KAPITEL 2 / *CHAPTER 2* [2]
IDENTIFICATION OF INDUCTION MOTOR PARAMETERS IN VECTOR CONTROL ELECTRIC DRIVES

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Introduction

The main development direction of the frequency-regulated electric drive of alternating current is to create a highly dynamic, widely regulated, asynchronous electric drive, that is made based on inverter frequency converters without sensors inside and on the shaft of the induction motor. Making an induction motor without sensors inside eliminates the need to manufacture a special or rework a serial motor. As a result, high operational properties of the drive are maintained (without additional devices inside the motor) and the availability of the electric drive increases. The latter is explained by the wide use of general industrial asynchronous electric motors for such electric drives, which in practice is especially effective in the case of reconstruction of non-regulated asynchronous drives into frequency-regulated ones, since the serial induction motors previously installed on the drives are preserved.

The highest accuracy, adjustment range and speed of highly dynamic widely adjustable asynchronous electric drives can be achieved only by using vector laws of frequency control. An induction motor is a non-linear and multi-connected system. When using the principles of vector control, the output coordinates of an induction motor are the flux linkage of the rotor and the angular speed of the shaft rotation. The accuracy of adjusting the angular speed of rotation of the shaft primarily depends on the accuracy of determining the flow linkage. Direct methods of measuring rotor flux linkage are associated with intervention in the design of the electric machine and are not sufficiently reliable. Methods based on the use of mathematical models are used for indirect determination of the flow linkage of the IM rotor. Their main disadvantage is the non-invariance of the received information from motor temperature, steel saturation and other factors. In order to take into account different factors that affect the value of the flux linkage of an induction motor, it is important to use surveillance

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devices that allow you to indirectly determine the flux linkage and motor parameters. The introduction of additional devices into the induction motor control system leads to some deterioration of the quality of electromechanical transient processes, which negatively affects the quality of products, therefore it is also important to apply methods to improve these transient processes.

The purpose of the research is to identify the coordinates and parameters of an induction motor and to improve the quality of the transient processes of an asynchronous electric drive with vector control. It should be made while indirectly measuring the value of the flux linkage of the rotor of an induction motor by adapting the control system to changing the parameters of the motor as a control object.

The object of the research is the process of identifying the coordinates and parameters of an asynchronous electric drive with vector control.

The subject of the research is definition of coordinates and parameters of an induction motor in order to improve the quality of electromechanical transients of an asynchronous electric drive with vector control during indirect measurement of the flux linkage value of the rotor of an induction motor.

The main tasks of the research:

–synthesizing of surveillance devices for indirect determination of flux linkage, electrical parameters of an induction motor and the angle between a stationary reference system and a reference system rotating synchronously with the spatial vector of the flux linkage of the rotor of an induction motor;

–obtaining expressions for the adjustment coefficients of the parametric surveillance device, based on the nominal parameters of induction motors of a wide power range;

–taking into account the change in motor parameters that occurs under the influence of steel saturation by using a surveillance device;

–improving the quality of electromechanical transient processes of an asynchronous electric drive with vector control during indirect determination of coordinates and parameters of an induction motor with a squirrel-cage rotor;

–conducting mathematical modeling and experimental studies that will confirm

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or deny the obtained results and the effectiveness of the use of the developed methods of identification and improvement of the quality of electromechanical transient processes of an asynchronous electric drive with vector control.

A lot of induction motor control problems can be eliminated if the instantaneous values of the motor's state variables and parameters are known during the control process. However, since not all state variables can be determined directly, it is advisable to organize a state identifier (surveillance device) on the basis of which it is possible to easily determine the coordinates and parameters of the system that are not subject to direct measurement. The information obtained with the help of surveillance devices will allow to adapt the control system to changes of motor parameters.

Automatic frequency control systems using the principles of vector control with built-in flow sensors inside the motor have not found wide practical application due to the need to perform an alteration of serial electric motors, which leads to a general decrease in the reliability of the electric drive when additional sensors are installed. Among general industrial electric drives and deep-regulated electric drives for CNC machine tools, electric drives that do not contain sensors inside the motor are the most common. They ensure smooth operation in dusty, aggressive and explosive environments with high operational reliability. The main principles of building automatic frequency control systems without sensors inside the motor are the use of indirect means of measuring the regulated coordinates of the motor based on the application of mathematical or physical models of the object – the induction motor (in systems with the vector control principle).

2.1. Statement of the research problem

Alternating current electric motors together with controlled converters are complex multi-connected nonlinear control objects. The main difficulty in creating systems for automatic speed control of an AC electric drive is to create independent control of the speed and magnetic flux of the motor. If this task is completed, then the automatic speed control system of the AC electric drive with speed feedback is performed in the same way as the automatic speed control system of the DC electric drive, including the control methods of starting and braking modes.

If we consider an induction motor as a system of two three-phase concentrated windings (on the stator and rotor), then due to the rotation of the rotor, the differential equations describing the operation of the motor will have periodic coefficients. Therefore, in the vast majority of cases, an induction motor is considered as a generalized electric machine with following traditional assumptions [1-4]:

1. The magnetomotive forces (MMF) created by phase currents are sinusoidally distributed along the air gap of the motor, i.e. the influence of higher harmonics of the magnetic field is not taken into account.

2. The machine is symmetrical, that is, the phase windings have the same number of turns and the phase windings are shifted by an angle of 120°.

3. The effect of grooves is not taken into account.

4. The air gap between the stator and rotor is uniform.

5. There are no saturations and losses in steel.

6. The real distributed windings of the motor are replaced by concentrated windings under the condition of MMF preserving.

7. The parameters of the motor windings are reduced to the parameters of the stator windings. According to Kirchhoff's second law, an induction motor in a Cartesian coordinate system rotating at an arbitrary speed ω_c is described by the Park-Gorev equations in vector form [5-10]:

$$\begin{cases} \overline{U}_s = \overline{I}_s R_s + \frac{d\overline{\Psi}_s}{dt} + j\overline{\Psi_s}\omega_c \\ \overline{U}_r = \overline{I}_r R_r + \frac{d\overline{\Psi}_r}{dt} + j\overline{\Psi_r}(\omega_c - Z_p\omega_{дв}) \end{cases} \quad (1)$$

where R_s, R_r are the active resistance of the stator and rotor phase windings, respectively; $\overline{U}_s, \overline{U}_r, \overline{I}_s, \overline{I}_r, \overline{\Psi}_s, \overline{\Psi}_r$ are the vector of voltage, current and flux linkage of the stator and rotor, respectively; Z_p is the number of motor pole pairs; ω is the angular rotation velocity of the motor rotor.

The electromagnetic torque of the motor is defined as the vector product of flux linkage and current:

$$M_{ем} = \frac{3}{2} Z_p(\overline{\Psi_s} \times \overline{I_s}) \quad (2)$$

The flux linkage vectors can be written in terms of the resultant vectors of the stator and rotor currents:

$$\begin{cases} \overline{\Psi_s} = L_s \overline{I_s} + L_0 \overline{I_r} \\ \overline{\Psi_r} = L_r \overline{I_r} + L_0 \overline{I_s} \end{cases} \tag{3}$$

where L_0 is the inductance from the main flow.

Since the stator and rotor windings are symmetrical, and the air gap between the stator and rotor is uniform – the inductances of the stator phase windings, the rotor phase windings, as well as the mutual inductances of the stator and rotor phases will be the same. The inductances of the stator phase windings L_s and the rotor phase windings L_r consist of the inductances from the scattering fields and the inductances from the main flux:

$$\begin{cases} L_s = L_{s0} + L_{s\sigma} \\ L_r = L_{r0} + L_{r\sigma} \end{cases} \tag{4}$$

where $L_{s\sigma}$, $L_{r\sigma}$ are stator and rotor inductance from scattering fields; L_{s0}, L_{r0} – stator and rotor inductance from the main flux.

Since the rotor windings are reduced to the stator, then

$$L_0 = L_{s0} = L_{r0} \tag{5}$$

The equation of motion of the electric drive is as follows:

$$M_{em} - M_c = J \frac{\mathrm{d}\omega}{\mathrm{dt}} \tag{6}$$

where M_c is the moment of resistance on the electric motor shaft; J is the reduced moment of inertia of the electric drive to the electric motor shaft.

For the synthesis of vector speed control systems of an electric drive with an induction motor, the recording of its equations in one of the coordinate systems associated with one of the reference vectors is used [9-11].

The main purpose of IM control is to form the flux linkage and stator current signals in such a way that their cross product is a constant value. Certain advantages from the point of view of the simplicity of the object representation and the synthesis of regulators are formed by the rational choice of the angular velocity and the orientation of the coordinate axes in stable and transient modes. Since the resulting spatial vectors of current, voltage and flux linkage of the stator and rotor in the steady state are mutually fixed, if the supply voltage is sinusoidal, then the coordinate system that is tied to one of these vectors is suitable for optimization.

The orientation of the coordinate system relative to the resultant vector of the rotor flux linkage $\overline{\Psi_r}$ provides maximum simplification of the motor torque equation, i.e., provides the relatively simplest speed regulation of the electric drive. Since the synthesis of vector control systems is usually carried out on the basis of the structural diagrams of the object, we will choose exactly this form of representation of the induction motor in the adopted coordinate system. If necessary, the system of differential equations can be obtained on the basis of the scheme of state variables compiled according to the structural scheme.

The system of initial vector equations will have the form:

$$\begin{cases} \overline{U}_s = \overline{I}_s R_s + \frac{d\overline{\Psi}_s}{dt} + j\overline{\Psi_s}\omega \\ \overline{U}_r = \overline{I}_r R_r + \frac{d\overline{\Psi}_r}{dt} + j\overline{\Psi_r}(\omega_s - Z_p\omega) \\ \overline{\Psi_s} = \overline{I_s}L_s + \overline{I_r}L_0 \\ \overline{\Psi_r} = \overline{I_s}L_0 + \overline{I_r}L_r \\ M_{em} = \frac{3}{2}Z_p\frac{L_0}{L_r}(\overline{\Psi_r} \times \overline{I_s}) \end{cases} \tag{7}$$

To obtain the expressions describing IM when oriented on the reference vector Ψ_{1r} it is necessary to exclude the stator flux linkage Ψ_{s3} and the rotor current L_r from the original equations (7). As a result of the transformations, we obtain a system of equations in projections that describes an induction motor with a squirrel-cage rotor, as a control object, in a frame of reference oriented along the rotor flux linkage vector:

$$\left.\begin{aligned} &U_{1s} = I_{1s}\left[R' + pL'_s\right] - I_{2s}L'_s\omega_s - \Psi_{1r}\frac{K_r}{T_r}; \\ &U_{2s} = I_{2s}\left[R' + pL'_s\right] + I_{1s}L'_s\omega_s - \Psi_{1r}K_r Z_p\omega; \\ &\Psi_{1r} = \frac{I_{1s}L_0}{T_r p + 1}; \\ &\omega_c = \frac{I_{2s}R_r K_r + \Psi_{1r}Z_p\omega}{\Psi_{1r}}; \\ &M_{em} = \frac{3}{2}Z_p K_r I_{1s}\Psi_{1r}; \\ &\omega_2 = \frac{\left(M_{em} - M_c\right)}{Jp}. \end{aligned}\right\}, \tag{8}$$

where $K_r = L_0 / L_r$ is the electromagnetic connection coefficient of the rotor; $L'_s = L_{s\sigma} + K_r L_{r\sigma}$ is the equivalent leakage inductance of the motor; $R' = R_s + K_r^2 R_r$ is the equivalent active resistance of the motor; $T'_l = L'_s / R'$ is the equivalent electromagnetic time constant of the stator winding; $T_r = L_r / R_r$ is the electromagnetic time constant of the rotor winding.

In an induction motor with a squirrel-cage rotor with vector control – the moment generating I_{2s} and flux generating I_{1s} components of the stator current, the angular speed of motor shaft rotation ω_2, as well as the flux linkage of the rotor Ψ_{1r} are subject to regulation. A current sensor and a coordinate converter are used to measure signals proportional to the stator current and to determine the components of the stator current. A speed sensor – a tachogenerator or an incremental sensor – is used to measure the speed. The motor flux linkage signal can be measured, for example, using a Hall sensor. The use of this sensor is complicated. This is due to the fact that its installation on the rotor of a serial motor (gluing) is associated with disassembling and assembling the motor, which entails a change in the motor parameters, as well as difficulties arising from the output of a useful signal beyond the sensor. You can install the sensor on the motor stator. However, with the simplicity of the signal output, this method also involves disassembling and assembling the motor. Therefore, it is necessary to use methods that would allow determining the flux linkage of the induction motor rotor and do not require the installation of additional sensors. One of the possible options for such an indirect determination of flux linkage is the use of surveillance devices. For the indirect determination of the flux linkage of the induction motor rotor, it is possible to use a full-scale surveillance device and a reduced (shortened) surveillance device (they reproduce the state vector of the object), as well as a parametric surveillance device, which allows, in addition to the state vector, to restore the parameters of the surveillance object.

2.2. Synthesis of a full-scale surveillance device

We will consider the object formed by the third, fifth and sixth equations of the system (8) as the object of surveillance (Fig. 1).

