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INFORMATION SUPPORT FOR PROCESS OBSERVING FLUX LINKAGE OF THE ROTOR ASYNCHRONOUS MOTOR

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ABSTRACT

The article examines the quality indicators of information support of the process of observing the flux linkage of the rotor of an induction motor in vector control systems under the conditions of the action of parametric disturbances. This line of research is intended to provide a solution to the problem of building a high-quality information control system for an asynchronous electric drive, which eliminates the high sensitivity to deviations in the parameters of the control object during its operation. First of all, this refers to temperature changes in the active resistances of the stator and rotor. The obtaining information about the rotor flux linkage is assigned to the observer, which consists of four circuits. In each of the four circuits of the observation system model, two correction signals of the non-agreement of the stator currents of the asynchronous machine and the observer are introduced through the weighting coefficients. The full vector of correcting feedbacks of the observation system contains in this case eight coefficients. The application of the principles of modal control to determine their numerical values leads to unwieldy equations. The problem is solved more elegant using the direct Lyapunov's method, which makes it possible to determine the possible structure of an observation information system that is stable under parametric disturbances. The numerical values of a part of the coefficients of correcting feedbacks are obtained by the way of the analysis of the quadratic form of the total time-respect derivative of the Lyapunov's function of the synthesized information system. To determine the optimal ranges of variation of the remaining coefficients, numerical methods were used to calculate the roots of the characteristic equation of a closed-circuit observation system. Thus, the idea of the study is to use the largest number of correcting feedbacks in the structure of the observation information system and to select their values using the direct Lyapunov's method and numerical methods to ensure its low sensitivity to deviations of the parameters of an asynchronous machine.

Keywords: Information system; flux linkage observer; parametric disturbances; parameters deviations; low sensitivity; Lyapunov's function; corrective feedbacks; correction coefficients

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INTRODUCTION

Installing physical sensors in control systems requires taking into account the additional dynamics of the sensors themselves in the control object model, which can cause problems in the synthesis of regulators due to an excessive increase of the order of the control object model. The use of observation information systems (hereinafter: observers) allows restoring state variables inaccessible for measurement and eliminating the installation of additional sensors, which contributes to improving the operational and cost characteristics of control systems.

The low sensitivity of observers to parametric disturbances of control objects makes it possible to bypass the computational difficulties of synthesizing control systems by using inaccurate values of part of the parameters of the control object and the simplicity of the technical implementation of controllers.

LITERATURE REVIEW

The main disadvantage of vector control systems for AC electric drives is their sensitivity to variations in the parameters of asynchronous machines (AM) [1-2]. The main parametric disturbances in such systems are changes in the active resistances of the stator and rotor windings AM due to their heating [3-4] or inaccuracies in setting the parameters [5-6]. Against this background, the conditions of field orientation are violated, as a result of which the quality indicators of control of state variables deteriorate, even loss of stability is possible, the efficiency of the process of electromechanical energy conversion [7-8] and the control accuracy [9-10] decreases.

There is practically difficult to implement the measurement of flux linkage in the gaps under the AM phase windings using Hall sensors [11]. Therefore, it is advisable to use information monitoring systems, which make it possible to restore the values of the components of the rotor's flux linkage in the axes α,β [12-13], [14] from readily available measurement signals of phase voltages and currents of the stator windings. The correcting feedbacks of the observation process model allow increasing the stability margin of the control system and its accuracy in the case of non-agreement of the parameters of the observer and the asynchronous machine [13, 15].

A significant part of the algorithms for observing the flux linkage vector and identifying the active resistance of the rotor under conditions of its uncertainty do not have a rigorous theoretical justification, and those that have been theoretically proven are usually very complex [16-17].

In the article [18], using the well-known methods of the theory of observers and modal control, the synthesis of the observer of the rotor flux linkage as part of the AM vector control system was accomplished. The operation of the control system is investigated only with a unidirectional change in one parameter, namely, the rotor resistance AM. The synthesis problem was initially simplified by decomposition of the mathematical model of the observer into two subsystems of lower dimension, which, with the simplification of the structure by reducing the number of correcting feedbacks, simultaneously leads to the scalability of the AM rotor flux linkage module when the electric drive control system is closed by the feedback on the magnetic flux calculated by such an observer.

In publications [19-20], using the Lyapunov stability theorem, observers of the rotor flux linkage are synthesized, which ensure the stability of vector control systems for asynchronous electric drives, however, it is noted that a change in the rotor resistance under the temperature differential leads to a significant observation error.

THE GOAL OF THE STUDY

The goal of the study is to improve the quality indicators of the process of controlling the state variables of asynchronous electric drive with vector control by synthesis based on the direct Lyapunov method of an observer of the rotor flux linkage with a full vector of correcting feedbacks and to study the qualitative indicators of the information system for observing the rotor flux linkage, which has low sensitivity to parametric disturbances in the form of changes active resistances of the stator and rotor windings of an induction machine.

