

The “transvector” control system, or vector control, was developed in the 70s–80s of the 20th century. In the most widespread vector control system, the main vector of the motor torque or the rotor flux vector is used as the reference vector.

The system of equations for the voltage and current vectors of the stator and rotor of short-circuited rotor asynchronous motors is written as follows:

$$\begin{aligned} \bar{i}_1(t) &= i_{a1}(t) + i_{b1}(t)e^{j\frac{2\pi}{3}} + i_{c1}(t)e^{j\frac{4\pi}{3}} \\ \bar{i}_2(t) &= i_{a2}(t) + i_{b2}(t)e^{j\frac{2\pi}{3}} + i_{c2}(t)e^{j\frac{4\pi}{3}} \\ \bar{u}_1(t) &= u_a(t) + u_b(t)e^{j\frac{2\pi}{3}} + u_c(t)e^{j\frac{4\pi}{3}} \end{aligned} \quad (4)$$

Where, $i_{a1}(t)$, $i_{b1}(t)$, $i_{c1}(t)$ are the values of the stator current, and $i_{a2}(t)$, $i_{b2}(t)$, $i_{c2}(t)$ are the values of the rotor, $u_a(t)$, $u_b(t)$, $u_c(t)$ are the values of the stator voltage. It is worth noting that the nature of the variation of the currents can be of any kind, although their sum is equal to zero at any moment of time (Kalashnikov, 2003; Liu et al., 2015). Taking into account the electrical and mechanical parameters, the system of differential equations for an asynchronous motor is written as follows:

$$\begin{aligned} R_1 \bar{i}_1 + L \frac{d\bar{i}_1}{dt} + L_m \frac{d}{dt}(\bar{i}_2 e^{j\varepsilon}) &= \bar{u}_1 \\ R_2 \bar{i}_2 + L_2 \frac{d\bar{i}_2}{dt} + L_m \frac{d}{dt}(\bar{i}_1 e^{-j\varepsilon}) &= 0 \\ J_\Sigma \frac{d\omega}{dt} &= m - m_c = \frac{2}{3} p_n L_m \operatorname{Im}(\bar{i}_1 \bar{i}_2 e^{j\varepsilon}) - m_c \\ \frac{d\varepsilon}{dt} &= \omega \end{aligned} \quad (5)$$

Where, $L_1 = (1 + \sigma_1) \cdot L_m$ and $L_2 = (1 + \sigma_2) \cdot L_m$ are the inductances of the stator and rotor windings, Hn; L_m - the inductance between the stator and rotor windings, Hn; $\sigma = 1 - L_m^2 / (L_1 \cdot L_2)$ - is the total dissipation factor of the motor; R_1 and R_2 - are the active resistances of the stator and rotor windings, ohm; J_Σ - is the total moment of inertia of the mechanical part of the electric motor, kg.m²; M and M_c - are the electromagnetic and mechanical resistance (load) moments developed by the motor, kgm; ω - is the angular velocity of rotation of the rotor, rad/s; ε - is the angle of rotation; p_n - is the number of pairs of poles.

In order to simplify the calculation formulas, let us assume that the phase windings of the stator and rotor of the motor are symmetrical, the magnetization characteristic of the magnetic system is linear from site to site, the active resistance of the magnetization circuit is zero, and for any value of the frequency of the voltage applied to the stator windings of the motor, there is no current leakage effect (Meshcheryakov & Voyekov, 2017). These assumptions allow us to constantly calculate the parameters of the motor replacement scheme, with a slight decrease in their accuracy (the error caused by such assumptions usually does not exceed 5%).

In the analysis of electric drive systems, a linear transformation of the system of calculation equations is adopted so that the effective values are replaced by new variables, provided that the new mathematical description of the physical object is adequate to the original.

In these conditions, it is preferable to write an asynchronous motor in a coordinate system rigidly connected to the stator, in a system rigidly connected to the rotor, or in a magnetic field system rotating with an angular velocity relative to a stationary stator. Such a transformation allows us to significantly simplify the mathematical description of the processes of electromechanical energy conversion (Chikhi et al., 2010; Venu Gopal, 2017).

