TECHNICAL SCIENCES

SYNTHESIS OF THE LOAD MOMENT OBSERVER IN ASYNCHRONOUS ELECTRIC DRIVE

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Abstract

The paper solves an actual scientific problem, which consists in the application of the modal control method for the synthesis of a modal observer the state of the active power channel of an asynchronous machine (AM) in the system of its vector control by the stator. The main task of the observer is to identify the moment of static load on the shaft AM in order to use this information in the extreme control circuit of the asynchronous electric drive. The asymptotic stability and sufficient accuracy of the observer of the moment of static load on the shaft AM to determine the coordinates of the minimum of the quality functions of the extreme control the asynchronous machine, which improves its energy indicators, has been proven by the method of mathematical modeling.

Keywords: Asynchronous machine, vector control, modal load moment observer, asymptotic stability, distribution of polynomial roots.

Introduction. The structure of the vector control system of the asynchronous machine with constant flow can be irrational, because stabilization system control of flow at the level of nominal value leads to a decrease in the power factor at the of loading of the electric drive less than the nominal. This disadvantage is inherent in adjustable electric drives of loading machines with a fan mechanical characteristic. Analytical expressions that allow to determine the value of the flow of asynchronous electric drive (ED), in which its energy characteristics reach the extremum obtained in [1,2]. Improve the energy indicators of the asynchronous electric drive with stator control is possible by changing the flow of rotor in the function of loading on the shaft of the asynchronous machine (AM) [3]. In order to optimize energy processes in such an electric drive, it is necessary to construct a two-channel system with independent control of the speed and flow of the AM rotor, which can be implemented in the vector control system with the addition of the circuit of extreme regulation in its composition. The purpose of regulation is to achieve the extremum of some function of a goal that describes the energy characteristics of AM [3].

Analysis of recent research and publications. The need to calculate the load moment on the shaft of an electric machine arises in electric drives for various purposes. Currently, there are a number of approaches to estimating the load moment in an electric drive. The classic solution is to estimate the load moment by the armature current of the electric drive [4]. In fact, this question consists in an indirect assessment of the electromagnetic moment and is used only in the stable mode of operation ED. To determine the position of the kinematic links, the assessment of deformation shifts in the hinges under the influence of the load moments fixed in the electric drives can be used. This task is relevant for robotic systems that have high requirements for dynamic accuracy. Papers [5,6] implement an approach in which the load moment is estimated based on the difference between two values of the speed electric drive: measured and restored by the observer. In this approach, the estimation of the load moment is performed indirectly through the estimation of the speed, and the quality of the estimation depends on the knowledge of the parameters electric drive model. The state vector of an asynchronous machine can be estimated using the Luenberger observer [7] or the extended Kalman filter algorithm [8]. Another approach is presented in works [9,10], where the restoration of the load moment is performed according to the data of the electromagnetic moment and the acceleration of the motor shaft, which directly follows from the equation of motion of the ED. However, the measurement of acceleration or its estimation often causes difficulties related to the probability and presence of noise in the measured signal. To restore the acceleration signal, it is possible to use a speed observer [11]. In the article [12], astatic speed regulation is proposed, which is implemented using the principle of combined control with positive feedback on the disturbance, as a corrective signal of the estimation of the static load moment. In [13], an observer with a sliding mode was synthesized, which asymptotically estimates the unknown load moment and determines the moment inertia of an ED based on a synchronous motor with permanent magnets. The paper [14] presents the method synthesis of the observer of mechanical speed and load moment in high-speed asynchronous ED of rolling stock. Such an observer is used for the purpose of diagnosing speed and torque sensors and ensures the operation of the ED in the event a malfunction of the physical sensors.