RESEARCH RESULTS

Let us carry out the synthesis of a closed information system for observing the AM rotor flux linkage, provided that the stator's voltages and currents are measured, as well as the angular speed of the rotor rotation. The correcting feedbacks of the observation system must ensure its stability under coordinate disturbances acting on the AM. In the article [18], from the AM equations in the u, v axes [8], the equations of an open-loop observation system of the rotor flux linkage in the axes α,β were obtained for the structure $\left(\vec{\Psi}_r, \vec{I}_s\right)$:

$$\begin{aligned}
p\hat{I}_{s\alpha} &= \frac{K_r R_r}{L_s L_r - L_m^2}\hat{\Psi}_{r\alpha} - \frac{\left(R_s + K_r^2 R_r\right)L_r}{L_s L_r - L_m^2}\hat{I}_{s\alpha} + \\
&\quad + \frac{L_m}{L_s L_r - L_m^2}\omega\hat{\Psi}_{r\beta} + \frac{L_r}{L_s L_r - L_m^2}u_{s\alpha};\\
p\hat{I}_{s\beta} &= \frac{K_r R_r}{L_s L_r - L_m^2}\hat{\Psi}_{r\beta} - \frac{\left(R_s + K_r^2 R_r\right)L_r}{L_s L_r - L_m^2}\hat{I}_{s\beta} - \\
&\quad - \frac{L_m}{L_s L_r - L_m^2}\omega\hat{\Psi}_{r\alpha} + \frac{L_r}{L_s L_r - L_m^2}u_{s\beta};\\
p\hat{\Psi}_{r\alpha} &= -\frac{R_r}{L_r}\hat{\Psi}_{r\alpha} + R_r K_r \hat{I}_{s\alpha} - \omega\hat{\Psi}_{r\beta};\\
p\hat{\Psi}_{r\beta} &= -\frac{R_r}{L_r}\hat{\Psi}_{r\beta} + R_r K_r \hat{I}_{s\beta} + \omega\hat{\Psi}_{r\alpha}.
\end{aligned} \tag{1}$$

In a matrix form the system (1) is written as follows:

$$\frac{d\hat{X}}{dt} = A\hat{X} + BU \;, \tag{2}$$

where

$$\hat{X} = \left(\hat{I}_{s\alpha} \quad \hat{I}_{s\beta} \quad \hat{\Psi}_{r\alpha} \quad \hat{\Psi}_{r\beta}\right)^T; \; U = \left(u_{s\alpha} \quad u_{s\beta}\right)^T;$$

$$A = \begin{pmatrix} -a_{11} & 0 & a_{13} & a_{14} \\ 0 & -a_{22} & -a_{23} & a_{24} \\ a_{31} & 0 & -a_{33} & -a_{34} \\ 0 & a_{42} & a_{43} & -a_{44} \end{pmatrix}. \tag{3}$$

The values of matrix (3) elements are:

$$\begin{gathered}
a_{11} = a_{22} = \frac{\left(R_s + K_r^2 R_r\right)L_r}{L_s L_r - L_m^2};\, a_{34} = a_{43} = \omega;\\
a_{13} = a_{24} = \frac{K_r R_r}{L_s L_r - L_m^2};\, a_{31} = a_{42} = K_r R_r;\\
a_{23} = a_{14} = \frac{L_m \omega}{L_s L_r - L_m^2};\;\; a_{33} = a_{44} = R_r/L_r;\\
b_{11} = b_{22} = \frac{L_r}{L_s L_r - L_m^2}.
\end{gathered} \tag{4}$$

To ensure low sensitivity to coordinate perturbations, observer (2) must be made closed, i.e. introduce corrective feedbacks into its structure. Then the dynamics of the observer will be described by a system of differential equations [21]:

$$\frac{d\hat{X}}{dt} = A\hat{X} + BU + G\left(\hat{I}_s - I_s\right), \tag{5}$$

where $G = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \\ g_{31} & g_{32} \\ g_{41} & g_{42} \end{pmatrix}$ is the matrix of coefficients of corrective feedbacks.

The equations (5) can be written as follows:

$$\frac{d\hat{X}}{dt} = A\hat{X} + BU + GC\left(\hat{X} - X\right), \tag{6}$$

where the matrix $\mathrm{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$ aligns the state error vector $\hat{\mathrm{X}}$ - X with the vector of error in determining currents $\Delta I = \hat{\mathrm{I}}_{\mathrm{s}} - I_s$.

Let us introduce the notation

$$e = X - \hat{X} = \left(I_{s\alpha} - \hat{I}_{s\alpha} \quad I_{s\beta} - \hat{I}_{s\beta} \quad \Psi_{r\alpha} - \hat{\Psi}_{r\alpha} \quad \Psi_{r\beta} - \hat{\Psi}_{r\beta}\right)^T = \\ = \left(\Delta I_{s\alpha} \quad \Delta I_{s\beta} \quad \Delta\Psi_{r\alpha} \quad \Delta\Psi_{r\beta}\right)^T . \tag{7}$$

Then we subtract from the equations of the electromagnetic processes of the engine the equations describing the estimate of the vector X :

$$\frac{dX}{dt} - \frac{d\hat{X}}{dt} = \frac{de}{dt} = \\ = AX + BU - A\hat{X} - BU - GC\left(\hat{X} - X\right) = \\ = \left(A + GC\right)\left(X - \hat{X}\right) = \left(A + GC\right)e. \tag{8}$$