Consider the conditions for regulating the electromagnetic moment of an asynchronous short-circuited motor from its frequency converter in the quadratic form.

The equations of dynamic processes of an asynchronous motor written in complex form with respect to the x, y

axes have the following form:

$$\begin{aligned} \bar{u}_1 &= R_1 \bar{i}_1 + \frac{d\bar{\Psi}_1}{dt} + j\omega_1 \bar{\Psi}_1 \\ 0 &= R_2 \bar{i}_2 + \frac{d\bar{\Psi}_2}{dt} + j(\omega_1 - \omega) \bar{\Psi}_2 \\ m &= \frac{3}{2} p_n L_m \operatorname{Im}(\bar{i}_1 \bar{i}_2^*) \\ \bar{\Psi}_1 &= L_1 \bar{i}_1 + L_m \bar{i}_2 \\ \bar{\Psi}_2 &= L_2 \bar{i}_2 + L_m \bar{i}_1 \end{aligned} \quad (6)$$

When controlling an asynchronous electric motor, they try to maintain the constancy of the stator or rotor flux. When maintaining the stator or rotor flux in a steady state, the dependences of the mechanical characteristics of the motor are constant. In this case, it does not matter what will be received as a control signal - the values of the stator current or voltage.

The system of equations written in complex form with respect to the axes x, y, of an asynchronous motor in a steady state has the following form:

$$\begin{aligned} u_{1x} &= \frac{1}{T_1'} \cdot \psi_{1x} - \Omega_1 \cdot \psi_{1y} - \frac{k_2}{T_1'} \cdot \psi_{2x}, \\ 0 &= \frac{1}{T_2'} \cdot \psi_{2x} - \Omega_2 \cdot \psi_{2y} - \frac{k_1}{T_2'} \cdot \psi_{1x}, \\ 0 &= \frac{1}{T_2'} \cdot \psi_{2y} - \Omega_2 \cdot \psi_{1x} - \frac{k_1}{T_2'} \cdot \psi_{1y}, \\ I_{1x} &= \frac{1}{L_1'} \cdot \psi_{1x} - \frac{k_2}{L_1'} \cdot \psi_{2x}, \\ I_{2x} &= \frac{1}{L_2'} \cdot \psi_{2x} - \frac{k_1}{L_2'} \cdot \psi_{1x}, \\ I_{1y} &= \frac{1}{L_1'} \cdot \psi_{1y} - \frac{k_2}{L_1'} \cdot \psi_{2y}, \\ I_{2y} &= \frac{1}{L_2'} \cdot \psi_{2y} - \frac{k_1}{L_2'} \cdot \psi_{1y} \end{aligned} \quad (7)$$

In steady state, if we keep the stator flux constant and ensure orientation with respect to the x axis, we obtain the following for the rotor flux ($\bar{\Psi}_1 = \Psi_{1x} = \text{const}, \Psi_{1x}' = 0, \Psi_{1y} = 0$) components:

$$\begin{aligned} \psi_{2x} &= \frac{k_1}{1 + \Omega_2^2 \cdot (T_2')^2} \cdot \Psi_1 \\ \psi_{2y} &= \frac{k_1 \cdot \Omega_2 \cdot T_2'}{1 + \Omega_2^2 \cdot (T_2')^2} \cdot \Psi_1 \end{aligned} \quad (8)$$

As a result, for the electromagnetic torque of the motor, we obtain:

$$\begin{aligned} m &= \frac{3}{2} p_n \frac{k_2 k_1}{L_1'} \Psi_1^2 \frac{1}{\Omega_2 T_2' + \frac{1}{\Omega_2 T_2'}} = \frac{2m_{kp}}{\frac{\Omega_2}{\Omega_{2kp}} + \frac{\Omega_{2kp}}{\Omega_2}}, \\ \Omega_{2kp} &= \frac{1}{T_2'} = \frac{R_2}{\delta L_2}, \\ m_{kp} &= \frac{3}{4} p_n \frac{k_2 k_1}{L_1'} \Psi_1^2 \end{aligned} \quad (9)$$

The mechanical characteristic of an asynchronous motor is given by the following equation: When the frequency of the supply voltage changes and the stator flux is kept constant, the mechanical characteristic changes along the ordinate axis parallel to the natural characteristic with the change in the frequency of the converter. At the same time, its slope and the value of the critical moment remain constant.