Formulation of the purpose research. From the analysis of the latest research and publications, it follows that the energy characteristics of asynchronous

ED in steady-state operation are functions of three variables: the angular speed of rotor rotation, the modulus of the rotor flux coupling vector, and the moment of static load. The angular velocity of the rotor and the flow coupling are among the state variables of AM and they are subject to measurement. The moment of static load is an external disturbing influence, effective methods of its measurement are not available. If, in order to improve the energy indicators of the AM, it is necessary to adjust its reactive power depending on the moment of load on the shaft, then it is necessary to synthesize an observer that would determine the estimate of the moment load on the shaft AM in the process of regulation and operation of the ED. Information about the moment of load on the shaft of an asynchronous machine is required for the implementation of extreme control circuits as part of vector control systems for asynchronous electric drives. In [3] a modal observer of the load moment is proposed, which works in the circuit of extreme regulation by the electric drive of the fan, in which the load moment changes smoothly as a function of speed. However, the properties of the observer during jump-like changes in the load at different rotation speeds of the rotor AM were not studied in detail. Therefore, in this work, the task is to apply the method of synthesis modal observers to build and study the mathematical model of the observer state variables of the active power channel and the load moment on the shaft of an asynchronous ED with vector control.

Presenting main material. The starting points for the synthesis of the observer are the AM equations in the Cauchy form, written in the coordinate axes oriented along the rotor flux coupling vector [2]:

$$p\Psi_r = -\frac{\Psi_r}{T_r} + \frac{L_m}{T_r} I_{su};$$

$$pI_{su} = -\frac{R'}{L_s'} I_{su} + \frac{K_r}{T_r L_s'} \Psi_r + N\omega_r I_{sv} + K_r R_r \frac{I_{sv}^2}{\Psi_r} + \frac{U_{su}}{L_s'};$$

$$p\omega_r = \frac{3NK_r\Psi_r}{2J} I_{sv} - \frac{M_s}{J}; \qquad (1)$$

$$pI_{sv} = -\frac{R'}{L_s'} I_{sv} - \frac{K_r N\Psi_r}{L_s'}\omega_r - N\omega_r I_{su} - K_r R_r \frac{I_{su} I_{sv}}{\Psi_r} + \frac{U_{sv}}{L_s'}$$

As can be seen from equations (1), AM is a multi-connected system, as it is characterized by non-linear connections between control channels and non-linear dependencies between controlled variables. Each adjustable value can be matched with its own regulator and thereby determine the direct influence transmission channels in the control object. Analysis of the system of equations (1) shows that AM as an object of regulation consists of two interdependent circuits. The connection between the active and reactive power control loops is due to four internal cross-connections in the AM: two cross-connections due to the dissipation fluxes $L_s'\omega_\kappa I_{su}$, $L_s'\omega_\kappa I_{sv}$, cross-connection due to the EMF of rotation $K_r\omega\Psi_r$ and cross-connection due to the electromagnetic moment $\frac{3}{2}NK_r\Psi_r I_{sv}$. Stabilization of the rotor flux coupling vector module unambiguously determines the dependence of the electromagnetic moment AM on the active component of the stator current I_{sv} and at the same time linearizes the links of the formation of the electromagnetic moment and feedback on the EMF of the motor. Cross-connections due to dissipation flows are considered as disturbing effects in the control channels of the active and reactive powers of the AM.

It is necessary to enter the value of the static moment M_s into the extreme control circuit, since the expressions of the objective functions come from the equations of the steady state operation of the electric drive, in which the electromagnetic moment is equal to the moment of the static load. However, the moment of static load on the AM shaft cannot be measured by instrumentation. In addition, for the implementation of the relay speed regulator, it is necessary to organize feedback on its first derivative. Direct differentiation of the signal from the output of the speed sensor, which inevitably contains a high-frequency component of interference, is associated with great technical difficulties. In order to solve the mentioned problems that arise during the technical implementation of the extreme control system AM , it is necessary to use a observer that identifies not only the variables of the state of the control object, but also the external influences that cannot be directly measured.