Then we write down the positive definite quadratic Lyapunov function for the observer synthesized

$$V = e^T e = \Delta I_{s\alpha}^2 + \Delta I_{s\beta}^2 + \Delta\Psi_{r\alpha}^2 + \Delta\Psi_{r\beta}^2 . \tag{9}$$

Taking into account (8), we find the total time derivative of this function

$$\frac{dV}{dt} = \left(\frac{de^T}{dt}\right)e + e^T\left(\frac{de}{dt}\right) = \\ = e^T\left(A + GC\right)^T e + e^T\left(A + GC\right)e = \quad , \\ = e^T\left[\left(A + GC\right)^T + \left(A + GC\right)\right]e = e^T Ke \tag{10}$$

where the matrix $K = \left(A + GC\right)^T + \left(A + GC\right)$ takes the form

$$K = \begin{pmatrix} -2a_{11} + 2g_{11} & g_{12} + g_{21} & a_{13} + a_{31} + g_{31} & a_{14} + g_{41} \\ g_{12} + g_{21} & -2a_{22} + 2g_{22} & -a_{23} + g_{32} & a_{24} + a_{42} + g_{42} \\ a_{13} + a_{31} + g_{31} & -a_{23} + g_{32} & -2a_{33} & -a_{34} + a_{43} \\ a_{14} + g_{41} & a_{24} + a_{42} + g_{42} & -a_{34} + a_{43} & -2a_{44} \end{pmatrix}. \tag{11}$$

Equation (11) shows that the matrix K is symmetric and $k_{34} = k_{43} = -a_{34} + a_{43} = 0$. The matrix coefficients can be determined using the Sylvester criterion [22]. In accordance with this criterion, for the negative definiteness of the quadratic form, it is necessary and sufficient that the angular minors of an even order of its matrix must be positive, and of an odd order must be negative.

According to Sylvester's criterion, the angular first-order minor of this matrix must be less than zero:

$$\Delta_1 = -2a_{11} + 2g_{11} < 0 . \tag{12}$$

This condition implies the requirement for the coefficient g_{11}:

$$g_{11} < a_{11} \Rightarrow g_{11} = na_{11} , \tag{13}$$

where $-\infty < \mathrm{n} < 1$.

The second-order angular minor of the matrix must be greater than zero:

$$\Delta_2 = \begin{vmatrix} -2a_{11} + 2na_{11} & g_{12} + g_{21} \\ g_{12} + g_{21} & -2a_{11} + 2g_{22} \end{vmatrix} = \\ = 4\left(n - 1\right)a_{11}\left(g_{22} - a_{11}\right) - \left(g_{12} + g_{21}\right)^2 > 0. \tag{14}$$

The inequality (14) implies that

$$g_{12} = -g_{21} , \tag{15}$$

$$4\left(n - 1\right)a_{11}\left(g_{22} - a_{11}\right) > 0 \Rightarrow -\left(g_{22} - a_{11}\right) > 0 \Rightarrow \\ \Rightarrow g_{22} < a_{11} \Rightarrow g_{22} = na_{11} \Rightarrow g_{22} = g_{11} . \tag{16}$$

We substitute the values of the found coefficients into the matrix K and find the angular minor of the third order

$$\Delta_3 = \begin{vmatrix} -2a_{11} + 2na_{11} & 0 & a_{13} + a_{31} + g_{31} \\ 0 & -2a_{11} + 2na_{11} & -a_{23} + g_{32} \\ a_{13} + a_{31} + g_{31} & -a_{23} + g_{32} & -2a_{33} \end{vmatrix} < 0 \tag{17}$$

or

$$4a_{11}^2\left(n - 1\right)^2\left(-2a_{33} + a_{13} + a_{31} + g_{31}\right) - \\ - 2a_{11}\left(n - 1\right)\left(g_{32} - a_{23}\right) < 0. \tag{18}$$

Let us assume that $g_{32} = a_{23}$. Then inequality (18) will be valid provided that

$$-2a_{33} + a_{13} + a_{31} + g_{31} < 0 . \tag{19}$$

Based on the convenience of calculating the fourth order minor, we can assume that

$g_{31} = -a_{13} - a_{31}$. In this case, an angular minor of the fourth order is

$$\Delta_4 = \begin{vmatrix} -2a_{11}+2na_{11} & 0 & 0 & a_{14}+g_{41} \\ 0 & -2a_{11}+2na_{11} & 0 & a_{24}+a_{42}+g_{42} \\ 0 & 0 & -2a_{33} & 0 \\ a_{14}+g_{41} & a_{24}+a_{42}+g_{42} & 0 & -2a_{44} \end{vmatrix} > 0 . \qquad (20)$$

Let us expand the determinant (20):

$$\begin{vmatrix} -2a_{11}+2na_{11} & 0 & a_{14}+g_{41} \\ 0 & -2a_{11}+2na_{11} & a_{24}+a_{42}+g_{42} \\ a_{14}+g_{41} & a_{24}+a_{42}+g_{42} & -2a_{44} \end{vmatrix} < 0 . \qquad (21)$$