Let us assume that in the steady-state mode the rotor flux is constant and coincides with the x-axis in the direction ($\psi'_2 = \psi'_{2x} = |\psi_2| = \text{const}$, $\psi'_{2x} = \psi'_{2y} = 0$), then from expression (9) for the components of the rotor flux we obtain:

$$\begin{aligned}\psi_{1x} &= \frac{1}{k_1} \cdot \psi_2 \\ \psi_{1y} &= \frac{\Omega_2 \cdot T'_2}{k_1} \cdot \psi_2\end{aligned}\quad (10)$$

Accordingly, the electromagnetic moment of the motor is equal to:

$$M = \frac{3}{2} \cdot p_n \cdot \frac{k_2 \cdot \Omega_2 \cdot T'_2}{L'_1 \cdot k_1} \cdot \psi_2^2 = \frac{3}{2} \cdot p_n \cdot \psi_2^2 \cdot \Omega_2 \quad (11)$$

As can be seen from figure (11): the torque developed by the motor is proportional to the slip, the mechanical characteristic does not have an unstable region, the motor's overload capability during $\psi_2 = \text{constant}$ speed regulation is limited only by the inductance of the machine's magnetic system and the voltage supply of the frequency converter (Chistyakov et al., 2011).

Thus, when the stator current vector is oriented relative to the rotor flux vector, an asynchronous motor with a short-circuited rotor has a mechanical characteristic similar to a DC-independently excited machine (Figure 3).

Because a short-circuited rotor induction motor has a small rotor moment of inertia and a large overload capacity in terms of torque when controlled by frequency than a DC machine, the induction motor has a much higher speed when controlled by frequency, which in our case is especially important for the optimal management of dynamic processes occurring in the moving-mechanical part of the ship's steering gear.

In the steady state, the projection of the stator current onto the rotor magnetic flux vector and its extension (the stator current flux-generating component) is proportional to the rotor magnetic flux vector, and the component of the stator current perpendicular to it at a constant magnetic flux is proportional to the torque turning the motor (the stator current torque-generating component). In practice, the control system can be implemented in two ways with this approach. First method - the method of orienting the stator current to the direction of the rotor

magnetic flux requires direct measurement of the magnetic flux in the motor air gap, or the creation of an appropriate mathematical model for an asynchronous machine and the appropriate calculations based on it. In addition, it is worth noting that in technical implementation, many options based on field-based speed regulation of an asynchronous motor require certain measures to take into account the difference between the real and calculated parameters of the asynchronous motor. The second method is based on the orientation of the stator current or voltage vector with respect to the rotor magnetic ψ_2^* flux vector. Accordingly, the required value and direction of the stator current are calculated using an appropriate mathematical model of the asynchronous machine.

If we assume that the stator magnetic flux vector is constant at any time and is directed along the x,y coordinate axes, i.e.

$$\psi_{2y} = 0, \frac{d\psi_{2y}}{dt} = 0, \psi_{2x} = \psi_2^* = \text{const}, \frac{d\psi_{2x}}{dt} = 0,$$

in a rotating coordinate system, based on the equations of the asynchronous machine, the mathematical model is written as follows:

$$i_{1x}^* = \frac{1}{L_m} \psi_{2x}^*; i_{1y}^* = \frac{X_2}{R_2 X_m} \omega_2^* \psi_{2x}^* \quad (12)$$