The state observer is built on the basis of the known structure and parameters of the linear object. The initial values of the state vectors of the control object and the observer must be the same, and the input influences are applied simultaneously to the real object and to the observer. The subsystem that describes the dynamic processes in the control channel of the active component of the stator current AM consists of the third and fourth equations of system (1), which are written separately and have the form:

$$p\omega_r = \frac{3NK_r\Psi_r}{2J} I_{sv} - \frac{M_s}{J};$$

$$pI_{sv} = -\frac{K_r N\Psi_r}{L_s'}\omega_r - \frac{R'}{L_s'} I_{sv} + \frac{U_{sv}}{L_s'} - \frac{U_{pr}}{L_s'}, \qquad (2)$$

where $U_{sv}-$ active component of the stator voltage; $U_{pr} = \left(\frac{R_r K_r I_{sv} I_{su}}{\Psi_r} + N\omega_r I_{su}\right) L_s' -$ cross-talk signal; $M_s -$ moment of static load on the shaft.

For the active power channel model AM (2), the variables U_{sv}, U_{pr} serve as input signals, and the quantity $M_s -$ serves as a disturbing influence. Then the characteristic equation of the object (2) will be determined as follows

$$\begin{vmatrix} p & -\frac{3NK_r\Psi_r}{2J} \\ \frac{NK_r\Psi_r}{L_s'} & p + \frac{R'}{L_s'} \end{vmatrix} = p^2 + \frac{R'}{L_s'} p + \frac{3N^2K_r^2\Psi_r^2}{2JL_s'} . \qquad (3)$$

When forming the state vector, we introduce the notation $x_1 = \omega_r, x_2 = I_{sv}$. Since the load torque disturbance M_s cannot be measured and entered into the monitoring device, it is considered as one of the state variables $x_3 = M_s$ of the control object extended in this way. If the working mechanism has a fan mechanical characteristic, then it is always possible to write its analytical expression in the following form, at least approximately

$$M_s = M_0 + \left(M_{sn} - M_0\right)\left(\omega_r / \omega_{rn}\right)^2, \quad (4)$$

where $M_s -$ moment of resistance of the production mechanism at speed ω_r; $M_0 -$ moment of friction in moving parts; $M_{sn} -$ moment of resistance of the mechanism at the nominal speed of rotation ω_{rn} .

Differentiating (4) by time using the first expression of system (2), we obtain the following equation, which relates the external influence M_C to the state variables of the object (2):

$$pM_s = -\frac{3NK_r\Psi_r b}{2J} I_{sv} - \frac{b}{J} M_s, \quad (5)$$

where $b = \dfrac{2\left(M_{sn} - M_0\right)\omega_r}{\omega_{rn}^2}$ – coefficient, which varies in proportion to the speed rotation of the rotor.

If expression (5) is added to system (2), then the dynamics equation of the extended control object in vector-matrix form will have the form

$$\begin{aligned} pX &= AX + BU; \\ Y &= CX, \end{aligned} \quad (6)$$

where $X -$ object state vector; $U -$ vector of measured input influences; A and $B -$ state and input matrices; $Y -$ vector of measured output variables and output matrix C, are found as:

$$X = \begin{pmatrix} \omega_r \\ I_{sv} \\ M_s \end{pmatrix}; \; U = \begin{pmatrix} U_{sv} \\ U_{pr} \end{pmatrix}; \; A = \begin{pmatrix} 0 & \dfrac{3NK_r\Psi_r}{2J} & -\dfrac{1}{J} \\ -\dfrac{NK_r\Psi_r}{L_s'} & -\dfrac{R'}{L_s'} & 0 \\ 0 & \dfrac{3NK_r\Psi_r b}{2J} & -\dfrac{b}{J} \end{pmatrix}; \; B = \begin{pmatrix} 0 & 0 \\ \dfrac{1}{L_s'} & -\dfrac{1}{L_s'} \\ 0 & 0 \end{pmatrix};$$

$$Y = I_{sv}; \; C = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}.$$

The rank of the observation matrix $Q = \left[C^T \vdots A^T C^T \vdots \left(A^T\right)^2 C^T \right]$ is equal to the order of system (6) $n = 3$, that is, the extended object is fully observed and the task of estimating its state has a solution.

The observing device is described by the equation

$$p\hat{X} = \left(A - KC\right)\hat{X} + BU + KY, \quad (7)$$

where $\hat{X} -$ the state vector of the object restored by the observer; $K -$ the vector of the coefficients of the observer's correction relations.