Based on inequality (21) assume that

$$g_{41} = -a_{14} = -a_{23} , \Rightarrow g_{41} = -g_{32} . \qquad (22)$$

Under condition (22), inequality (21) takes the form

$$2a_{11}(1-n)\left[4a_{11}a_{44}(n-1) + (a_{24}+a_{42}+g_{42})^2\right] < 0 \qquad (23)$$

or

$$4a_{11}a_{44}(n-1) + (a_{24}+a_{42}+g_{42})^2 < 0 . \qquad (24)$$

Let us accept the condition $g_{42} = -a_{24} - a_{42}$, under which inequality (24) is satisfied for all values of the factor n possible by condition (13). It is necessary to take into account the equalities $a_{13} = a_{24}$ and $a_{31} = a_{42}$, from which it follows that

$$g_{42} = g_{31} = -a_{13} - a_{31} . \qquad (25)$$

The analysis performed according to Sylvester's criterion for the negative definiteness of the quadratic form (10) made it possible to write down the conditions, being guided by which we can find the matrix of coefficients of correcting feedbacks:

$$G = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \\ g_{31} & g_{32} \\ g_{41} & g_{42} \end{pmatrix} = \begin{pmatrix} na_{11} & g_{12} \\ -g_{12} & na_{11} \\ -a_{13}-a_{31} & a_{23} \\ -a_{23} & -a_{13}-a_{31} \end{pmatrix} ,$$

$$-\infty < n < 1 . \qquad (26)$$

Four coefficients g_{ij} are uniquely determined: the coefficients $g_{42} = g_{31}$ are constant numbers, and the coefficients $g_{41} = -g_{32}$ are linearly dependent on the rotor speed. When forming four more coefficients, it is necessary to select a factor (multiplier) n from the specified range and the coefficient g_{12}.

Taking into account (1) – (5) and (26), the equations of the observer of the rotor flux linkage take the form

$$\begin{aligned} p\widehat{\Psi}_{r\alpha} &= -a_{33}\widehat{\Psi}_{r\alpha} + a_{31}\widehat{I}_{s\alpha} - \omega\widehat{\Psi}_{r\beta} + \\ &+ g_{31}\left(\widehat{I}_{s\alpha} - I_{s\alpha}\right) + \bar{a}_{23}\omega\left(\widehat{I}_{s\beta} - I_{s\beta}\right) ; \\ p\widehat{I}_{s\alpha} &= -a_{11}\widehat{I}_{s\alpha} + a_{13}\widehat{\Psi}_{r\alpha} + \bar{a}_{14}\omega\widehat{\Psi}_{r\beta} + \\ &+ g_{11}\left(\widehat{I}_{s\alpha} - I_{s\alpha}\right) + g_{12}\left(\widehat{I}_{s\beta} - I_{s\beta}\right) + b_{11}u_{s\alpha} ; \\ p\widehat{\Psi}_{r\beta} &= -a_{44}\widehat{\Psi}_{r\beta} + a_{42}\widehat{I}_{s\beta} + \omega\widehat{\Psi}_{r\alpha} - \\ &- \bar{a}_{23}\omega\left(\widehat{I}_{s\alpha} - I_{s\alpha}\right) + g_{42}\left(\widehat{I}_{s\beta} - I_{s\beta}\right) ; \qquad (27) \\ p\widehat{I}_{s\beta} &= -a_{22}\widehat{I}_{s\beta} + a_{24}\widehat{\Psi}_{r\beta} - \bar{a}_{23}\omega\widehat{\Psi}_{r\alpha} + \\ &+ g_{21}\left(\widehat{I}_{s\alpha} - I_{s\alpha}\right) + g_{22}\left(\widehat{I}_{s\beta} - I_{s\beta}\right) + b_{22}u_{s\beta} , \end{aligned}$$

where $\bar{a}_{23} = \bar{a}_{14} = \dfrac{L_m}{L_s L_r - L_m^2}$.

Taking into account (4), (13), (15), (16), (22) and (25), system (27) can be written as follows:

$$\frac{d\widehat{X}}{dt} = A_1\widehat{X} + BU - B_1 I_{s\alpha} - B_2 I_{s\beta} , \qquad (28)$$

where

$$A_1 = \begin{pmatrix} -a_{11}+g_{11} & g_{12} & a_{13} & \bar{a}_{14}\omega \\ g_{21} & -a_{22}+g_{22} & -\bar{a}_{23}\omega & a_{24} \\ a_{31}+g_{31} & \bar{a}_{23}\omega & -a_{33} & -\omega \\ -\bar{a}_{23}\omega & a_{42}+g_{42} & \omega & -a_{44} \end{pmatrix} =$$

$$= \begin{pmatrix} (n-1)a_{11} & g_{12} & a_{13} & \bar{a}_{14}\omega \\ -g_{12} & (n-1)a_{11} & -\bar{a}_{23}\omega & a_{24} \\ -a_{13} & \bar{a}_{23}\omega & -a_{33} & -\omega \\ -\bar{a}_{23}\omega & -a_{24} & \omega & -a_{44} \end{pmatrix} ,$$

$$B_1 = \begin{pmatrix} g_{11} \\ g_{21} \\ g_{31} \\ g_{41} \end{pmatrix} , \; B_2 = \begin{pmatrix} g_{12} \\ g_{22} \\ g_{32} \\ g_{42} \end{pmatrix} , \quad -\infty < n < 1 , \qquad (29)$$

vectors and matrices $\widehat{X}$, B, U are the same as in expressions (3).