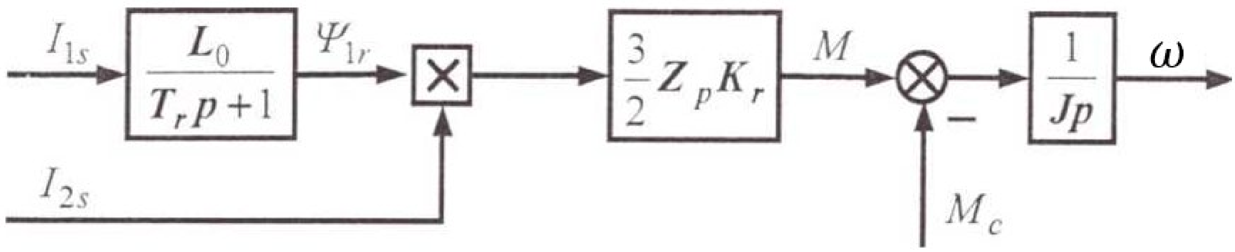

Figure 1 – Surveillance object for designing a full-scale surveillance device

The diagram shows the output variables of the rotor flux linkage Ψ_{1r} and the angular velocity of motor shaft rotation ω. Thus, in this system, which has the order of the operator $n = 2$ – the vector of state variables $\boldsymbol{x}$ has following form

$$x = [\Psi_{1r}\ \omega]^T$$

The system of equations in matrix form, which describes the selected surveillance object, looks like:

$$\dot{x} = A \cdot x + B \cdot u,$$

$$A = \begin{bmatrix} -\frac{1}{T_r} & 0 \\ \frac{3I_{2s}Z_pK_r}{2J} & 0 \end{bmatrix}; \ B = \begin{bmatrix} \frac{L_0}{T_r} \\ 0 \end{bmatrix}; \qquad u = I_{1s}.$$

Let's assume that the only coordinate that is measured in the object of surveillance is the speed of motor shaft rotation $x_2 = \omega$. Therefore, the matrix of the output signal will have following form:

$$C = [0 \quad 1].$$

For the selected object, the observation matrix $Q_H(n = 2)$ has following form:

$$Q_H = (C^T; A^T C^T) = \begin{bmatrix} 0 & \frac{3K_IK_rZ_p}{2J} \\ 1 & 0 \end{bmatrix}. \tag{9}$$

Since the rank of the observation matrix is equal to two, that is, the selected object of surveillance is completely observable.

For the synthesis of a complete surveillance device, we introduce the modal feedback matrix in the observer K

$$K = \begin{bmatrix} k_{12} \\ k_{22} \end{bmatrix}.$$

Let's define the characteristic polynomial of the observer

$$H_2(p) = \det(pI - A + KC)$$

The values of elements of the modal feedback matrix in the observer *K,* which determine the dynamics of the observer's work, can be found from the expression for the determinant $\det[pI - (A - KC)] = 0$, which has following form:

$$\det[pI - (A - KC)] = \begin{vmatrix} p + \dfrac{1}{T_r} & k_{12} \\ -\dfrac{3}{2} \cdot \dfrac{I_{2s} Z_p K_r}{J} & p + k_{22} \end{vmatrix} =$$

$$= p^2 + \left(k_{22} + \frac{1}{T_r}\right) p + \frac{k_{22}}{T_r} + \frac{3}{2} \cdot \frac{I_{2s} Z_p K_r k_{12}}{J}. \quad (10)$$

To provide the surveillance device with the desired dynamic properties, we choose the standard 2nd order Butterworth filter for the distribution of the roots of the characteristic equation of the surveillance device:

$$\mathrm{H}_2(\mathrm{p}) = p^2 + 1{,}4\omega_0 p + \omega^2{}_0, \quad (11)$$

where ω_0 is the geometric mean root of the characteristic equation of the surveillance device:

$$\frac{2}{T_\mu} \le \omega_0 \le K \frac{1}{T_\mu}, \quad K \epsilon [1 \dots 13] \quad (12)$$

By equating the coefficients with the same powers of p in equations (11) and (12), we obtain the values of the elements of the feedback matrix in the observer:

$$k_{21} = \frac{J}{1{,}5 I_{2s} K_r Z_p} \left(\omega^2{}_0 - \frac{1{,}4\omega_0}{T_r} + \frac{1}{T^2{}_r}\right); \quad (13)$$

$$k_{22} = 1{,}4\omega_0 - \frac{1}{T_r}. \quad (14)$$

The coefficient k_{12} is a function of the torque-generating component of the stator current I_{2s}. This coefficient can be written as a product of two parts: a constant part –

k_{const} and a variable part – k_{var}:

$$k_{12} = k_{const} \cdot k_{var}$$

$$k_{const} = \frac{2J}{3K_r Z_p}\left({\omega^2}_0 - \frac{1{,}4\omega_0}{T_r} + \frac{1}{{T^2}_r}\right), \qquad k_{var} = \frac{1}{I_{2s}}.$$

The variable part k_{var} of the coefficient k_{12} is inversely proportional to the moment-generating component of the stator current I_{2s}, that is, the coefficient k_{var} adapts to I_{2s}. At the value of the current $I_{2s} \to 0$ the variable part of the coefficient k_{12} approaches infinity, and therefore the entire coefficient k_{12} will also approach infinity. One of the ways to overcome the problem is to limit the value of the signal of the moment-generating component of the stator current I_{2s}, which is introduced into the observer, from below within the range of $\pm\Delta I$. Stator current limit value ΔI is determined on the basis of the necessary dynamic indicators of speed regulation in modes close to idling of the motor.

The state matrix of the full-scale surveillance device looks as follows:

$$A_{cn} = A - KC = \begin{bmatrix} -\dfrac{1}{T_r} & -k_{12} \\ \dfrac{3}{2}\dfrac{I_{2s}Z_p K_r}{J} & -k_{22} \end{bmatrix}.$$

Then the state equations of the full-scale surveillance device, written in the state space, will have the following form:

$$\hat{\dot{x}} = A_{cn} \cdot \hat{x} + B \cdot u + K \cdot \tilde{y}.$$

Let's write the observer's equation in expanded form:

$$\begin{bmatrix} \hat{\dot{\Psi}}_{1r} \\ \hat{\dot{\omega}} \end{bmatrix} = \begin{bmatrix} \frac{1}{T_r} & -k_{12} \\ \frac{3}{2}\frac{I_{2s}Z_p K_r}{J} & -k_{22} \end{bmatrix} \cdot \begin{bmatrix} \hat{\Psi}_{1r} \\ \hat{\omega} \end{bmatrix} + \begin{bmatrix} \frac{1}{T_r} & 0 \end{bmatrix} \cdot I_{1s}(t) + \begin{bmatrix} k_{21} \\ k_{22} \end{bmatrix} \cdot \tilde{\omega}(t), \quad (15)$$

where $\tilde{\omega}(t) = \tilde{y} = \omega(t) - \hat{\omega}(t)$ is the vector of the state variable restoration error, which can be measured.

Considering the scheme shown in Fig. 1, we will present a synthesized full-scale surveillance device. Its structural diagram is shown in Fig. 2.

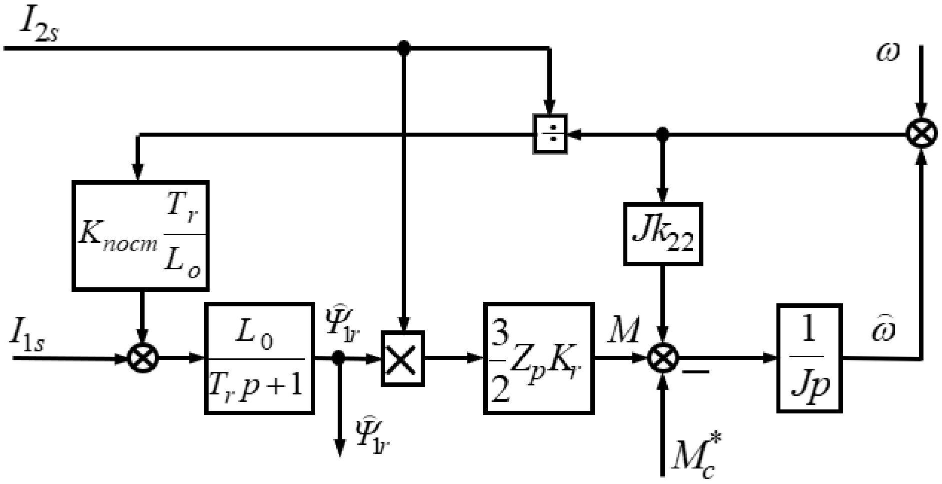

Figure 2 – Synthesized full-scale surveillance device

Full-order surveillance device (Fig. 2) contains two integrators. The input of the first one (aperiodic element) is fed with a control signal I_{1s} and an error signal multiplied by the coefficient k_{const}, and at the input of the second integrator – the restoration of the mechanical part – the error signal multiplied by the coefficient k_{22}, and the difference signal between the motor torque and the load torque.

The main part of the structure of the observer completely repeats the object of surveillance. As a result, the first integrator has a coefficient equal to $\frac{T_r}{L_0}$, and the second integrator has a coefficient inversely proportional to the total moment of inertia *of the* motor shaft and reduced moment of inertia of the mechanism. Therefore, connections are introduced to their inputs according to the coefficients $k_{const}\frac{T_r}{L_0}$ and Jk_{22}, not k_{const} and k_{22}.

In an induction electric drive with vector control and with the use of a full-scale surveillance device (if the resistance moment applied to the motor shaft is not taken into account in the surveillance device), the fluctuation of the restored value of the rotor flux linkage is significantly greater than the fluctuation of the rotor flux linkage, while the amplitude of the fluctuations of the restored value of the rotor flux linkage is about 20% of the set value. The fluctuation of the moment is due to the presence of a disturbing influence in the object of observation, which is not taken into account in the surveillance device. Neglecting the moment of resistance in the surveillance device leads to a significant error in restoring the rotor flux linkage.

2.3. Restoration of the load moment

In order to reduce fluctuations of the value of the restored flux linkage coordinate of the rotor, which causes a large fluctuation of the electromagnetic moment of the motor and the speed, it is necessary to introduce the value of the load moment $\mathrm{M_c}$ into the observer. To obtain a signal proportional to the load moment, you can use following equation:

$$\mathrm{M_c} = \mathrm{M} - \mathrm{M_{din}}. \tag{16}$$

That is, in order to obtain a signal proportional to the resistance moment, it is necessary to have signals proportional to the electromagnetic moment of the motor and the dynamic moment of the motor. To determine the electromagnetic moment, the signals of the moment-generating component of the stator current I_{2s} and the current of the rotor flux linkage Ψ_{1r} are used. Dynamic motor torque $\mathrm{M_{din}} = \mathrm{J\omega p}$ can be obtained by:

– measuring with an accelerometer (this option involves installing an additional sensor on the motor shaft, which is not always possible);

– differentiating the motor shaft speed signal.

When using the differentiation of the motor shaft rotational speed signal, a real type differential element is used

$$W_d(p) = \frac{T_1 p}{1+T_2 p}. \tag{17}$$

The structural scheme of obtaining the resistance moment signal is shown in Figure 3.

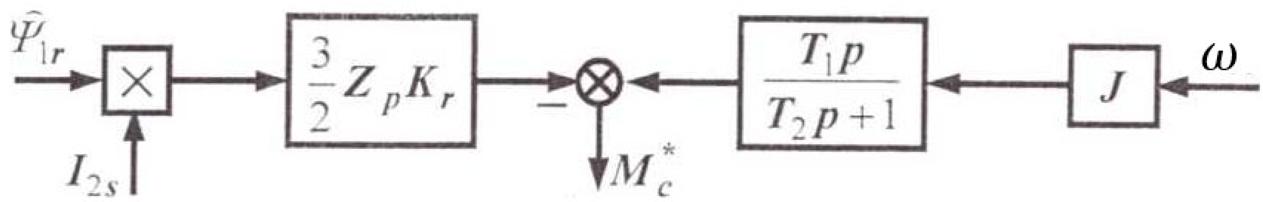

Figure 3 – Structural scheme of obtaining the resistance moment signal

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When using a real differentiation element, the error of restoring the flux linkage signal in transient modes is equal to 10% of the set value of the flux linkage of the motor rotor. The duration of the oscillations damping and the value of the recovery error $\widehat{\Psi}_{1r}$ depend on the values of the time constants T_1 and T_2 of the differentiation element.

In the stable mode, the error of restoring the rotor flux linkage when taking into account the moment by using a real differentiation element is less than in the case when the resistance moment is not taken into account. At the same time, the error of restoring the flow linkage decreases by 10...15 times and is approximately 1...2%. The error of restoring the rotor flux linkage when adjusting the speed up from the nominal value does not exceed 4%.

When restoring the resistance moment and taking it into account in the surveillance device, the fluctuation of the electromagnetic moment decreases by 10...15 times, and the accuracy of restoration of the rotor flux linkage increases (up to 98...99% when adjusting the speed below the nominal value, and up to 95...96% when adjusting the speed above the nominal value).