The selection of the elements of the modal feedback vector $K = \begin{pmatrix} k_1 & k_2 & k_3 \end{pmatrix}^T$ means the task of a certain form of the characteristic equation of the observer, which is written in the following way

$$det\left[pI - \left(A - KC\right)\right] = \begin{pmatrix} p & -\dfrac{3NK_r\Psi_r}{2J} + k_1 & \dfrac{1}{J} \\ \dfrac{NK_r\Psi_r}{L_s'} & p + \dfrac{R'}{L_s'} + k_2 & 0 \\ 0 & -\dfrac{3NK_r\Psi_r b}{2J} + k_3 & p + \dfrac{b}{J} \end{pmatrix} = p^3 + \left(\frac{R'}{L_s'} + \frac{b}{J} + k_2\right)p^2 +$$

$$+ \left(\frac{3N^2K_r^2\Psi_r^2}{2JL_s'} - \frac{NK_r\Psi_r k_1}{L_s'} + \frac{bR'}{JL_s'} + \frac{bk_2}{J}\right)p + \frac{NK_r\Psi_r k_3}{JL_s'} - \frac{NK_r\Psi_r bk_1}{JL_s'}. \quad (8)$$

To give the observer the desired dynamic properties, let's assume the standard polynomial form of the distribution of the roots characteristic equation of the third order

$$D(p) = p^3 + A_1\Omega_0 p^2 + A_2\Omega_0^2 p + \Omega_0^3, \quad (9)$$

where $\Omega_0 -$ mean geometric root of the characteristic equation of the observing device.

The coefficients A_1 and A_2 determine the location of the roots characteristic equation of the observer on the complex plane. For distribution according to Butterworth we have $A_1 = A_2 = 2$, according to Newton – $A_1 = A_2 = 3$. From the comparison of the coefficients with the same powers of the operator p in equations (8) and (9), there are analytical expressions for the coefficients K of the observer feedback vector:

$$k_2 = A_1\Omega_0 - \frac{R'}{L'_s} - \frac{b}{J};$$

$$k_1 = \frac{3NK_r\Psi_r}{2J} + \frac{bR'}{JNK_r\Psi_r} + \frac{bL'_s k_2}{JNK_r\Psi_r} - \frac{A_2\Omega_0^2 L'_s}{NK_r\Psi_r};\quad(10)$$

$$k_3 = bk_1 + \frac{\Omega_0^3 JL'_s}{NK_r\Psi_r}.$$

After transforming the matrix equation of the observer (7), we obtain the equation

$$p\widehat{X} = A\widehat{X} + K\left(Y - C\widehat{X}\right) + BU, \quad (11)$$

which for each coordinate is written separately as follows:

$$p\widehat{\omega}_r = \frac{3NK_r\Psi_r}{2J}\widehat{I}_{sv} - \frac{\widehat{M}_s}{J} + k_1\left(I_{sv} - \widehat{I}_{sv}\right);$$

$$p\widehat{I}_{sv} = -\frac{NK_r\Psi_r}{L'_s}\widehat{\omega}_r - \frac{R'}{L'_s}\widehat{I}_{sv} + k_2\left(I_{sv} - \widehat{I}_{sv}\right) + \frac{U_{sv}}{L'_s} - \frac{U_{pr}}{L'_s};\quad(12)$$

$$p\widehat{M}_s = \frac{3NK_r\Psi_r b}{2J}\widehat{I}_{sv} - \frac{b}{J}\widehat{M}_s + k_3\left(I_{sv} - \widehat{I}_{sv}\right).$$

System (12) determines the structure of the observer and its work algorithm. The control object is always affected by disturbances that cannot be measured and entered into the observer, and there may also be some discrepancy between the mathematical description of the control object and the observer. Therefore, it is recommended to choose Ω_0 such that the speed of the observer is slightly higher than the speed of the system that contains the observer in the feedback loop. Object speed control is determined by its average geometric root, which is found by the formula

$$\Omega_{ob} = \sqrt{\frac{a_2}{a_0}} = NK_r\Psi_r\sqrt{\frac{3}{2JL'_s}}, \quad (13)$$

where a_0 and a_2 – coefficients at p^2 and p^0 characteristic equation (3), and it is accepted $\Omega_0 = (2..3)\Omega_{ob}$ [15].