In the above mathematical model of an asynchronous motor, the angle between the stator current vector and the stator and rotor magnetic flux vectors are taken into account as a coordinate transform (kg), as well as the angle between the stator current vector $\vec{i}_1^*$ and the stator and rotor magnetic ε_φ flux vectors. In the steady-state mode, this angle is constant and the stator current rotation frequency corresponds to the angular frequency $\omega_{1i} = \omega_1$ of the rotor magnetic flux vector. In dynamic modes, this correspondence is violated, since the value depends on the engine operating mode. Therefore, when supplying the stator current angular frequency, it must be calculated taking into account the change in angle:

$$\omega_{1i}^* = \omega + \omega_2^* + \frac{d}{dt}(\varepsilon_\varphi) \quad (13)$$

The drawback of the automated control system of the electric motor, built on such a principle in order to ensure high dynamic characteristics, is that the rotor magnetic flux does not remain constant in transient modes. This is explained by the fact that direct measurement of the angle ε_φ is practically impossible. At the same time, an additional problems are the inadequacy of the parameters of the mathematical model and the parameters of the real machine. Oscillations of the rotor magnetic flux cause distortion of the magnetizing i_{1x} and torque-generating

i_{1y} currents. Failures of the rotor magnetic flux curve cause an intensive increase in the stator current, which will lead to intensive heating of the power elements of the frequency converter and the motor.

A comparison of the control system control methods discussed above showed that the first method provides better regulation of the torque-generating component of the stator current, and therefore successful control of the torque developed by the motor. The advantage of the second method is that it is technically easy to implement. As a result of the transition to microprocessor control of electric drives, this advantage has lost its significance. Therefore, we will consider only systems based on controlling the motor by the magnetic flux of the rotor (Varga & Kuczmam, 2018).

To regulate the orientation of the electromagnetic field of a short-circuited rotor asynchronous motor, it is necessary to equip the control system with information simultaneously about the amplitude of the rotor magnetic flux, as well as about its location. The rotor flux is determined by the formula:

$$\bar{\Psi}_2 = \frac{X_2}{X_m} \bar{\Psi}_m - X_{2\delta} \bar{i}_1 \quad (14)$$

Where, $\bar{\Psi}_m$ is the magnetic flux vector in the air gap, which is measured by a Hall sensor.

The magnetic flux of an asynchronous motor can be measured in another way using a special three-phase measuring winding. In this case, the voltage u_1 induced in the winding will be proportional to the change in the magnetic flux in the air gap:

$$\bar{u}_{1i} = \frac{d\bar{\Psi}_m}{dt} \quad (15)$$

To calculate the magnetic flux in the air gap $\bar{\Psi}_m$ -s, it is necessary to integrate the signal received from the measuring coils. This method is unacceptable at low frequencies due to the influence of zero drift in real integrators.

A Hall sensor or a special three-phase winding can be used only in asynchronous motors of special performance. Therefore, these methods have not found practical application (Gracheva et al., 2016).

Various options for determining the flux are known, which are based on measuring voltage, current, angular velocity of rotation, and the angle of rotation of the rotor. They are characterized by low accuracy of measuring the motor parameters and are distinguished by the complexity of technical implementation (Kodkin et al., 2017; Meshcheryakov & Sibirtsev, 2017).

The determination of the rotor flux, within the limits of permissible errors, is possible using current and voltage transformers. It is acceptable at a minimum frequency of the stator voltage up to 3 Hz. Another feature of the regulation system is that the engine parameters change during operation, which has an undesirable effect on the dynamic and static properties of the drive.

At low frequencies, the temperature change of the active resistance R of the stator winding has a particularly negative effect. This is due to the fact that at low frequencies the inductive component of the voltage drop decreases and becomes proportional to the voltage drop across the active resistance. Therefore, when creating a regulated electric motor based on a squirrel-cage induction motor with a 100:1 regulation range, it is necessary to develop a method for zero drift compensation at low frequencies.

When the motor is operating in a zone of weakened magnetic field, it is important for the drive to take into account the effect of saturation of the magnetic system. When moving to the zone of weakened magnetic flux, the value of mutual inductance will change instantly and this will lead to incorrect determination of the rotor flux by the mathematical model. If the flux calculation model is compiled for the nominal mode, then the maximum error in determining the rotor time constant varies within 0.75-1.5 of the calculated value. While the motor is operating at partial load, the change in the rotor time constant is imperceptible, because whether the actual value of the flux is greater or less than the actual one, the speed controller still gives a signal according to the i_{1y}^* corresponding moment. At this time, the slip value differs from the calculated value. When the motor is fully loaded, the situation changes and the value i_{1y}^* is limited.