From (28), (29) it follows that the stator voltages and currents are external influences for the observer, and the angular velocity of the rotor is included in the structure of the observer and changes the numerical values of its parameters in transient processes. The free motion of the observer is determined by the eigenvalues of the state matrix A_1, which are the roots of the characteristic equation

$$\left|A_1 - \lambda E\right| = 0 . \qquad (30)$$

To select the coefficients g_{12} and n at different rotor velocities from the range, for example, $-\omega_0 \le \omega \le \omega_0$ it is necessary to affix some values of the coefficient g_{12} and plot the dependence of the real parts of the roots of the characteristic equation (30) on the factor n. Fig. 1 shows the dependences

$\mathrm{Re}(A_1) = f(n)$ at different velocities ($\alpha = \omega/\omega_0$) and coefficient g_{12} values. The calculations were carried out for an asynchronous machine 4A132M4U3 with the following technical data [23]: $P_n = 11\ \text{кW}$, $U_{s1} = 380\ \text{V}$; $n_{nom} = 1460\ \text{rpm}$.

From the graphs in Fig. 1 it follows that the observer maintains stability in a wide range of rotor rotation velocities, and the stability margin increases when the speed changes from lower values to higher ones. Additional calculations have shown that with a stationary rotor, the observer is also stable, although the stability margin is the smallest. The coefficient g_{12} within the range of $g_{12} = a_{11} \div 100\, a_{11}$ practically does not affect the nature of the dependencies $\mathrm{Re}(A_1) = f(n)$ and with its further increase, the stability margin begins to decrease. Therefore, the specified range is the most appropriate for choosing a coefficient g_{12}. At $g_{12} = a_{11} \div 100\, a_{11}$ the function $\mathrm{Re}(A_1) = f(n)$ reaches its lowest values in a fairly wide interval of flatness $n = (-1000) \div (-300)$, in which the observer's stability margin is greatest and remains practically unchanged. Thus, the analysis of the roots of the characteristic equation (30) at different velocities of rotation of the rotor and coefficients of correcting feedbacks made it possible to determine the best (in terms of the observer stability margin) intervals of the numerical values of those coefficients of correcting feedbacks, which are not fixed and must to be selected, for the adjusting of the control system.

In the Matlab / Simulink package, the simulation is performed of an asynchronous electric drive with a control system which is vector-oriented basing on rotor flux linkage vector. An asynchronous machine of the 4A132M4U3 type with the known parameters of the equivalent circuit and the above nominal data was simulated. The results of the study of the dynamics of the electric drive are presented in the form of transient processes in Fig. 2 and Fig. 3. First, the AM is simultaneously excited and started to a reduced speed. After the rotor magnetic flux module has reached the nominal value, the engine starts to accelerate to the nominal, followed by deceleration to a reduced speed. Transient processes occur with a fan load on the shaft.

In the torque diagrams, the electromagnetic torque of the motor M_e is highlighted in blue, and the load torque M_{st} is highlighted in red, which varies as a function of the speed according to the expression $k_0 + k_1\omega^2$. The load moment is removed and then applied again at the nominal rotation speed in the time interval 0.9 s – 1.3 s for the purpose of studying the properties of the flux linkage observer.