The structural diagram of the observer, compiled according to the system of equations (12), is shown in Figure 1. To correct the values of the current variables of the observer of the load moment, the active component of the stator current I_{sv} is monitored, which is compared with a similar variable calculated by the observer $\widehat{I}_{sv}$. Their difference through corrective feedback blocks (k_1, k_2, k_3) is applied to the inputs of the observer's integrators.

When the values of the control object's state variables and their estimates differ, the observer's corrective circuit works because a current identification error appears I_{sv}. The external influence U_{sv} is measured and fed to the input of the observer.

In order to simplify the structure of the observer, when determining the cross-connection signal due to dissipation currents U_{pr}, the stator current I_{sv} is replaced by its estimate $\widehat{I}_{sv}$, and instead of dividing by the modulus of the rotor flux Ψ_r, its nominal value is taken Ψ_{rn}. In the

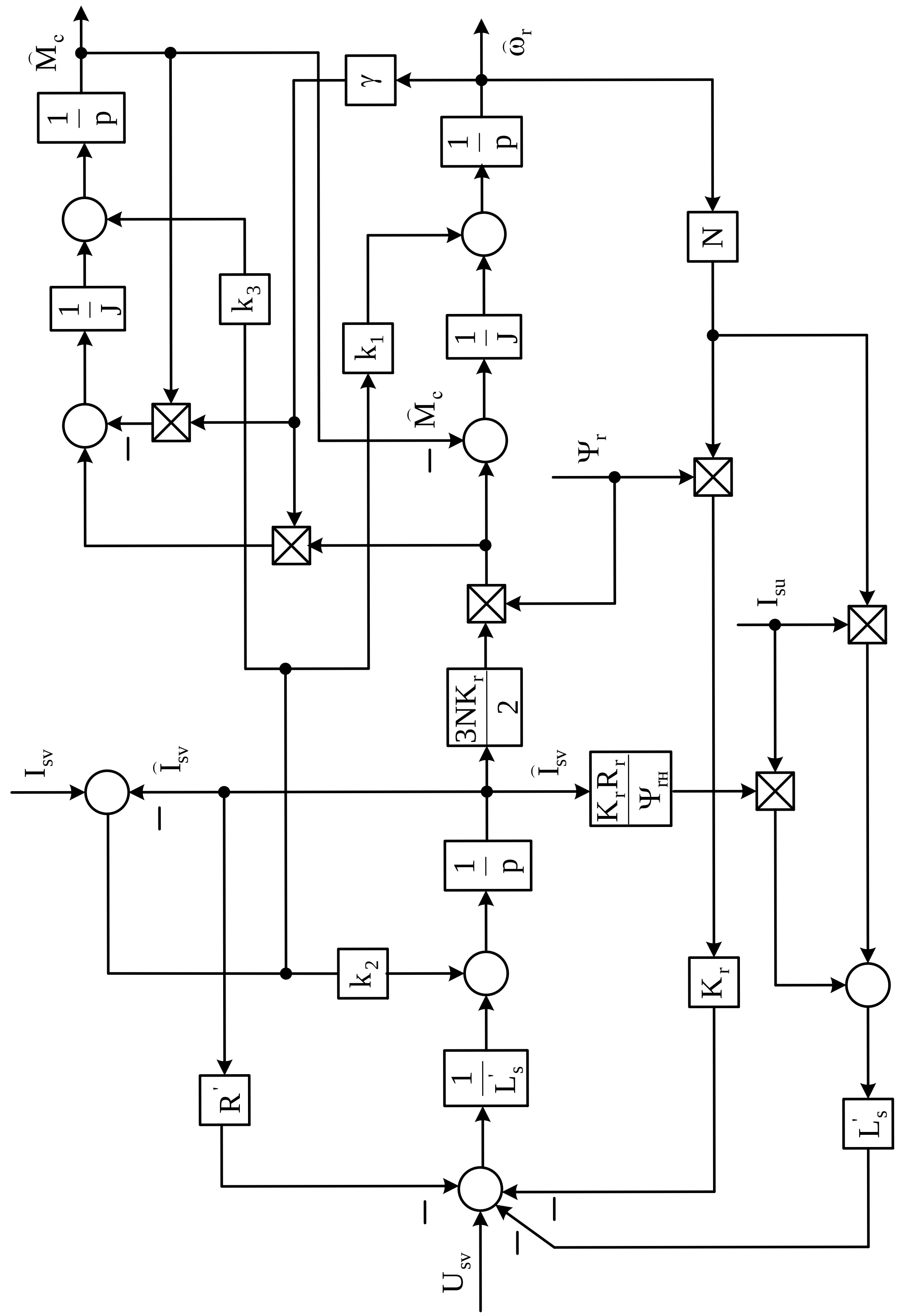

Fig. 1. Structural diagram of the status observer of the active power channel of an asynchronous machine

expression for the coefficient b, instead of the speed of rotation rotor, its estimated value $\hat{\omega}_r$ is used, and the coefficient is $\gamma = 2(M_{sn} - M_0)/\omega_{rn}^2$.

As can be seen from formulas (10), the coefficients of the connections k_1, k_2, k_3, which adjust the observer to the control object, depend on Ω_0 and change as a function of the rotor flow and the estimation of its rotation speed. Dynamic errors in the estimation of state variables of the control object will be smaller, the larger the value Ω_0. However, the possibilities of the increase Ω_0 are limited, because it causes the growth of the coefficients vector K, which will lead to oscillations and further to the loss of stability of the control system closed through the observer.

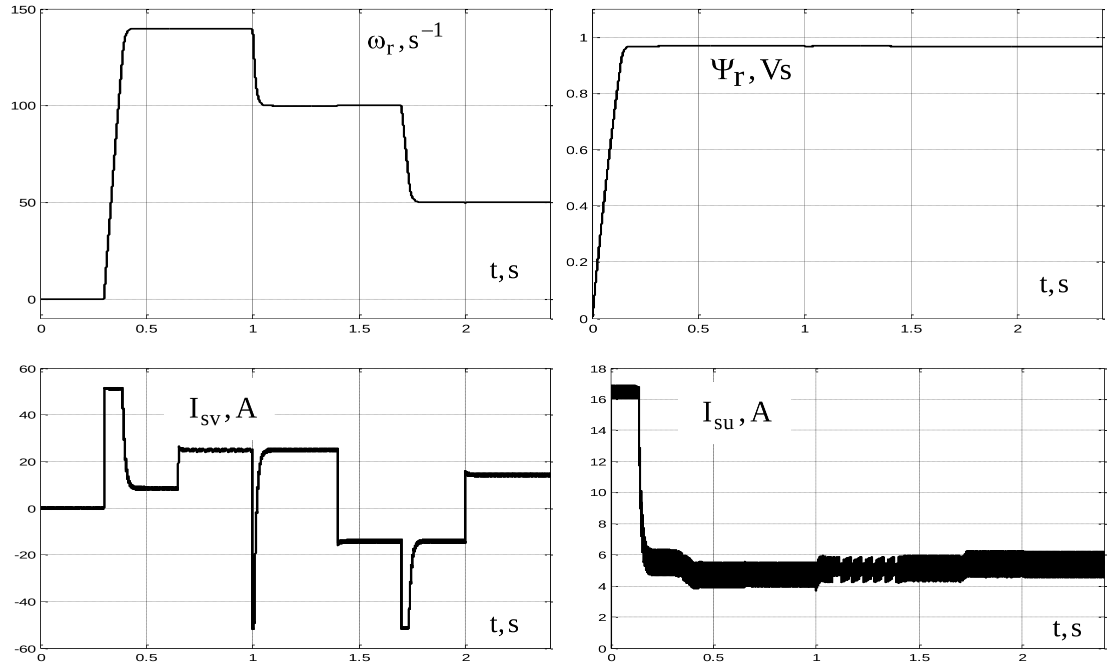

Fig. 2. State variables of an asynchronous electric drive with a vector control and observer of the load moment AM