2.4. Restoration of the flux linkage signal in an AC electric considering elastic connections in mechanical transmission

It was assumed above that the kinematic connection between the executive body and the motor is not subject to elastic deformations and does not contain a gap. With this assumption, the speed of the motor and the reduced speed of the executive body are equal to each other at each moment of time. The influence of the mechanism on the operation of the motor turns out to be only in the fact that the mechanism determines the nature of the load on the motor shaft, and the moment of inertia is equal to the sum of the moments of inertia of the motor shaft, the gearbox and the moment of inertia of the executive body brought to the motor. However, in some cases, neglecting the elasticity can lead to incorrect results in the synthesis of electric drive control systems and deterioration of the quality of transient processes in terms of speed.

Let’s consider a two-mass electromechanical system. In this case, the system of equations describing the induction motor as a control object, when the reference system is oriented to the rotor flux linkage vector (8), is supplemented with equations that take into account the behavior of the considered system when elastic connections are taken into account and has the form:

$$\left.\begin{aligned} \omega_1 &= (M - M_{f1} - M_{12} + b(\omega_1 - \omega_2))\frac{1}{J_1 p} \\ \omega_2 &= (M_{дв} - M_{f1} - M_{12} + b(\omega_1 - \omega_2))\frac{1}{J_1 p} \\ M_{12} &= (\omega_1 - \omega_2)\frac{c_{12}}{p} \end{aligned}\right\}$$

where c_{12} is the equivalent stiffness of the elastic connection; b is the coefficient of internal friction; M_{f1} and M_{f2} are moments of forces of external viscous friction in the first and second masses; M_{12} is the moment in the elastic connection between the first and second masses; $\omega_1 = \omega$, ω_2 is an angular speed of rotation of the first and second masses, respectively; J_1, J_2 are the moments of inertia of the first and second masses, respectively.

$$M_{f1} = \omega \cdot a_1$$

$$M_{f2} = \omega_2 \cdot a_2$$

where a_1 and a_2 are coefficients of viscous friction

Let’s consider the use of a full-scale surveillance device for an electromechanical system in which elastic connections in mechanical transmission are taken into account. The surveillance object is described by the system of equations (18) and the third equation of the system (8). As the state vector in the selected surveillance object, which has the order of the operator n = 4, we will accept the vector:

$$x = [\,\psi_{1r} \quad \omega_2 \quad M_{12} \quad \omega_2\,]^T \tag{18}$$

The state matrix of the surveillance object, the control matrix, and the disturbance matrix have following form:

$$A = \begin{bmatrix} -1/T_r & 0 & 0 & 0 \\ 3I_{2s}Z_pK_r/(2J_1) & -(a_1+b)/J_1 & -b/J_1 & b/J_1 \\ 0 & c & 0 & -c \\ 0 & b/J_2 & 0 & -(a_2+b)/J_2 \end{bmatrix}$$

$$B_{cont} = \begin{bmatrix} \frac{L_0}{T_r} & 0 & 0 & 0 \end{bmatrix}^T; \qquad B_{\text{dist}} = [0 \quad 0 \quad 0 \ -\tfrac{1}{J_2}]^T$$

The vectors of the control and disturbance signals are equal to:

$$u_{\text{cont}} = [\, I_{1s} \quad 0 \quad 0 \quad 0\,]^T; \qquad u_{\text{dist}} = [0 \quad 0 \quad 0 \quad M_c].$$

As before, we consider that the only coordinate of the surveillance object that is measured is the angular speed of rotation of the motor shaft ω_1, then the matrix of the output signal has the form:

C= [0 1 0 0].

The selected object is observable because the rank of the observation matrix Q_H:

$$Q_H = [C^T \quad A^TC^T \quad (A^T)^2C^T \quad (A^T)^3C^T]$$

is equal to the order of the operator.

For the synthesis of the observer, we should introduce the feedback matrix in the surveillance device K:

$$Q_H = [k_{12} \quad k_{22} \quad k_{32} \quad k_{42}]^T$$

Let’s define the characteristic polynomial of the observer:

$$H_2(p) = det[pI - A + KC].$$

The values of the elements of the modal feedback matrix in the observer K, which determine the dynamics of the observer's work, can be found from the expression for the determinant $det[pI - A + KC]$:

$$det[pI - A + KC] =$$

$$= det\begin{bmatrix} p + (1/T_r) & k_{12} & 0 & 0 \\ (3I_{2s}Z_pK_r)/(2J_1) & p + (a_1+b)/J_1 + k_{22} & 1/J_1 & -1/J_1 \\ 0 & -c + k_{32} & p & c \\ 0 & -b/J_2 + k_{42} & -1/J_2 & p + (a_2+b)/J_2 \end{bmatrix} \qquad (19)$$

To give the surveillance device the desired dynamic properties, we choose the standard 4th order Butterworth filter for the distribution of the roots of the characteristic equation of the observer:

$$H(p) = p^4 + 2.6\omega_0 p^3 + 3.4\omega_0^2 p^2 + 2.6\omega_0^3 p + \omega_0^4 \tag{20}$$

where ω_0 is the geometric mean root of the observer (12).

By equating the coefficients with the same powers p, we obtain the values of the coefficients feedback matrix in the observer.

The coefficient k_{21} with the function of the moment-generating component of the static current and that is why this coefficient can be written in the following form:

$$k_{21} = \frac{1}{I_{2s}} k'_{12} \tag{21}$$

where:

$$k'_{12} = -\frac{2J_1 J_2}{3Z_p K_r T_r^2}\left(\frac{T_r^4\omega_0^4 - 2.6T_r^3\omega_0^3 + 3.4T_r^2\omega_0^2 - T_r\omega_0 + 1}{T_r(a_2 + b) - T_r^2 c\beta - J_2}\right).$$

The coefficient k_{21} adapts to the value of the moment-generating component of the stator current I_{2s} the same way as in the synthesis of a full-scale surveillance device for an electromechanical system with a rigid connection between the shaft and the mechanism.

Based on the obtained results, a full-scale surveillance device was synthesized. The surveillance device (Fig. 3) contains four integrators. The input of the first one is fed with a control signal – the flow-forming component of the stator current I_{2s} is taken on a scale determined by the amplification factor of the current sensor.

Also, an error signal taken on a scale determined by the coefficients $k_{12}, k_{22}, k_{32}, k_{42}$ is introduced to the inputs of all integrators. Coefficients $k_{12}, k_{22}, k_{32}\ amd\ k_{42}$ are elements of the observer's feedback matrix. A signal proportional to the recovered value of the moment of resistance M_c^* is also introduced into the observer. The following cases of ratio of moments of inertia of power and mechanism are of greatest interest for consideration:

– the moment of inertia of the motor J_1 is approximately equal to the moment of inertia of the mechanism J_2;

– moment of inertia of the motor J_1 is much less than the moment of inertia of the mechanism J_2.

For the second case, the deviation of the restored value of flux linkage from the real one during start-up is significantly greater than the deviation of the restored value of flux linkage for the case when $J_1 \approx J_2$. If the coefficients of internal and viscous friction are not taken into account, the error of restoration of flow linkage increases by 2-3 percent.

This does not significantly affect the quality of the adjustment of the angular speed of rotation of the motor shaft. It was established that the accuracy of restoration of the rotor flux linkage depends on the stiffness of the elastic connection between the motor and the mechanism.

The largest recovery error $\hat{\Psi}_r$ occurs when the moment of inertia of the mechanism exceeds the moment of inertia of the motor for more than 8 times.

A complete device for monitoring state variables has redundancy, which is expressed in the fact that this device evaluates the entire state vector of the object $x(t)$, although some part of this vector can be determined by the results of direct measurement of the output signal. This redundancy is eliminated when using a surveillance device, the order of which is less than the order of the object of surveillance – a reduced surveillance device.

2.5. Reduced surveillance device

Let’s consider the structural diagram shown on Fig. 4 as surveillance object.

Cross wiring $\omega_s I_{2s} L_s'$ taken with the simplification, which comes down to the fact that in the fourth equation of system (8):

$$\omega_c = \frac{I_{2s} K_r R_r}{\Psi_{1r}} + \omega Z_p$$

Is neglected by component $\frac{I_{2s} K_r R_r}{\Psi_{1r}}$

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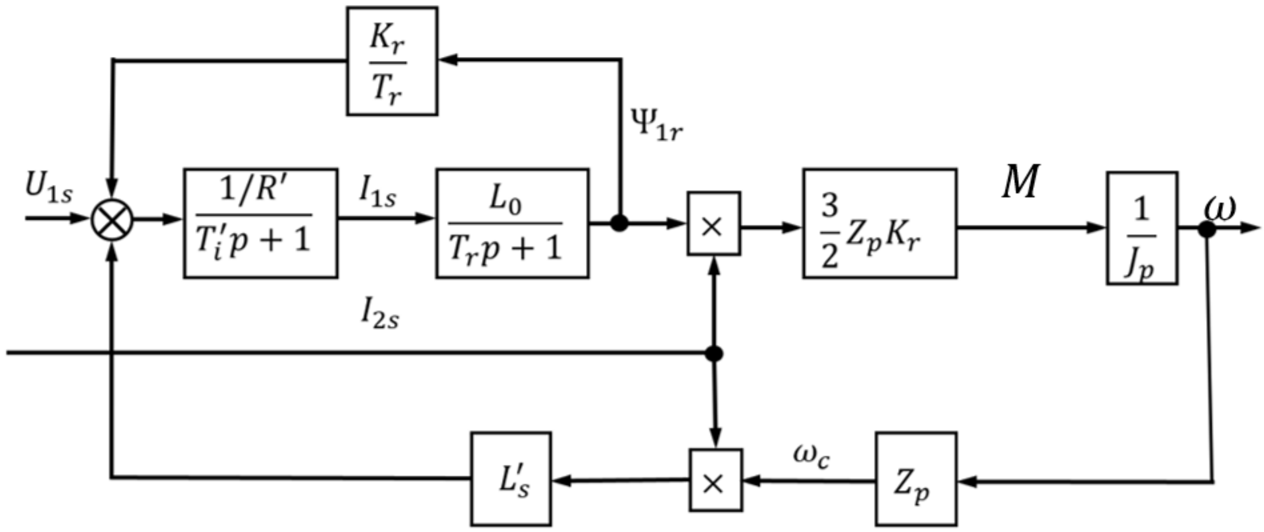

Figure 4 – Object of surveillance for the synthesis of a reduced observer

Let's have following notation:

$$x_1 = I_{1s}, \qquad x_2 = \Psi_{1r}, \qquad x_3 = \omega.$$

The selected system has an order $n = 3$. Let's take the state vector of the variables in the form:

$$x = [I_{1s} \quad \Psi_{1r} \quad \omega]^T.$$

The system of equations in matrix form describing the object of surveillance has the form:

$$\dot{x} = Ax + Bu,$$

where

$$A = \begin{bmatrix} -\frac{1}{T_l'} & \frac{K_r}{T_r T_l' R'} & I_{2s}L_s'Z_p \\ \frac{L_0}{T_r} & -\frac{1}{T_r} & 0 \\ 0 & 0 & \frac{3}{2}\cdot\frac{I_{2s}Z_pK_r}{J} \end{bmatrix} \qquad B = \begin{bmatrix} \frac{1}{R'T_l'} \\ 0 \\ 0 \end{bmatrix}; \qquad u = \begin{bmatrix} U_{1s} \\ 0 \\ 0 \end{bmatrix}.$$

Since the angular velocity of motor shaft rotation is available in the object of measurement surveillance and with the help of a coordinate converter, the flux-forming component of the stator current is $x_1 = I_{1s}$ and $x_3 = \omega$, the matrix of the output signal has the form:

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The observation matrix for the selected surveillance object has a non-zero determinant and a rank that is equal to three. Thus, the selected surveillance object is observable. The matrix of coefficients of the surveillance object A and the matrix of the input signal can be written in the form:

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}; \qquad B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}; \tag{23}$$

where

$$A_{11} = \begin{bmatrix} -\frac{1}{T_j'} & I_{2s}L_s'Z_p \\ \frac{L_0}{T_r} & 0 \end{bmatrix}; A_{12} = \begin{bmatrix} \frac{K_r}{T_rT_j'R'} \\ -\frac{1}{T_r} \end{bmatrix}; B_1 = \begin{bmatrix} \frac{1}{R'T_j'} \\ 0 \end{bmatrix};$$

$$A_{21} = \begin{bmatrix} 0 & \frac{3}{2} * \frac{I_{2s}Z_pK_r}{J} \end{bmatrix}; \qquad A_{22} = [0]; \qquad B_2 = [0];$$

According to [4], the equations describing the surveillance object in the state space can be written in the form:

$$\left.\begin{aligned} \dot{y} = A_{11}y + A_{12}w + B_1u \\ \dot{w} = A_{21}y + A_{22}w + B_2u \end{aligned}\right\}, \tag{24}$$

where y is the vector of output data of the surveillance object; u is the vector of input signals; $\dot{y}$ is state vector of the surveillance device; w is the output vector of the surveillance device.

Taking into account the accepted notations, transformations and the first equation of the system (24), we obtain the equation of the reduced surveillance device:

$$\widehat{\dot{w}} = (A_{22} - LA_{12})\widehat{w} + L(\dot{y} - A_{11}y - B_1u) + A_{21}y + B_2u\ . \tag{25}$$

This equation takes into account the external signal $A_{21}y + B_2u$, which is also present in the second equation of system (24). By selecting the matrix L – the roots of the surveillance device (25) can be given the desired values. The matrix L that is included in the equation of the reduced surveillance device has the dimension $n_1 \times r_1$. For the selected surveillance object, it looks like this:

$$L = [l_1 \quad l_2].$$

The general appearance of the reduced surveillance device is shown in Figure 5.