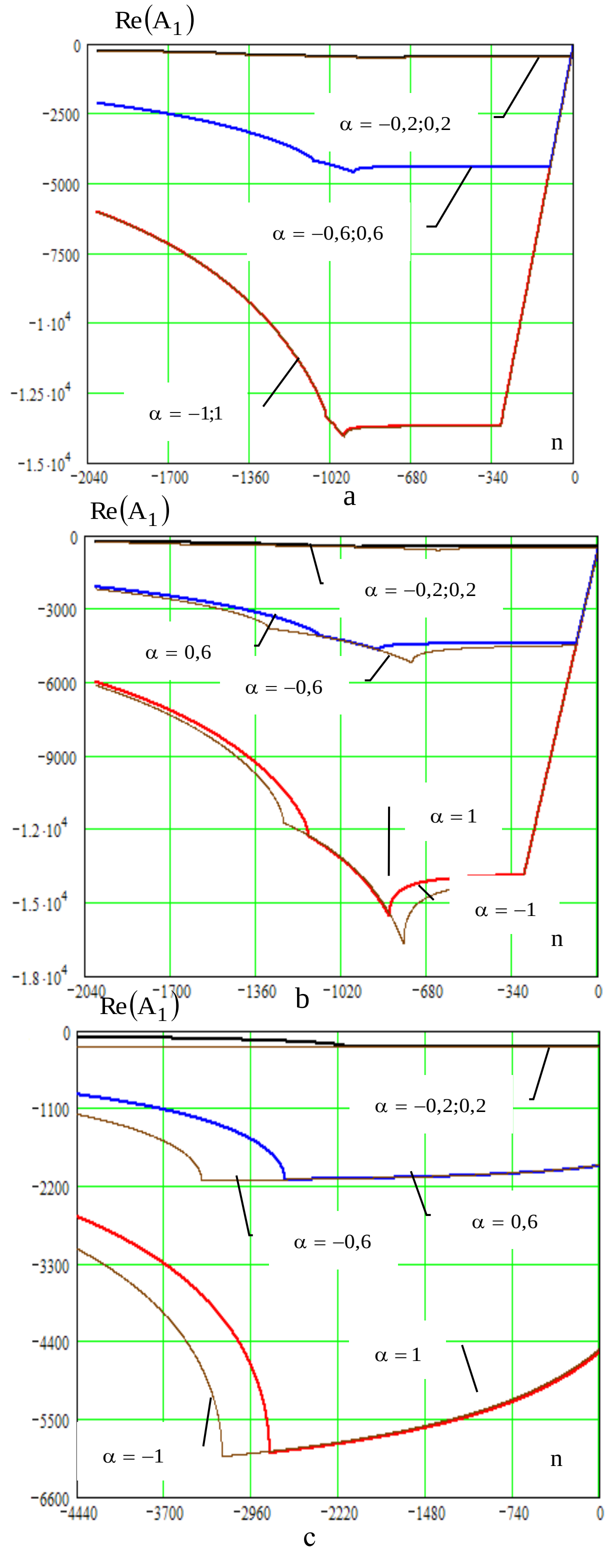

Fig. 1. **Dependencies of the smallest values of the real part of the roots of characteristic equation (30) of the matrix A_1 from the multiplier n under the correction coefficients g_{11} and g_{22} for different coefficient g_{12} values: a –** $g_{12} = a_{11}$; **b –** $g_{12} = 100\, a_{11}$; **c –** $g_{12} = 1000\, a_{11}$

***Source*: compiled by the author**

In the reactive power channel, the magnetic flux is stabilized at the nominal level, and the rotor rotation speed is controlled through the active power channel.

In the process of studying the influence of parametric disturbances on the observer's accuracy, the following parametric disturbances were initially set in the AM mathematical model: the active resistance of the rotor of an electric machine R_r is 30 % more (Fig. 2) and 30 % less (Fig. 3) the active resistance of the rotor in the observer model $\hat{R}_r$, which is taken equal to the nominal value of this parameter; the active resistance of the stator of the machine R_s is 20 % more (Fig. 2) and 20 % less (Fig. 3) the active resistance of the stator in the observer's model $\hat{R}_s$, which is taken equal to the nominal value of this parameter. As indicated in many literary sources, for example [2-3], [4], [7], [13], [19-20], the observer coordinates have the greatest sensitivity to the deviation of active resistances R_r and R_s, moreover, the sensitivity to a deviation of R_r is 3-4 times greater than to the deviation of R_s, and is the highest in comparison with other parameters of the equivalent circuit.

The matrix A_1 provides asymptotically stable free motion for any values of the rotation speed ω, coefficient g_{12} and multiplier n from the range specified in (29).

The vector control system with an open-circuited observer (1) with the above mentioned sufficiently large deviations of the active resistances of the engine from the same observer's parameters - ceases to function properly, passing into the oscillation mode of the support vector of the rotor's magnetic flux. Figure 4 shows the transient processes of identification of the rotor flux linkage by an open-circuited observer with an increase in the rotor resistance by 30 %, and the stator resistance – by 20 %. The signal at the output of the open-circuited observer is shown in red. The regulator of the rotor flux linkage module tends to stabilize it, while the actual flux linkage shown in blue differs significantly from that identified by the observer, which leads to a deterioration in the quality of control processes and may even lead to a loss of stability of the vector control system.

An observer with corrective feedback synthesized within this study has a low sensitivity to parametric disturbances of the engine in the real ranges of their changes encountered in practical operation. This property of the observer is demonstrated by the transient processes in Fig. 2 and Fig.3 where the number 1 denotes the real flux linkage Ψ_r of AM, and the number 2 denotes the estimate of the flux linkage $\hat{\Psi}_r$, according to which the negative feedback on the flux linkage regulator is closed. It should be noted that the observer better tracks the flux linkage of the AM rotor with positive resistance increments than with negative ones. To ensure the same quality of the observer's work, which is shown in Fig. 2 and Fig.3, it is necessary for the case of negative increments of resistance to increase in modulus the correction coefficients g_{11}, g_{22} three times compared to their values that were set when studying the operation of the system with positive increments of resistance.

Thus, the regulation and stabilization is carried out for the flux linkage $\hat{\Psi}_r$ estimate, which is calculated by the observer's information system. At the same time, the real flux linkage Ψ_r of AM deviates from the reference value of the estimate $\hat{\Psi}_r$ insignificantly, despite the significant deviations of the active resistances of the observer and the asynchronous machine, different in sign. Therefore, from consideration of the graphs of the rotor flux linkage modulus under the numbers 1 and 2 in Fig. 2 and Fig.3, it follows that the synthesized observer has asymptotic stability with incomplete invariance to parametric disturbances. The complete invariance to disturbances in the active resistances of the stator and rotor will be in the absence of a load on the AM shaft, when the rotor currents are equal to zero in the ideal idle mode. However, the stability in general (which guarantees the direct Lyapunov method) is observed, and the observation accuracy is ensured (under parametric disturbances and the values of the coefficients g_{ij} of correcting feedbacks recommended in the article) which is sufficient for the operability of the vector control system in a wide range of regulation of the rotor rotation velocity.