The dynamics of the load moment observer applied to the shaft of an asynchronous electric drive with a vector control system is investigated using a mathematical model created in Matlab/Simulink. The electric drive is made on the basis of an asynchronous machine type 4A132M4У3 with the following technical data: $P_n = 11kVt$; $U_{sl} = 380V$; $n_n = 1460\,rpm$. Figures 2 and 3 show transient processes: Figure 2 shows the state variables of the ED, and Figure 3 shows the load moment on the shaft AM as a disturbing influence acting on the ED and its estimate, which is calculated by the synthesized observer. From the graphs in Figure 2, it can be seen that the relay-vector control system works out different levels of speed stabilization at different moments of load on the shaft AM, which is done to test the dynamic properties of the observer when he evaluates moments of load that jump change at different speeds. The graphs in Figure 2 show the excitation of the AM with a stationary rotor by increasing the module of the rotor flux coupling vector to its nominal value and stabilizing it at this level in all subsequent operating modes by the appropriate relay regulator in the reactive power channel. At the same time, the relay regulator of the reactive component of the stator current I_{su} is subordinate to the regulator of the rotor flux coupling vector module Ψ_r.

After stabilizing the rotor flux coupling at the nominal level, the acceleration process begins by adjusting the active power channel. The structure of the active power channel is determined by subordination to the relay regulator of the speed rotation of the rotor ω_r of the regulator of the active component stator current I_{sv}. Stabilization of the dynamic moment occurs by the regulator of the active component of the stator current I_{sv} by limiting its value in transient processes. As the speed increases, the moment of load on the shaft AM increases, which is monitored by the observer of the state of the active power channel as a result of the real-time solution of the system of equations (12). Figure 3A shows the dynamics of the load observer during the distribution of the roots of the characteristic polynomial according to Butterworth, and Figure 3B shows the calculated transient processes in the observer during the distribution of the roots of its characteristic equation according to the Newton binomial. At moments of time 0.65s, 1.4s and 2s, load moments of different signs are added to the shaft AM. These actual values of the load moment on the shaft AM are shown in Figure 3 by the blue line. The red line (number 1) represents the transient processes of the observer's calculation of the state of disturbance along the load moment channel. From the comparison of the graphs marked with the number

1 in Figure 3, it can be seen that when working out the disturbance along the load channel by the moment observer with the distribution of roots according to Butterworth, a small over-regulation occurs, while there are no over-regulations when the roots are distributed according to the Newton binomial. All load additions were carried out at