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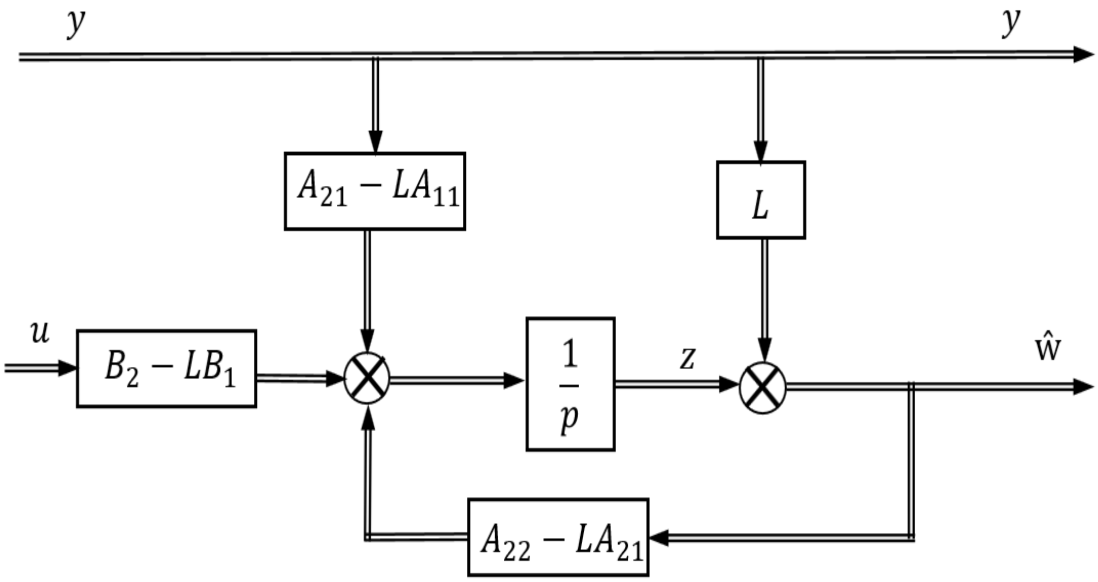


Figure 5 – General view of the reduced surveillance device

The observer coefficients are equal to:

$$B_2 - LB_1 = -\frac{l_1}{R'T_j'}.$$

$$A_{21} - LA_{11} = \left[\frac{l_1}{T_j'} - \frac{l_2 L_0}{T_r} \quad \frac{3Z_p K_r}{2J} - l_1 I_{1s} L_s' Z_p\right].$$

$$A_{22} - LA_{12} = \frac{l_2}{T_j'} - \frac{l_1 K_r}{T_r T_j' R'}.$$

The structural diagram of the reduced surveillance device with matrix coefficients is presented in Figure 6-a. After transformation and transition to scalar transfer functions, the complete structural diagram of the reduced surveillance device of the variable $x_2 = \Psi_{1r}$, with scalar transfer functions of elements is presented on Figure 6-b.

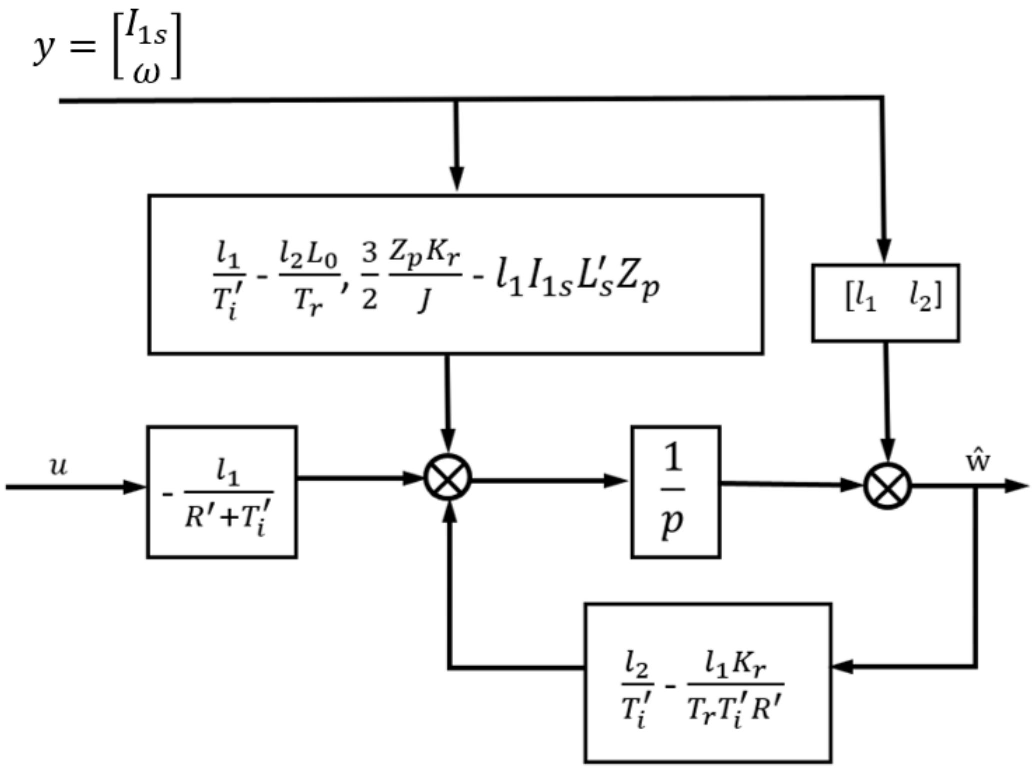
The characteristic polynomial of the reduced surveillance device, which has the form

$$\det[pl - (A - KC)] = p + \frac{l_2 T_r R' - l_1 K_r}{T_r T_j' R'}. \tag{26}$$

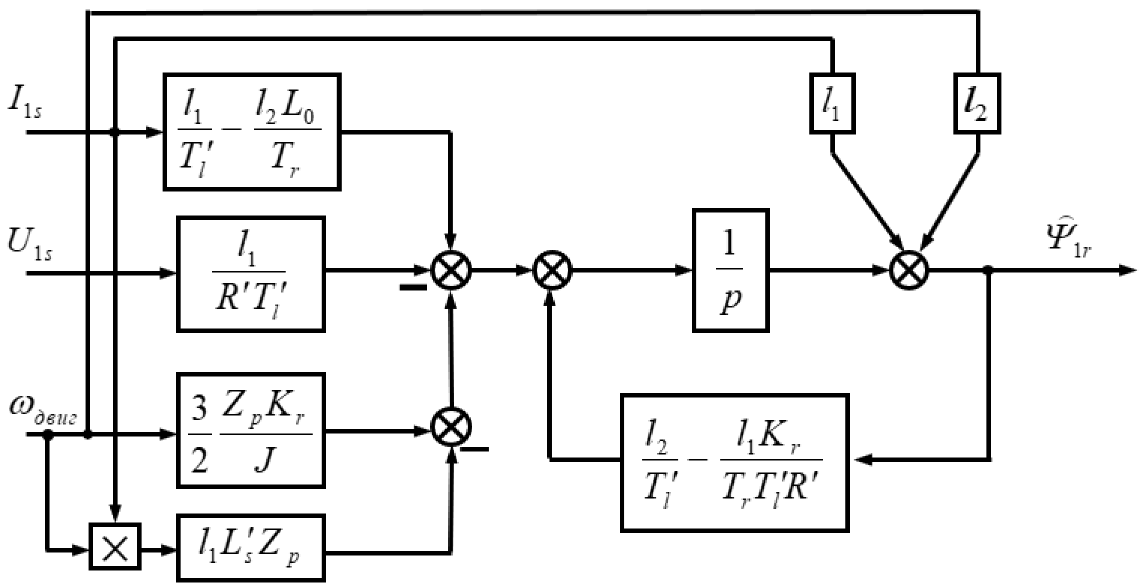
allows us to determine the values of the elements of the matrix *L*.

In order to give the surveillance device the desired dynamic properties, we choose standard 1th order Butterworth filter for the distribution of the roots of the characteristic equation of the observer:

$$H_2(p) = p + \omega_0, \tag{27}$$



a



b

Figure 6 – Structural diagram of the reduced rotor flux linkage surveillance device with matrix coefficients (a) and with scalar transfer functions (b)

The analysis of the coefficients of the observer l_1 and l_2 shows that it is possible to consider four cases of choosing the values of the coefficients that are included in the matrix L and that affect the dynamics of the system (three extreme cases and one arbitrary):

1. $l_1 = l_2 = 0$; 2. $l_1 = 0$; $l_2 \neq 0$; 3. $l_1 \neq 0$; $l_2 = 0$; 4. $l_1 \neq 0$; $l_2 \neq 0$;

In the first case, when the matrix elements will be equal to zero, the surveillance device degenerates and the restored value depends only on the speed and gain:

$$\frac{3Z_pK_r}{2J}.$$

Such a surveillance device will not allow you to reproduce the value of the flux linkage of the motor rotor correctly, since the obtained value will actually depend only on the output coordinate of the object of surveillance – $\omega_{дв}$ and input and disturbing signals will not affect it.

In the second case, the restored coordinate will depend on the stator current I_{1s}, speed ω and positive feedback on the restored value of the rotor flux linkage (Fig. 7). The value of the coefficient l_2 is determined by comparing expressions with the same degrees of p in equations (26) and (27). In this case, the coefficient l_2 will be equal to:

$$l_2 = \omega_0 T_j' \tag{28}$$

In the third case, the restored coordinate will depend on the input influence U_{1s}, the component of the stator current I_{1s}, the speed ω, and also on the positive feedback on the restored value of the rotor flux linkage (Fig. 7, b). The value of the coefficient l_1 is determined by comparing expressions with the same degrees of p in equations (26) and (27). In this case, the coefficient l_1 will be equal to:

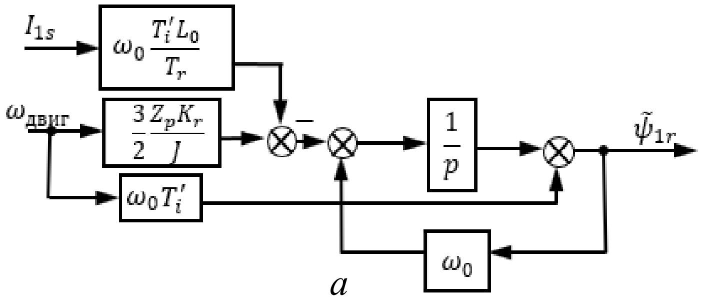
$$l_1 = -\omega_0 \frac{T_r T_j' R'}{K_r}. \tag{29}$$

In the fourth case, when the coefficients of the matrix L are not equal to zero, in order to find them in the expression:

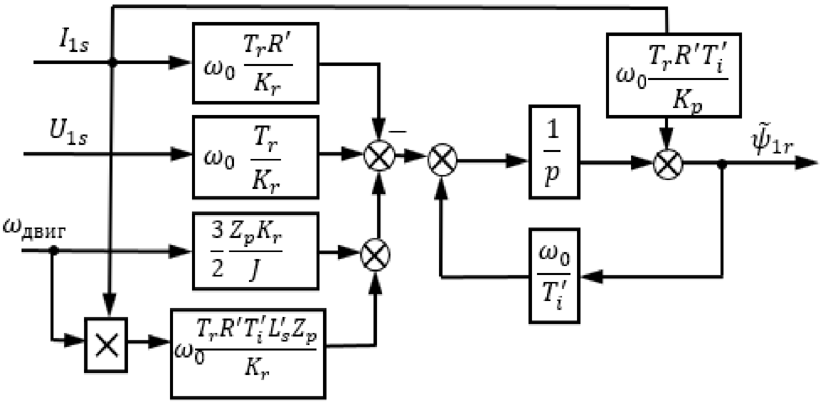
$$\frac{l_2 T_r R' - l_1 K_r}{T_r T_j' R'} = \omega_0,$$

we should assume that the coefficient l_2 is determined by the expression: $l_2 = 2\omega_0 T_l'$. Then the coefficient l_1 will be equal to:

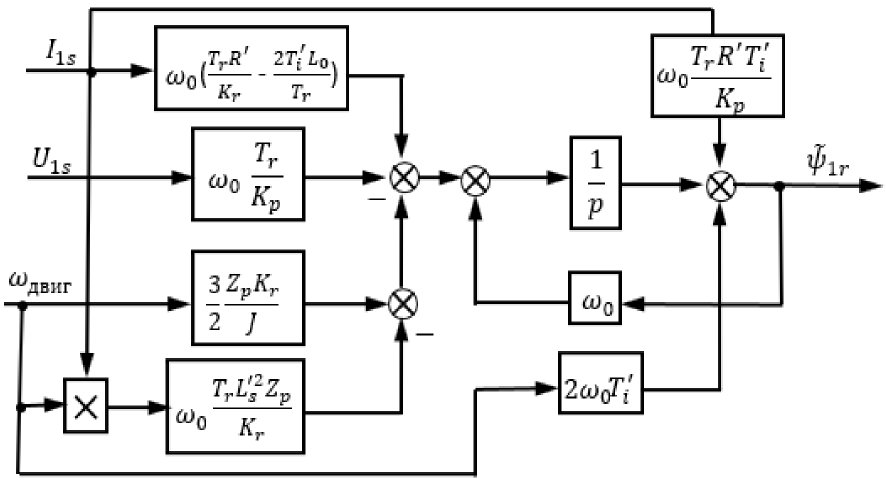
$$l_1 = \omega_0 \frac{T_r T_j' R'}{K_r} \tag{30}$$



a



b



c

Figure 7 – Structural diagrams of the reduced surveillance device at the limit values of the coefficients l_1 and l_2:

a – $l_1 = 0, l_2 \neq 0$; b – $l_2 = 0, l_1 \neq 0$; c – $l_1 \neq 0, l_2 \neq 0$.