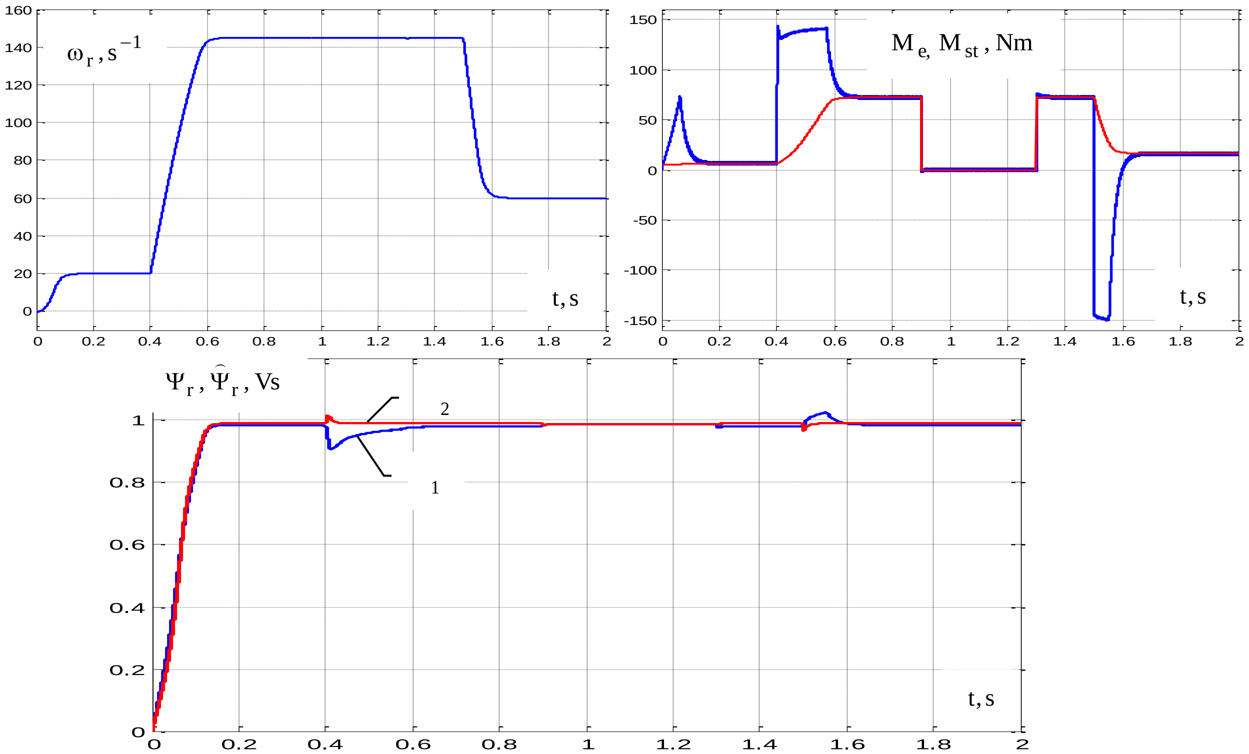

Fig. 2. **Transient processes in an asynchronous electric drive with an observer of flux linkage in the vector control system within the case of positive increment of resistances of the stator and rotor windings: 1 – flux linkage of asynchronous machine; 2 – flux linkage of observer**