Various methods are known for describing the saturation of the magnetic system of an asynchronous machine (Meshcheryakov et al., 2020; Toirov et al., 2023). In our case, we consider only the saturation of the main magnetizing circuit. This is explained by the fact that the flux of the rotor is mainly confined in the air gap and can be assumed to vary linearly with the current. If we represent the rotor and stator fluxes in terms of the stray and air gap $(\bar{\Psi}_{12})$ magnetic fluxes, we obtain:

$$\begin{aligned} R_1 \bar{i}_1 + L_{1\sigma} \frac{d\bar{i}_1}{dt} + \frac{d\bar{\Psi}_{12}}{dt} &= \bar{u}_1, \\ R_2 \bar{i}_2 + L_{2\sigma} \frac{d\bar{i}_2}{dt} + \frac{d}{dt} (\bar{\Psi}_{12} e^{-j\epsilon}) &= 0 \end{aligned} \quad (16)$$

Let us assume that the machine has symmetrically arranged windings and the mutual inductance of the machine phases depends on the location of the operating point on the magnetization curve, which is determined unilaterally by the magnitude of the magnetization current vector. The magnetization current vector consists

of the sum of the stator and rotor current vectors:

$$\bar{i}_{12} = \bar{i}_1 + \bar{i}_2 e^{j\epsilon} \quad (17)$$

Electromagnetic induction is calculated by the formula:

$$\frac{d\bar{\Psi}_{12}}{dt} = \frac{d\bar{\Psi}_{12}}{d\bar{i}_{12}} \frac{d\bar{i}_{12}}{dt}. \quad (18)$$

For dynamic mutual induction, it is advisable to introduce a new notation:

$$L_{12,\delta} = \frac{d\bar{\Psi}_{12}(\bar{i}_{12})}{d\bar{i}_{12}}. \quad (19)$$

In the representations of the electromagnetic moment of the motor, static mutual induction is used:

$$L_{12} = \frac{\Psi_{12}(\bar{i}_{12})}{\bar{i}_{12}}; \quad (20)$$

$$m_{el} = \frac{2}{3} p_n L_{12}(\bar{i}_{12}) \text{Im} \left[\bar{i}_1(t) (\bar{i}_2(t) e^{j\epsilon})^* \right] \quad (21)$$

If we take into account equations (19) and (20), we obtain:

$$R_1 \bar{i}_1 + L_{1\delta} \frac{d\bar{i}_1}{dt} + L_{12,\delta} \frac{d}{dt} (\bar{i}_1 + \bar{i}_2 e^{j\epsilon}) = \bar{u}_1. \quad (22)$$

$$R_2 \bar{i}_2 + L_{2\delta} \frac{d\bar{i}_2}{dt} + L_{12,\delta} e^{-j\epsilon} \frac{d}{dt} (\bar{i}_1 + \bar{i}_2 e^{j\epsilon}) - j\omega L_{12} e^{-j\epsilon} \frac{d}{dt} (\bar{i}_1 + \bar{i}_2 e^{j\epsilon}) = 0 \quad (23)$$

To determine the effect of saturation of the magnetic system of the motor, as well as to design a control system that will correspond to the field weakening range, it is necessary to introduce a fictitious rotor magnetizing current. At the same time, the rotor scattering coefficient is taken as a constant value and is defined as follows:

$$\delta_2 = \frac{L_{2\delta}}{L_{12}}. \quad (24)$$

If we exclude the rotor current from equations (22) and (23) and switch to a coordinate system rotating at the field speed, then we arrange the resulting expressions according to the real and imaginary parts, we obtain a system of differential equations (25).