Then the structural diagram of the reduced surveillance device will take the form presented on Fig.7, c.

At the beginning of the start, the deviation error of the restored rotor flux linkage value from the motor rotor flux linkage value is about 10%. But then the recovery error drops to zero. When $l_1 = 0;\ \ l_2 \neq 0$ – the recovery error decreases exponentially, and when $l_1 \neq 0;\ \ l_2 = 0$ – the error decreases according to the law that is close to linear. Also, the reduction of the rotor flux linkage recovery error leads to a reduction in the system's oscillations and an improvement in the system's dynamic properties.

In case when $l_1 \neq 0;\ \ l_2 \neq 0$ and the angular velocity of rotation of the motor shaft reaches a given value in the system; there are fluctuations in the angular speed, the restored value of the flux linkage of the motor rotor, as well as the electromagnetic moment, which decay according to the exponential law. The amplitude of speed fluctuations is about 15% of the set value. Thus, by choosing the value of the coefficients, it is possible to give the system a certain value of oscillation and the error of restoration of the flux linkage of the rotor, which affects the dynamic properties of the electric drive.

2.6. Parametric surveillance device

Between the main functional nodes of an electric machine there is not only a close electromagnetic and mechanical connection, but also a mutual relationship between the technical condition of these nodes. This means that the occurrence of damage to some node leads to a change in the electromagnetic, thermal, vibrational and acoustic processes of the functioning of the nodes. When operating electric motors, deviations in the state of the main components are not immediately apparent. However, the parameters of the machine such as resistance, time constants, inductance of the windings in the presence of any damage begin to change, which leads to a deterioration in the quality of adjustment by the output coordinates.

As a result of saturation and heating, the parameters of the control object change. A change in the constant time of the rotor circle can reach 100% and lead to system disruption [14-16]. The instability of this parameter, as well as the instability of resistance R_r and R_s, and the constant time T_j' leads to the need to build a rough control.

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In addition, uneven heating of the rotor and stator windings leads to an increase in the resistance of the rotor and stator windings and, as a result, changes in the time constants T_r and T_j'. As a result of slow change in the value of the time constant of the rotor, it is possible to identify the parameters of the object in real time. The obtained values of the object parameters are used for fine-tuning of control system.

To adapt the automatic control system to changes in motor parameters that occur during long-term operation (for example, when the temperature of the motor windings increases), it is necessary to restore those parameters of the machine that are most prone to change. As an object of surveillance, we will take the part of the induction motor described by the system of equations:

$$\left.\begin{aligned} pI_{1s} &= \frac{1}{R'T_j'}\left(U_{1s} + \Psi_{1r}\frac{K_r}{T_r} + I_{2s}L_s'Z_p\omega\right) - I_{1s}\frac{1}{T_j'} \\ p\Psi_{1r} &= I_{1s}\frac{1}{T_r} - \Psi_{1r}\frac{1}{T_r} \end{aligned}\right\}. \tag{31}$$

Let's assume that the motor control system fully compensates all cross-connections that take place in the control object. Therefore, in the given equations, the component

$$I_{2s}L_s'Z_p\omega$$

can be ignored. As a result, we will get a system of equations describing the object of surveillance:

$$\left.\begin{aligned} pI_{1s} &= \frac{1}{R'T_j'}\left(U_{1s} + \Psi_{1r}\frac{K_r}{T_r}\right) - I_{1s}\frac{1}{T_j'} \\ p\Psi_{1r} &= I_{1s}\frac{1}{T_r} - \Psi_{1r}\frac{1}{T_r} \end{aligned}\right\}. \tag{32}$$

In this object, with the help of coordinate converter, we can get information about the signals of the component of the stator current I_{1s} and the component of the stator voltage U_{1s}, moreover – the latter signal is the input coordinate. We will assume that the coordinate Ψ_{1r} is not subject to direct measurement. The transfer function connecting the input and output signals in the object of surveillance has the form:

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$$W(p)=\frac{I_{1s}(p)}{U_{1s}(p)}=\frac{\frac{T_r^2}{R'}p+\frac{T_r}{R'}}{p^2+\frac{T_r+T_l'}{T_rT_l'}p+\frac{T_r-K_rL_0}{T_r^2T_l'}}. \quad (33)$$

We take the vector of state variables x as:

$$x=[I_{1s}\ \ \Psi_{1r}]^T$$

The system of equations, in the vector-matrix form, in the state space, which describes the object of surveillance has the form:

$$\begin{cases}\dot{x}=Ax+Bu;\\ \quad y=Cx\end{cases}$$

where:

$$A=\begin{bmatrix}-\frac{1}{T_l'} & \frac{K_r}{T_rT_l'R'}\\ \frac{L_0}{T_r} & -\frac{1}{T_r}\end{bmatrix};\ B=\begin{bmatrix}\frac{1}{T_l'R'} & 0\\ 0 & 0\end{bmatrix};\ C=[1\quad 0];$$

$$y=\begin{bmatrix}I_{1s}\\ 0\end{bmatrix};\ u=\begin{bmatrix}U_{1s}\\ 0\end{bmatrix};$$

Observation matrix Q_H (n=2) for the selected object has the form:

$$Q_H=(C^T;\quad A^TC^T)=\begin{bmatrix}1 & -\frac{1}{T_r}\\ 0 & \frac{K_r}{T_rT_l'R'}\end{bmatrix}.$$

The rank of the observation matrix is equal to two, that is, the selected object is observable. To synthesize a parametric observer, we divide the numerator and denominator of the transfer function of the control object by a polynomial ($p+\lambda_2$) and write the transfer function of the surveillance object in the form:

$$W(p)=\frac{I_{1s}(p)}{U_{1s}(p)}=\frac{b_1+b_2\frac{1}{p+\lambda_2}}{p-a_1-a_2\frac{1}{p+\lambda_2}}. \quad (34)$$

where:

$$a_1=\lambda_2-\frac{T_r+T_l'}{T_rT_l'};\ a_2=\frac{(\frac{T_r+T_l'}{T_rT_l'}-\lambda_2)(-2\frac{T_r-K_rL_0}{T_r^2T_l'}+3\lambda_2)}{-\lambda_2};$$

$$b_1=\frac{T_r^2}{R'};\quad b_2=-2\frac{(\frac{T_r}{R'}-\frac{T_r^2}{R'}\lambda_2)}{\lambda_2}$$

Based on (34), we can write down the expression

$$\left(p - a_1 + \lambda_1 - \lambda_1 - a_2 \frac{1}{p + \lambda_2}\right) I_{1s} = (b_1 + b_2 \frac{1}{p + \lambda_2}) U_{1s}. \tag{35}$$

After the transformation, we get the expression for the measured coordinate:

$$I_{1s} = \frac{1}{p + \lambda_1}\left(b_1 + \frac{b_2}{p + \lambda_2}\right) U_{1s} + (a_1' + \frac{a_2}{p + \lambda_2}). \tag{36}$$

The control object determined by the transfer function (34) is characterized by the equations regarding the state variables:

$$\left.\begin{matrix} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} a_1 & 1 \\ a_2 & -\lambda_1 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \cdot u \\ y = x_1 \end{matrix}\right\}. \tag{37}$$

The equation describing the adaptive surveillance device in the state space has the form [15-20]:

$$\left.\begin{matrix} \hat{\dot{q}} = -\lambda_2 \hat{q} + u \\ \begin{bmatrix} \widehat{\dot{x_1}} \\ \hat{\dot{z_1}} \end{bmatrix} = \begin{bmatrix} \widehat{a_1} & \widehat{a_2} \\ 1 & -\lambda_2 \end{bmatrix} \times \begin{bmatrix} y \\ z_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \times \left([\widehat{b_1} \quad \widehat{b_2}] \times \begin{bmatrix} u \\ \widehat{q_2} \end{bmatrix} - \lambda_1 \tilde{y}\right) \end{matrix}\right\}. \tag{38}$$

where:

$$\widehat{a_1} = -y_1 y \tilde{y}; \quad \widehat{b_1} = -\delta_1 u \tilde{y}; \quad \tilde{y} = y - \hat{y};$$

$$\widehat{a_2} = -y_2 y \tilde{y}; \widehat{b_2} = -\delta_2 \widehat{q_2} \tilde{y}.$$

δ_1 and δ_2 are the gain coefficients of the adaptation circles, which determine the quality indicators of the surveillance device. To ensure the stability of the surveillance device [15-20], the coefficients must be positive, and

$$\lambda_i \geq \frac{1}{T_{min}}$$

where T_{min} is the minimum time constant in the control object.

According to the obtained equations, a parametric surveillance device was synthesized (Fig. 8, the surveillance device is circled by a dotted line), which simultaneously restores the motor parameters and one of its rotor flux linkage coordinates Ψ_{1r}.

The parametric surveillance device is a significantly nonlinear object, for which it is impossible to obtain analytically the dependences that would connect the adjusting coefficients of the surveillance device δ_1, δ_2, γ_1 and γ_2 with the motor parameters: inductance L_0, equivalent resistance R', time constants of the rotor T_r and stator T_l'. Therefore, these dependencies were obtained by using the experiment planning method:

$$\delta_1 = \left(16.02 + 0.575T_l'^* - 0.649L_0^* - 0.975T_r^*T_l'^* + 1.27T_r^*R'^* + 0.3T_l'^*L_0^* - \right.$$
$$\left. - 0.81T_l'^*R'^* + 0.65L_0^*R'^* - 0.38T_r^{*2} - 0.344T_l'^{*2} + 1.02L_o^{*2}\right) \cdot 10^{-6};$$

$$\gamma_1 = \left(17.9 + 4.145T_l'^* - 1.393L_0^* + 0.799R'^* + \right.$$
$$\left. + 0.62T_l'^*R'^* - 1.854T_r^{*2} - 1.6L_0^{*2} - 2.265R'^{*2}\right) \cdot 10^{-2};$$

$$\delta_2 = \left(5.306 + 0.475T_r^* + 0.394T_l'^* - 0.308L_0^* + 0.309T_r^*T_l'^* - \right.$$
$$- 0.24T_r^*L_0^* + 0.365T_r^*R'^* - 0.322T_l'^*L_0^* + 0.372T_l'^*R'^* +$$
$$\left. + 0.578L_0^*R'^* - 0.24T_r^{*2} - 0.308T_l'^{*2} - 1.27L_o^{*2}\right) \cdot 10^{-6};$$

$$\gamma_2 = \left(21.95 + 0.801T_r^* - 0.732T_l'^* + 1.758L_0^* - 1.063T_r^*T_l'^* + 2.313T_r^*R'^* - \right.$$
$$\left. - 0.875T_l'^*L_0^* + 2T_l'^*R'^* - 1.12L_0^*R'^* - 0.735T_l'^{*2} - 0.777L_o^{*2} - 8.19R'^{*2}\right) \cdot 10^{-3}.$$

However, change of the motor parameters at constant values of δ_1, δ_2, γ_1 and γ_2 causes a deterioration in the quality of regulation in the case when the motor parameters change beyond the accepted limits: rotor time constant − $(0.5\ldots2.0) \cdot T_r$; equivalent time constant of the stator windings $(0.5\ldots1.5) \cdot T_l'$; equivalent stator resistance $(0.75\ldots2.5) \cdot R'$; inductance from the main flow $(0.8\ldots1.2)L_0$. T_r, T_l', R', L_0 are values that are determined according to the passport data of the motor. The obtained expressions for adjustment coefficients are intended for determining these coefficients in electric drives with power from 1.1 to 90 kW.