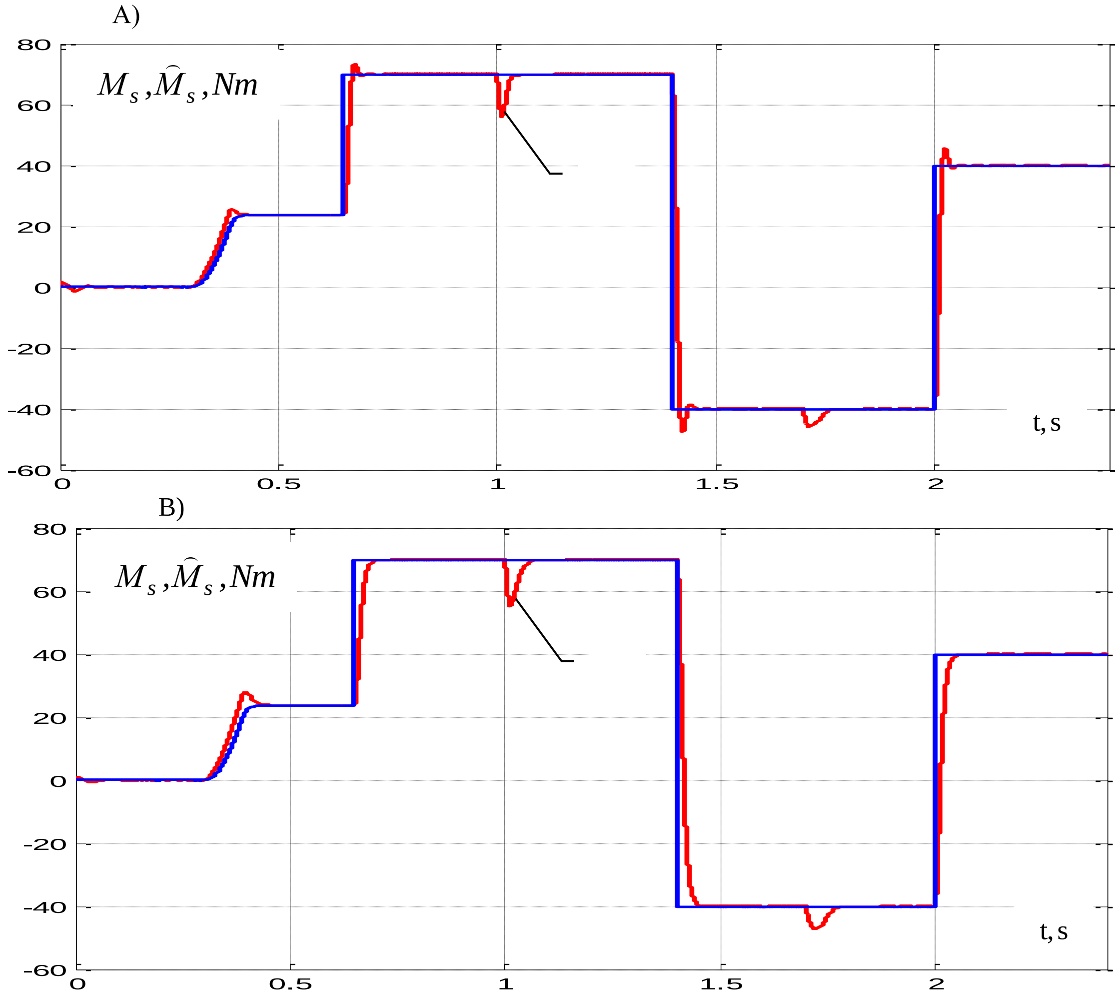

Fig. 3. The estimation signal of the static load moment at the observer's output (red graph, number 1) and the actual load moment on the shaft of the asynchronous machine (blue graph): A – distribution of the roots characteristic polynomial of the observer according to Butterworth; B – distribution of the roots characteristic polynomial of the observer according to the Newton binomial

stabilized rotor speeds. The quality of the observer's assessment of the load moment does not depend on the level of speed stabilization. However, the adjustment coefficients k_1, k_2, k_3 of the observer through the coefficient b (formula (10)) depend on the speed of the rotor AM. Therefore, when the transient processes of rotor speed regulation begin in the active power channel at time points 1s and 1.7s, short-term dynamic errors in the observer's assessment of the load moment appear. Further, the errors of estimating the load moment go to zero due to the fact that the change of coefficients k_1, k_2, k_3 during speed regulation does not violate the asymptotic stability of the observer. Moreover, the coefficients k_1, k_2, k_3 in the function of speed change in such a way that the distribution of the roots characteristic equation of the observer, given by the coefficients A_1 and A_2, also does not change at different speeds of rotation of the rotor. This is confirmed by the same form of the transient process of load moment estimation at different levels of rotor speed stabilization. The observer presented in Figure 1 also allows to estimate the rotor speed and its first derivative.

Conclusions. In this work, the problem synthesis of a modal observer of the state of the active power channel of an asynchronous electric drive with vector control for identifying the moment of load on the shaft of an asynchronous machine is solved. The dynamics of the load moment observer at different speeds of the rotor AM and the jump-like changes of the load moment on its shaft were investigated using a mathematical model. Due to the speed dependence of expressions

(10) for determining the elements of the modal feedback vector K, the obtained observer (10), (12) can be considered nonlinear. However, the elements of the corrective feedback vector K are changed in such a way that the load moment observer keeps the transient characteristics given by the standard polynomial forms at different levels of speed stabilization unchanged.

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