***Source*: compiled by the author**

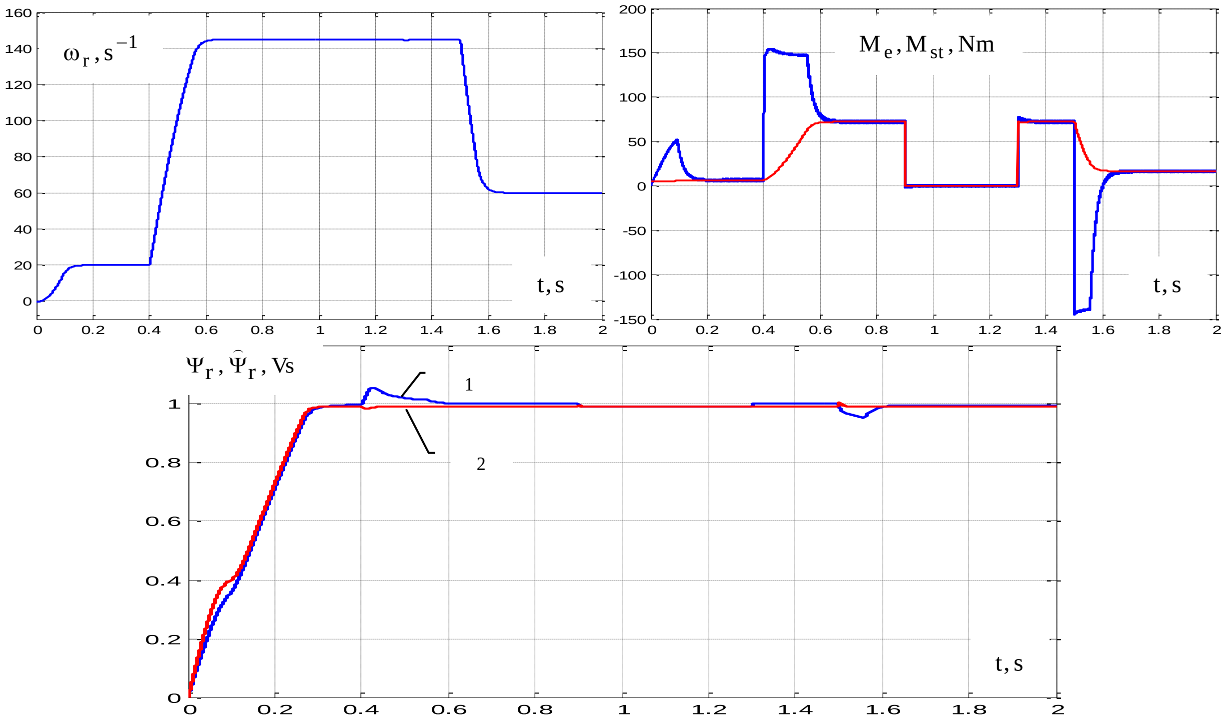

Fig. 3. **Transient processes in an asynchronous electric drive with an observer of flux linkage in the vector control system within the case of negative increment of resistances of the stator and rotor windings: 1 – flux linkage of asynchronous machine; 2 – flux linkage of observer**

***Source*: compiled by the author**

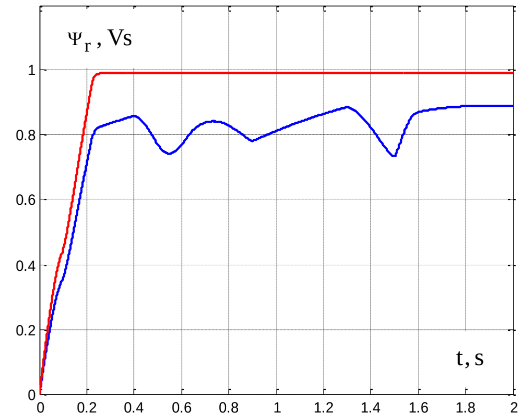

Fig.4. **Identification of flux linkage by an open-circuited observer**
***Source*: compiled by the author**

CONCLUSIONS

In this study, the structure of the AM's rotor flux linkage observer is determined and the values of the correcting feedback coefficients desirable by the criterion of the maximum observer stability margin are found, for which the direct Lyapunov method is applied together with numerical methods. The operation of the observer of the rotor flux linkage as a part of the vector field-oriented control system of an asynchronous electric drive has been investigated. By the method of mathematical modeling, it has been proved that an observer with the proposed informational structure and selected numerical values of the feedback coefficients has a low sensitivity to the inevitable multidirectional deviations in the active resistances of the stator and rotor of the electric motor during operation, which increases the stability margin of control system and the range of regulation of the rotation speed of asynchronous electric drives with vector control.

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ІНФОРМАЦІЙНА ПІДТРИМКА ПРОЦЕСУ СПОСТЕРЕЖЕННЯ ПОТОКОЗЧЕПЛЕННЯ РОТОРА АСИНХРОННОГО ДВИГУНА

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АНОТАЦІЯ

У статті досліджуються показники якості інформаційної підтримки процесу спостереження потокозчеплення ротора асинхронного двигуна в системах векторного керування в умовах дії параметричних збурень. Такий напрямок досліджень призначений розв'язати задачу побудови високоякісної інформаційної системи керування асинхронного електроприводу, в якій ліквідовано високу чутливість до змін параметрів об'єкту керування в процесі його роботи. Перш за все, це стосується температурних змін активних опорів статора і ротора, які суттєво впливають на потокозчеплення ротору. Отримання інформації відносно потокозчеплення ротору призначено на спостерігач, у складі якого чотири контури. У кожний з чотирьох контурів спостерігача з використанням вагових коефіцієнтів вводяться два коригувальних сигнали неузгодженості струмів статора асинхронної машини і спостерігача. Повний вектор коригувальних зворотних зв'язків спостерігача містить в такому випадку вісім коефіцієнтів. Застосування принципів модального управління для визначення їх числових значень приводить до громіздких рівнянь. Розв'язання задачі суттєво спрощується шляхом використання прямого методу Ляпунова, який дозволяє визначити можливу структуру спостерігача, стійку при параметричних збуреннях. Числові значення частини коефіцієнтів коригувальних зворотних зв'язків отримані шляхом аналізу квадратичної форми повної похідної функції Ляпунова за часом спостерігача, який синтезується. Для визначення оптимальних діапазонів зміни коефіцієнтів, що залишилися, застосовані чисельні методи обчислення коренів характеристичного рівняння системи спостерігача, замкненого зворотними зв'язками. Таким чином, ідея роботи полягає в тому, щоб в структурі спостерігача використовувати найбільше число коригувальних зворотних зв'язків і так підібрати їх значення із застосуванням прямого методу Ляпунова і чисельних методів, щоб забезпечувалася його низька чутливість до змін параметрів асинхронної машини.

Ключові слова: інформаційна система; спостерігач потокозчеплення; параметричні збурення; зміна параметрів; низька чутливість; функція Ляпунова; коригувальні зворотні зв'язки; коефіцієнти корекці

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