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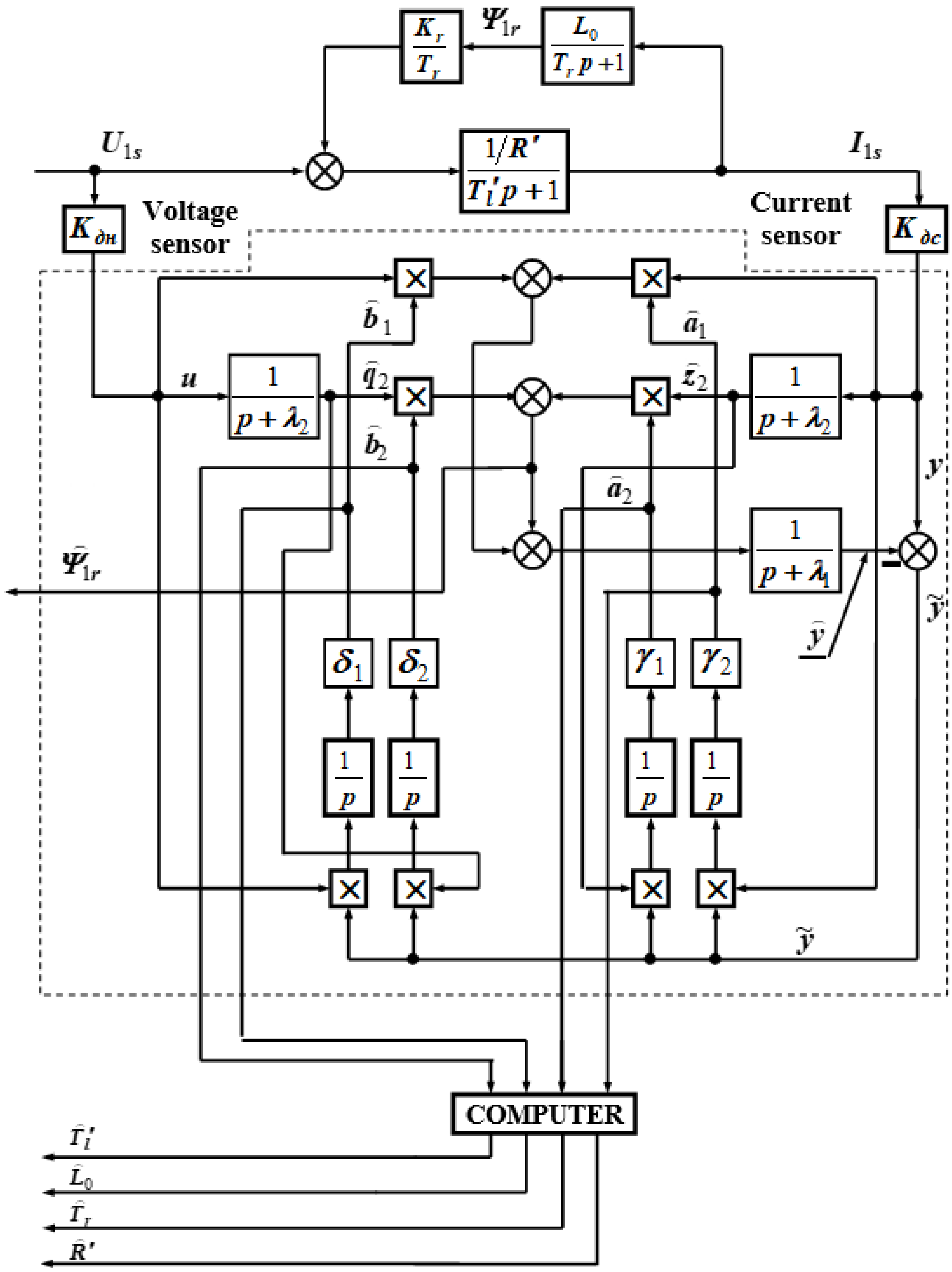

Figure 8 – Parametrical surveillance device

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2.7. Combined surveillance device.

The surveillance devices discussed above (full-scale surveillance device – Fig. 2, reduced surveillance device – Fig. 3, and parametric surveillance device – Fig. 8) have their own advantages and disadvantages compared to the direct determination of rotor flux linkage. Thus, the presence of any surveillance device complicates the control system. The main advantages of the reduced surveillance device are the reduction of the order of the surveillance device in comparison with the full-scale surveillance device. With the optimal choice of coefficients l_1 and l_2 it is possible to obtain the necessary quality of transient processes and accuracy from the flux linkage of the rotor of an induction motor. The disadvantage of the reduced surveillance device is the difficulty of choosing the coefficients l_1 and l_2 and their significant influence on the dynamics of the electric drive. If we compare the parametric surveillance device with the full-scale surveillance device, then it provides less accuracy in restoring the flux linkage of the induction motor rotor. In addition, it is necessary to calculate the adjustment coefficients of the surveillance device for each individual motor. Its advantage, in comparison with other surveillance devices, is the possibility of restoring the parameters of the induction motor.

The accuracy of restoration of the rotor flux linkage for each of the surveillance devices under consideration is unchanged, and when the electric drive is operating in the second speed control zone, the accuracy of the rotor flux linkage recovery decreases. At the same time, the largest error for a parametric surveillance device does not exceed 10% of the specified value; for a reduced surveillance device – 11%, and for a full-scale surveillance device – it does not exceed 4%. The reduced surveillance device is also characterized by a sharp decrease in the accuracy of restoring the rotor flux linkage when the angular velocity is adjusted above the nominal value. Research was carried out by mathematical modeling of an asynchronous electric drive with a 4A132M6UZ motor with a power of 5.5 kW.

We will combine in one surveillance device the advantages of a full-scale surveillance device (high accuracy of restoration of rotor flux linkage) and a parametric

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surveillance device (possibility of restoring induction motor parameters). The general structural diagram of such a surveillance device is shown on Figure 9.

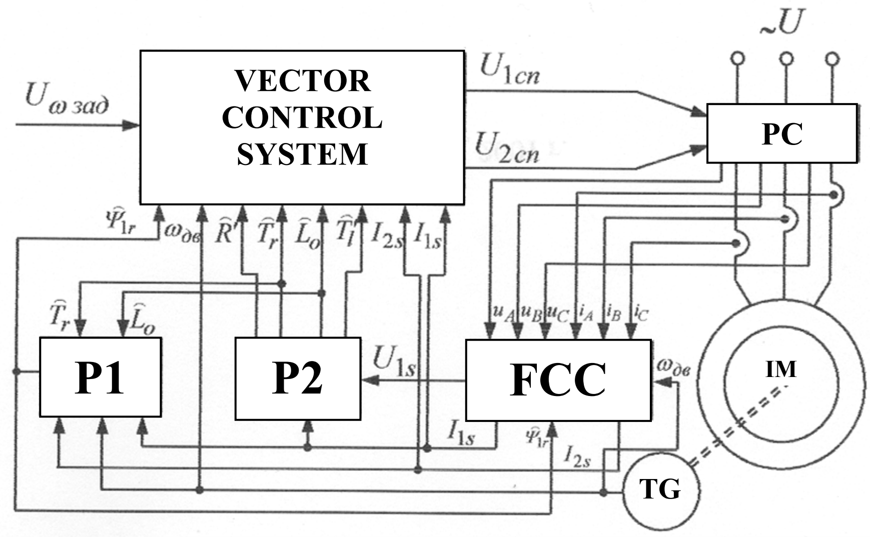

Figure 9 – Combined surveillance device:
P1 – full-order surveillance device; P2 – parametric surveillance device;
FCC – functional coordinate converter; PC – power converter

Information about the restored values of the parameters of the induction motor is entered into the control system (restored values of inductance from the main flow $\widehat{L}_0$, equivalent resistance $\widehat{R}'$, time constants of the rotor $\widehat{T}_r$ and stator $\widehat{T}_l'$) and into the full-scale surveillance device (restored values of inductance $\widehat{L}_0$ and rotor time constant $\widehat{T}_r$). Feedback on the rotor flux linkage vector is formed due to the full-scale surveillance device. In this case, both the full-scale surveillance device and the motor management system will adapt to changes in motor parameters.

The use of a combined surveillance device (Fig. 9), which adapts to the change in the motor parameters, while simultaneously adapting the control system to the change in the induction motor parameters, leads to an increase in the quality of transient processes and a reduction in the error of restoration of the flux linkage of the rotor of the induction motor. The error of restoration of the rotor flux linkage, when adjusting the angular speed down from the nominal, is less than 0.5%, and when adjusting the angular speed up from the nominal, it does not exceed 3%.

The nature of the transient processes of the electromagnetic moment and the recovered value of the flux linkage of the induction motor rotor when using a combined surveillance device is close to the nature of the transient processes of the angular speed of rotation of the motor shaft, the electromagnetic moment and the flux linkage of the rotor when directly measuring the flux linkage of the rotor using special devices.

2.8. Restoring the angle between the coordinate system rotating synchronously with the rotor flux vector and the stationary coordinate system using surveillance devices

When considering surveillance devices, it was assumed that the components of the stator current I_{1s} and I_{2s} of the induction motor with a squirrel-cage rotor are known. However, since the induction motor, as an object of control, is described in a frame of reference that rotates and is oriented to the vector of flux linkage of the rotor, it is impossible to determine these components by direct measurement. The transition from the stator current that was defined in a stationary coordinate system (α, β) to the flux- and moment-generating components of the stator current in the coordinate system rotating synchronously with the rotor flux linkage vector is carried out according to the equations:

$$\left.\begin{aligned} i_{1s} &= i_\alpha \cos\theta + i_\beta \sin\theta \\ i_{2s} &= i_\beta \cos\theta - i_\alpha \sin\theta \end{aligned}\right\},$$

where i_{1s}, i_{2s} are the instantaneous values of the flux- and torque-generating component of the stator current, respectively; i_α, i_β are instantaneous values of the stator current in a fixed coordinate system; θ is the angle between the instantaneous values of the stator current in a stationary coordinate system and the stator current of an induction motor in a coordinate system that rotates with the rotation frequency of the space vector of the rotor flux linkage. The definition of an angle ψ can be done using following expression

$$\theta = \int_0^t \left(\omega_{\partial в} Z_p + \frac{I_{2s} K_r R_r}{\Psi_{1r}} \right) dt \quad (39)$$

The current value of the angle between the coordinate systems can be written in the form $\theta = \theta_1 + \theta_0$, where θ_0 is the value of the initial angle between the coordinate systems, θ_1 is the instantaneous value of the angle between the rotating coordinate system and the stationary coordinate system, which is determined from (38).

In order to determine the initial phase, it is necessary to apply a test voltage and current $i_{test} < i_{start}$ to the motor winding for a short time, which will not lead to rotation of the motor shaft, that is, the following condition must be fulfilled $\omega = 0$. Under such conditions, the value of the initial phase between the coordinate systems can be accepted

$$\theta_0 = \frac{I_s K_r R_r}{\hat{\Psi}_{1r}}.$$

Expression (38) finds its application when using the surveillance devices. The structural diagram of the surveillance device for restoring the angle θ performed on the basis of the full-scale surveillance device is shown on Figure 10.

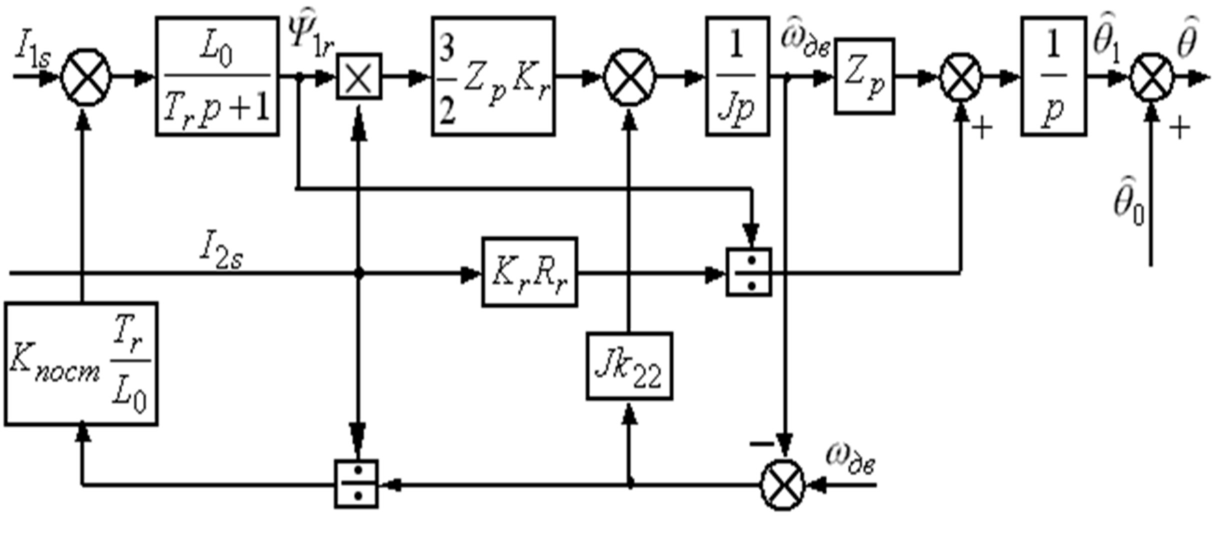

Figure 10 – Surveillance device for restoring the angle

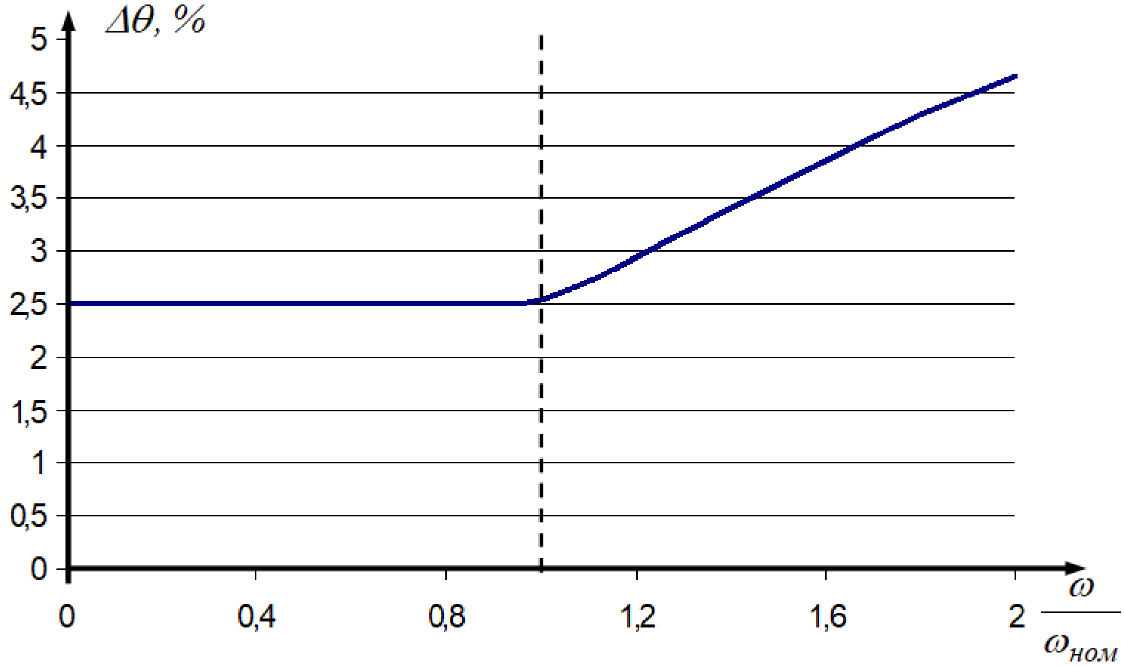

Figure 11 – Dependence of the accuracy of the angle restoration on the angular speed of the shaft rotation