Based on the comparison of the representations of saturated and unsaturated machines, we come to the following conclusion: the number of terms in the stator differential equations has not changed, and the time constant depends on the state of the magnetic circuit. Additional terms have appeared in the rotor differential equations, and all time depend on the location of the operating point constants on the magnetization curve. Representations that contain the difference between the quantities $L_{2\delta}, L_{12,\delta}, \delta_2 L_{12}$ have a negligible effect on the properties of a saturated machine. Taking into account

the significant influence of the time constant in the mathematical representations, it is possible to improve the flow model, which will allow us to take into account the saturation of the magnetic system and the temperature change of the rotor impedance. The feedback circuit of the integrator includes the inverse magnetization curve. In the mathematical model, the effect of adapting the rotor impedance R_2/R_{20} is additionally taken into account. The value of the calculated rotor resistance R_{20} and the time constant T_{20} are taken from the machine parameters without taking into account their change. In the machine model, the correct stationary characteristic is obtained taking into account the magnetization curve. Compared to the rigid flux model, the dynamic properties of the regulation are improved.

$$\left. \begin{aligned} & \frac{L_{1\delta} + \frac{\delta_2}{1+\delta_2} L_{12,\delta}}{R_1} \frac{di_{1x}}{dt} + i_{1x} = \frac{u_{1x}}{R_1} - \\ & - \frac{1}{1+\delta_2} \frac{L_{12,\delta}}{R_1} \frac{di_{1\mu}}{dt} + \frac{L_{2\delta} + \frac{\delta_2}{1+\delta_2} L_{12,\delta}}{R_1} \omega_1 i_{1y}; \\ & \frac{L_{1\delta} + \frac{\delta_2}{1+\delta_2} L_{12,\delta}}{R_1} \frac{di_{1y}}{dt} + i_{1y} = \frac{u_{1y}}{R_1} - \frac{L_{12,\delta}}{R_1(1+\delta_2)} i_{1\mu} \omega - \\ & - \frac{L_{2\delta} + \frac{\delta_2}{1+\delta_2} L_{12,\delta}}{R_1} \omega_1 i_{1x}; \\ & \frac{L_{2\delta} + L_{12,\delta}}{R_2} \frac{di_{1\mu}}{dt} + i_{1\mu} = i_{1x} + \frac{L_{2\delta} - \delta_2 L_{12,\delta}}{R_2} \frac{di_{1x}}{dt} + \\ & + \frac{(\delta_2 L_{12,\delta} - L_{2\delta}) \omega_1 + (L_{2\delta} - \delta_2 L_{12}) \omega}{R_2} i_{1y}; \\ & \frac{\delta_2 L_{12,\delta} - L_{2\delta}}{R_2} \frac{di_{1y}}{dt} - i_{1y} + \frac{(L_{2\delta} + L_{12,\delta}) \omega_1 - (L_{2\delta} + L_{12}) \omega}{R_2} i_{1\mu} + \\ & + \frac{(\delta_2 L_{12,\delta} - L_{2\delta}) \omega_1 + (L_{2\delta} - \delta_2 L_{12}) \omega}{R_2} i_{1x} = 0 \end{aligned} \right\} \quad (25)$$

Based on the comparison of the representations of saturated and unsaturated machines, we come to the following conclusion: the number of terms in the stator differential equations has not changed, and the time constant depends on the state of the magnetic circuit. Additional terms have appeared in the rotor differential equations, and all time depend on the location of the operating point constants on the magnetization curve. Representations that contain the difference between the quantities $L_{2\delta}, L_{12,\delta}, \delta_2 L_{12}$ have a negligible effect on the properties of a saturated machine. Taking into account the significant influence of the time constant in the mathematical representations, it is possible to improve the flow model, which will allow us to take into account the saturation of the magnetic system and the temperature change of the rotor impedance. The feedback circuit of the integrator includes the inverse magnetization curve. In the mathematical model, the effect of adapting the rotor impedance R_2/R_{20} is additionally taken into account. The value of the calculated rotor resistance R_{20} and the time constant T_{20} are taken from the machine

parameters without taking into account their change. In the machine model, the correct stationary characteristic is obtained taking into account the magnetization curve. Compared to the rigid flux model, the dynamic properties of the regulation are improved.