Fig. 11 shows the dependences that reflect the accuracy of restoring the angle between the coordinate systems depending on the adjustment of the angular speed of rotation of the motor shaft. The adjustment of the angular speed of motor shaft rotation in two zones was considered: in the first zone – from 0 to the nominal speed value ω_{nom}, in the second – from ω_{nom} to $2\omega_{nom}$. The largest error of restoring the angle between the coordinate systems does not exceed 5 percent (when adjusting the angular speed above the nominal).

In the established mode, the accuracy of restoring the angle between the coordinate systems is at least 98...99%. When adjusting the angular speed from 0 to $\pm\,\omega_{nom}$ the accuracy of the angle recovery $\hat{\theta}$ does not change and is 98%. When adjusting the angular speed in the second zone, the accuracy of restoring the angle between the coordinate systems decreases, but it is not lower than 95...98%. The increase in the error of restoring the angle between the coordinate systems depends on the restored value of the flux linkage of the rotor and the accuracy of its restoration (in the second zone, the accuracy of restoring the flux linkage decreases).

2.9. Taking into account the steel saturation in the vector control system of an induction motor

For the control system of an induction motor with a squirrel-cage rotor that is considered, the main assumption about the linearity of the magnetic properties of materials was adopted. This happens when the control system provides stabilization of flux linkage, that is, the electric drive works in the vicinity of one point on the magnetization curve of the magnetic circuit of the induction motor. It is known that algorithms for vector control of an induction motor are sensitive to changes in its parameters.

Most of all, this sensitivity is manifested in relation to the change in the inductive resistance of the rotor and stator. Since a change in the inductive resistance of the rotor leads to a change in the motor current, this, in turn, leads to a change in the flux linkage of the rotor. As a result, the indicators of the quality of the angular speed control deteriorate.

Since the stabilization of the rotor flux linkage is disturbed, the magnetic circuit of the machine may fall into the steel saturation zone. In this case, the linear model of the induction motor will not fully reflect the processes that occur in the machine during control.

Taking into account the influence of the saturation of magnetic materials, the following motor parameters become non-stationary: inductance from the main flow, rotor time constant. The saturation of the machine's magnetic system is reflected in the value of the mutual inductance.

In addition, the non-linear change of the mutual inductance from the magnetizing current causes the appearance of higher harmonics in the air gap and affects the static and dynamic properties of the drive as a whole.

The non-stationarity of the induction motor parameters, their non-linearity with respect to time make it difficult to control the motor, reduce the accuracy of the adjustment of the angular speed of rotation of the motor shaft.

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materials can be considered in two ways:

– to use corrective signals in the control system;

– restore the value of the active resistance of the rotor and the parameters of the motor with the help of a parametric observer.

In order to use the correction signals in the control system and take into account the change in inductance from the main flow, and, in turn, other parameters of the motor, it is necessary to know the value of the stator current and the current linkage of the rotor at each moment of time.

To obtain information about the flux linkage of the rotor, Hall sensors are used with subsequent conversion of the received signal, a special measuring winding in the stator, as well as surveillance devices.

Knowing the value of the rotor flux linkage and the stator current, based on the expressions:

$$\left.\begin{aligned} I_s &= \frac{\Psi_s - K_r\Psi_r}{L'_s(I_{s)}} \\ I_r &= \frac{\Psi_r - K_s\Psi_s}{L'_r(I_s)} \end{aligned}\right\} \quad (39)$$

we can calculate the modulus of the magnetization current:

$$I_\mu = \sqrt{I^2{}_s + I^2{}_r}, \quad (40)$$

where $L'_r(I_{s)}, L'_s(I_s)$ are the equivalent dissipation inductance of the motor of the rotor and stator respectively as a function of the stator current:

$$L'_s(I_s) = L_{s\sigma}(I_s) + K_r(I_s)L_{r\sigma}(I_s);$$
$$L'_r(I_s) = L_{r\sigma}(I_s) + K_s(I_s)L_{s\sigma}(I_s).$$

The algorithm for calculating and determining motor parameters are shown on Figure 12.

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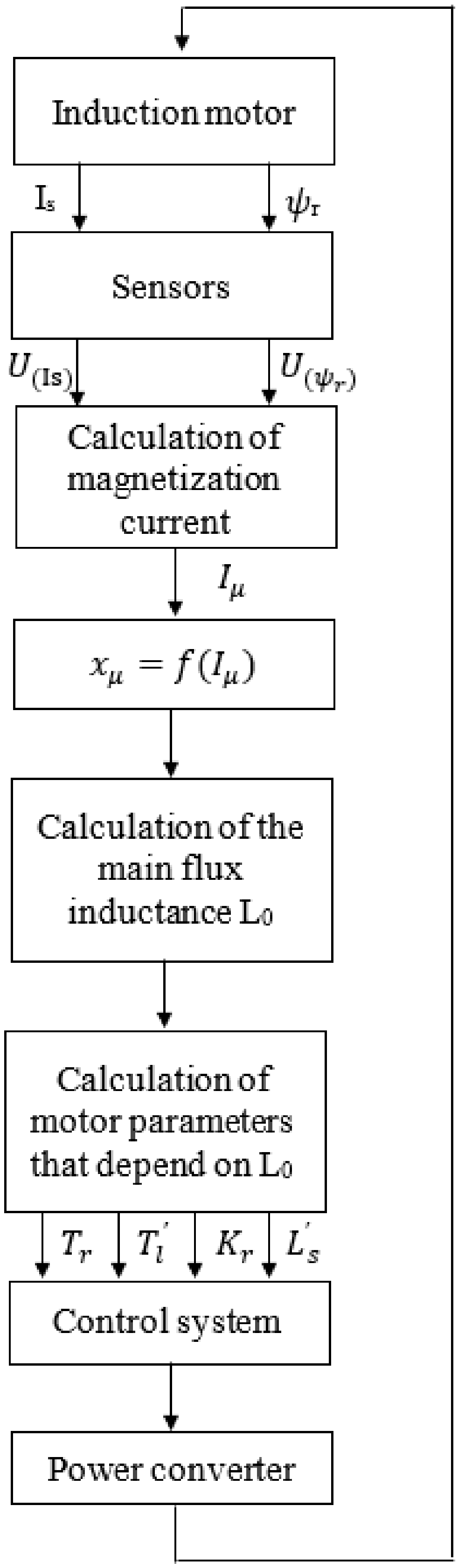

Figure 12 – Algorithm for obtaining corrective signals in order to take into account changes in motor parameters during steel saturation

The calculated signals, proportional to the received parameters, are entered into the control system and used in regulators and compensating elements .

Let us consider the possibility of restoring the values of motor parameters with the help of a parametric observer.

A change in the inductive resistance leads to a change in the time constant of the rotor T_r, as well as to a change in the reduced resistance R':

$$T_r(I_s) = \frac{R_r}{L_r(I_s)}, \quad R' = R_s + (K_r(I_s))^2 R_r.$$

Since the discrepancy between the actual value of the active resistance of the rotor and the value for which the control system is adjusted leads to the fact that the value of the flux linkage of the rotor does not correspond to the specified value, we introduce a signal proportional to the value of the active resistance of the rotor to the control system. Based on the obtained values of the motor parameters ($R'$and T_l') and knowing the value of the rotor inductance L_r in the calculation unit, it is also possible to calculate the rotor constant $T_r(I_s)$, the coefficient of rotor electromagnetic linkage $K_r(I_s)$ and the equivalent stator inductance as a function of the stator current $L_s'(I_s)$ and enter a signal into the control system that is proportional to the obtained values. In addition, a signal that is proportional to the time constant $T_l'(I_s)$ as a function of the stator current can be input to the control system from the calculation unit.

With small deviations of the rotor flux coupling from a constant value, when the motor operates in the vicinity of the point on the magnetization curve, which determines the nominal value of the rotor flux coupling and the nominal parameters of the motor, better results are obtained when using corrective links. But with significant deviations of the rotor flux coupling (more than 5...8%), the parametric monitoring device provides better results than the correcting links.

It is possible to use two options at the same time (Fig. 13), i.e., with a small deviation of the rotor flux linkage from a constant value, signals are entered into the control system, which are received with the help of a corrective device. In transient modes, with a significantly large deviation of the rotor flux linkage above the nominal value, due to the presence of flexible feedback on the rotor flux linkage, a surveillance

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device is connected to the control system. The construction of the corrective device as a system with a variable structure allows us to obtain the best dynamic performance in transient and stable modes, as well as when the saturation of steel in the motor changes.

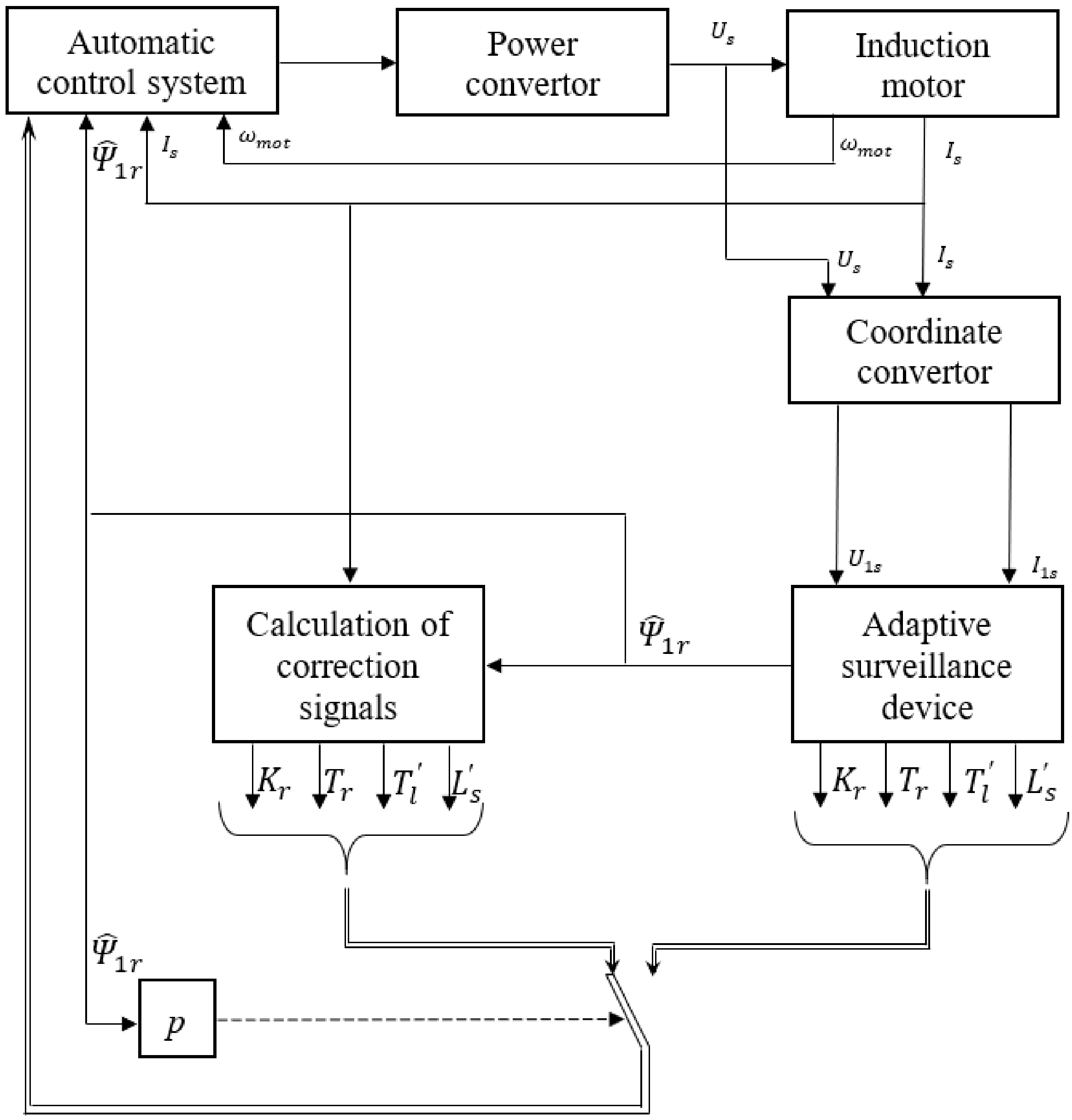

Figure 13 – Consideration of parameters in the motor under the influence of motor steel saturation by using a system with a variable structure

2.10. Evaluation of the stability of the electric drive with vector control and the use of surveillance devices

One of the evaluations of the quality of the operation of the electric drive is the determination of the stability of the entire system. Let's determine whether the AC electric drive with vector control, with rotor flux-coupling feedback, closed through a full-scale surveillance device, is a stable system or not. If we consider each of the components of the electric drive – the automatic regulation system, the induction motor with a squirrel-cage rotor, the surveillance device; then each of them (taken separately) are stable systems. However, if they are combined into one system – an electric drive – the principle of superposition may not be fulfilled for them, since each of them is a non-linear system (they contain elements that ensure the multiplication of different coordinates).