During long-term operation of the motor, may occur a change in the rotor resistance. The change refers to the process of slowly changing the rotor resistance, which is caused by the heating of the rotor due to losses in steel and copper. In a short-circuited rotor machine, the rotor temperature increases as a result of the load and, accordingly, its resistance is 50% higher than that of a cold machine. Accordingly, this causes the motor to deviate from the calculated values of the torque value and the dynamics of the machine. Since it is impossible to accurately determine the losses in steel, the rotor resistance in the flux model is controlled only by an indirect method.

In vector control of an asynchronous electric motor, it is of great importance to accurately determine the parameters of the motor. Therefore, it is advisable to measure these parameters using a microprocessor control system. It is worth noting that using a self-configuring program, the service personnel are freed from the need to directly calculate the regulator coefficient and enter it into the system.

In the microprocessor-based control system of the electric drive, resolution of which is $N = 2^{16} = 65536$ and whose signal delivery pulse period is $T = 1.28$ ms, the vector transformations (the rotor flux linkage modulus, the parameters of the angular velocity control channel regulators, and the values of the main flux linkage components (Naik, 2014; Kalashnikov, 2003) as well as the service programs can be controlled by two microprocessors.

It is possible to provide the control accuracy required for controlling ship steering drives with the control system "Transvector". Vector transformations (the values of the rotor flux module, the parameters of the angular velocity control channel regulators and the main flux component (Rudakov et al., 1987) and service programs can be controlled by two microprocessors.

It is possible to control the frequency regulator control drive with the microprocessor CP (Figure 2). This system has two control channels (CP1, CP2) - magnetic flux linkage (in this case it corresponds to the steering angle signal) and engine angular velocity. The magnetic flux control channel contains an integrator of the engine excitation level (I) and two magnetic flux control circuits with a regulator (FR) and an excitation current regulating (RT_d) Regulator. The electromagnetic torque control channel contains an engine speed regulator (SR) and a torque regulator (TR).

A block correction (CB) is included to compensate for the engine electromotive force. The structural scheme of the system is given in Figure 2.

The second microprocessor carries out vector analysis of the motor current components i_{sd} , i_{sq} , and also converts and inputs analog signals from the (d,q) coordinate system to the (α, β) system. In addition, this microprocessor converts digital signals U_A, U_B, U_C , into analog.

To check the proper operation of the system, after turning on the drive, the operation of the microprocessors of the control system is checked first of all. The results of the testing are given by indicators, the data is shown on control panel.

After positive test results, the passport data of the asynchronous motor is entered from the control panel of the microprocessor control system ($U_n, I_n, f_n, \cos \varphi_n$, maximum permissible current and speed) and the powers of the connected motor and frequency converter are checked. According to the control signal, the electric drive is started with a switched-off system, the duration of which is 200 milli seconds. According to the current and voltage data, both the operation of the power unit and the measuring devices of the control parameters and the determination of their transmission coefficients are controlled.

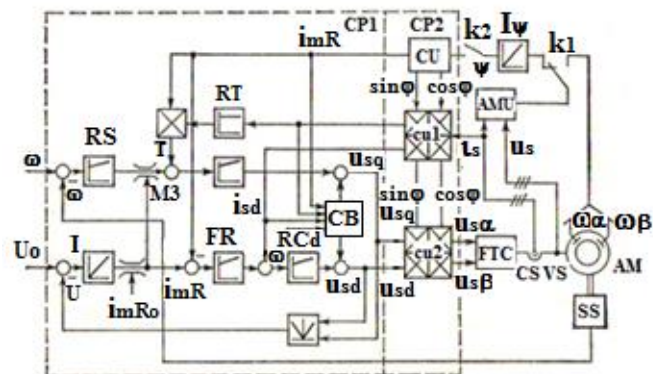


Figure 2. Structural diagram of the "transvector" control microprocessor system.

The rotor drive connected to the frequency control module fully meets the requirements for the steering wheel shift time interval. In particular, the main drive must provide steering wheel shift from -35° to $+30^\circ$ within 28 seconds. If the maximum shift angle is less than 35° , then the steering wheel shift time is proportionally reduced from $-\alpha_{\max}$ to $+(\alpha_{\max} - 5^\circ)$:

$$T = 28 \frac{2\alpha_{\max} - 5}{65} \quad (26)$$

When the ship is moving at the maximum operating speed, the steering gear must withstand 350 turns per hour on a given course.

The conducted experiment proved the effectiveness of the frequency control system for a squirrel-cage motor in performing this requirement. Table 1 shows the parameters obtained during operation in modes (idle, nominal, less loaded).

As the experiment shows, despite the constant power factor ($\cos \varphi$ the efficiency changes sharply - a decrease in frequency is accompanied by a decrease efficiency. Its value also decreases when the motor load moment decreases. The mechanical characteristics of the motor during frequency regulation maintain rigidity. During overload (e.g. $M/M_n=1.3$) the motor maintains stable operation.

The main problem that concerns the induction motor is the presence of a limited / critical moment. This problem can be solved by using a vector control system (transvector). This specific type of frequency control allows the induction motor to no longer have a critical moment. In particular, the electromechanical characteristic of an asynchronous squirrel-cage motor takes the form of a characteristic of a DC independent excitation motor (Figure 3).

According to the data given in Table 1, it is possible to determine the drive's efficiency in different operating modes according to the frequency change, which is graphically shown in Figure 4.

Table 1. Obtained parameters of the frequency control system of a squirrel-cage motor in different modes.

N		1	2	3	4	5	6	7	8	9
M/M _n		0 (idle mode)			0,385 (low-load mode)			1 (nominal mode)		
M	Nm									
U	V	217	141	97	210	141	97	210	141	97
I	A	1,02	1,35	1,3	0,97	1,23	1,16	1,23	1,28	1,24
N	1/min	1485	890	590	1446	860	520	1350	785	460
Reversal time	C	24	12	10	15	12	10	15	14	12
PM	W	174,86	150	99,12	160,92	137	88,89	204,06	141,6	95,02
S	VA	221,34	190,35	126,1	203,7	173,43	112,52	258,3	179,2	120,3
PL	W	0	0	0	75,67	45	27,21	183,7	106,8	62,59
Cos φ		0,79			0,79			0,79		
η	%				47	32	30,6	90	75	65
f	Hz	50	30	20	50	30	20	50	30	20

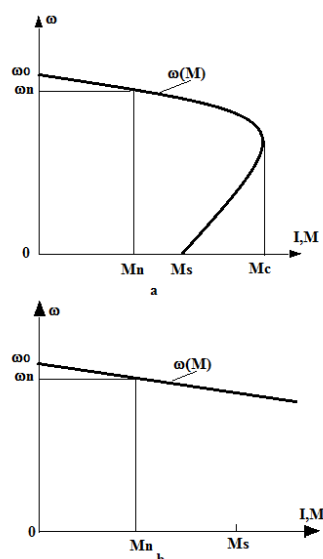


Figure 3. (a) Electromechanical characteristics of an asynchronous engine/induction motor;
(b) Electromechanical characteristics of an asynchronous engine/induction motor with a "transvector" control system.

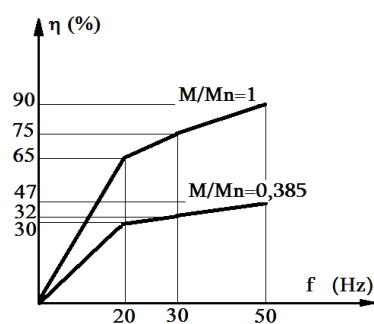


Figure 4. Frequency dependence characteristic of the efficiency of an electric drive with a frequency control system

3. CONCLUSION

- The use of a microprocessor system for vector control in frequency-controlled drives allows to implement various control algorithms.
- It is possible to ensure the shifting of the ship's rudder by the required amount, with high accuracy and in the shortest possible time, with vector control of servo motors, which will minimize the magnitude and duration of the ship's deviation from the course.

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