When determining the stability of the electric drive, we will assume that the control system provides compensation for all cross and internal feedbacks that take place in the control object – an induction motor with a squirrel-cage rotor.

To determine the stability of a nonlinear system, it is necessary to consider any mode of operation of the system. Let's consider one of the most difficult modes of operation of any electric drive – the "voltage jump" mode.

The nonlinearity of this system is due to the presence of a nonlinear element $\varphi(U_{\text{set}})$ and the multiplication and division of coordinates (in different parts of the system): in the second equation – division by the restored value of the rotor flux linkage; and multiplication in the first, third, fifth, and sixth equations – in the equations describing control system; multiplication and division of coordinates in the seventh, eighth and tenth equations – induction motor and in the last two equations – equations describing a full-scale surveillance device through which the negative feedback on the rotor flux linkage is closed.

In order to determine the stability of the system, we will construct phase trajectories of the type $y_i = f(z_i)$, where the value of the coordinate is plotted along the abscissa axis, and the value of the derivative of this coordinate along the ordinate axis. Phase trajectories were calculated using a personal computer. The calculated phase trajectories are shown on Figure 14 (a – phase trajectory for the angular velocity $\omega = f\left(\frac{d\omega}{dt}\right)$, b – phase trajectory for the restored value of the flux linkage of the induction motor rotor $\Psi_{1r} = f\left(\frac{d\Psi_{1r}}{dt}\right)$). Phase trajectories are constructed starting from

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the moment of the greatest deviation of the angular velocity from a constant value. This system is stable during a voltage jump, because the phase trajectories, after applying a disturbance to the system, have the form of a spiral that contracts to the origin of the coordinates (the origin of the coordinates is moved to a point that corresponds to the value of the angular speed of rotation of the motor shaft in the steady state before the application of the disturbing signal). Therefore, the system is stable and the transition process has the form of damped oscillations.

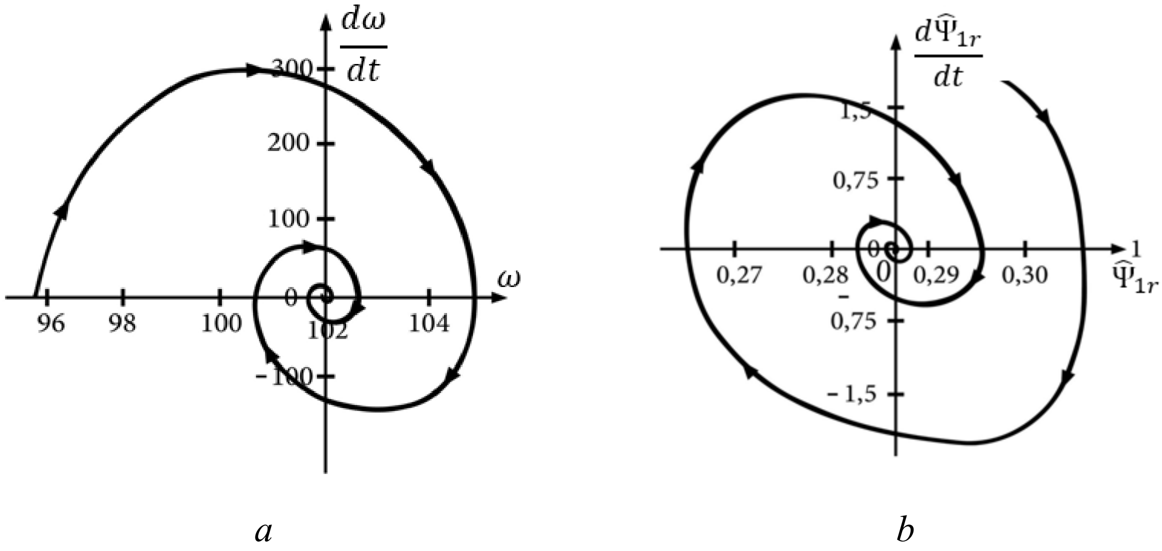

Figure 14 – Phase trajectories of coordinates of an electric drive with vector control and a full-scale surveillance device:

a – angular speed of motor shaft rotation ω;

b – the restored value of the flux linkage of the rotor Ψ_{1r}

If the restoration of the flux linkage of the induction motor rotor is carried out with the help of a combined surveillance device (Fig. 9), the system of equations describing the entire asynchronous electric drive with vector control will be supplemented with equations describing the combined surveillance device instead of the last two equations. The resulting system will have a greater number of actions that carry out the multiplication of coordinates, which is due to the nonlinear structure of the parametric surveillance device, which is a part of the combined surveillance device and the adaptation of the control system and the complete surveillance device to the motor parameters, which are restored with the help of the parametric surveillance device.

In order to determine the stability of an electric drive with vector control and a combined surveillance device, it is necessary to obtain phase portraits for the angular speed of the motor shaft rotation $\omega = f\left(\frac{d\omega}{dt}\right)$, the restored value of the flux linkage of the induction motor rotor obtained at the output of the full-scale surveillance device, which is a part of the combined surveillance device is $\Psi_{1r} = f\left(\frac{d\Psi_{1r}}{dt}\right)$; as well as for the restored values of motor parameters obtained at the output of the parametric surveillance device: the electromagnetic time constant of the rotor – $T_r = f\left(\frac{dT_r}{dt}\right)$, the equivalent time constant of the windings – $T_l' = f\left(\frac{dT_l'}{dt}\right)$, the equivalent active resistance of the motor – $R' = f\left(\frac{dR'}{dt}\right)$ and the inductance formed by the main magnetic flux $L_0 = f\left(\frac{dL_0}{dt}\right)$.

Figure 15 shows the corresponding phase trajectories of the coordinates and parameters of the electric drive when using a combined surveillance device:

a – phase trajectory for rotor angular speed;

b – phase trajectory for the restored value of the rotor flux linkage;

c – phase trajectory for the electromagnetic time constant of the rotor;

d – phase trajectory for the equivalent motor time constant;

e – phase trajectory for the equivalent active resistance of the motor;

f – phase trajectory for the inductance from the main flow.

As well as in the previous case, the origin of coordinates for each phase trajectory is moved to points that correspond to the value of the corresponding parameter or coordinate of the system state before the load is applied to the motor shaft. The characteristics are plotted from the moment of time when the angular velocity of rotation of the motor shaft reached its maximum. The analysis of the given phase trajectories shows that in the presence of a disturbing signal, the phase trajectories of both the restored motor parameters and the initial coordinates coincide with the origin of the coordinates. It means that the system is stable and the transient process has the form of damped oscillations.

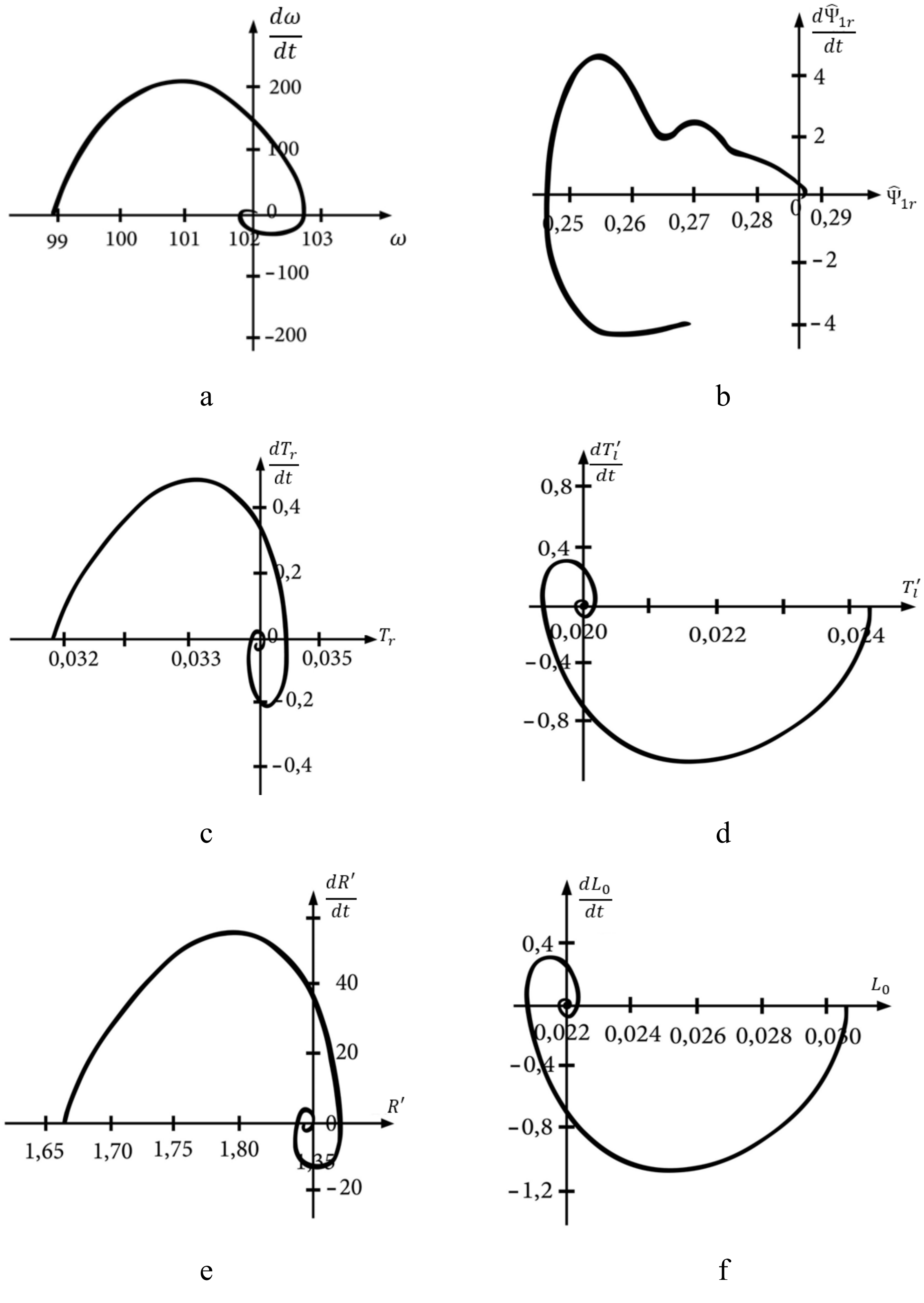

Figure 15 – Phase trajectories of an electric drive with a parametric surveillance device: *a – angular velocity, b – rotor flux linkage, c – rotor time constant, d – equivalent stator time constant, e – equivalent motor resistance, f – inductance from the main flow*

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Thus, the use of a combined surveillance device (Fig. 9) in an electric drive with vector control to restore the rotor flux linkage vector and motor parameters does not lead to deterioration of the stability of the entire electric drive.

Conclusions

1. The possibility is substantiated and a structural diagram of surveillance devices has been developed to improve the dynamic properties of an asynchronous electric drive with a vector control system without direct measurement of flux linkage in case of non-stationarity of the parameters of the control object. It is proposed to simultaneously use surveillance devices of two types – full-scale and parametric one. In these devices (unlike known methods of identification) information about the restored instantaneous values of active resistance and time constants of the stator and rotor windings is used for simultaneous adaptation of both the control system regulators and the full-scale observer, the output of which provides information about the amplitude and spatial position of the flux linkage vector, which is necessary for building a vector control system. This ensures an increase in the accuracy of restoring the flow coupling and an improvement in the dynamic properties of the electric drive.

2. When using a reduced surveillance device for the restoring of the rotor flux linkage signal by choosing the values of the coefficients of the observer feedback matrix — the speed residuals, it is possible to give the system a certain value of the oscillation and the rotor flux linkage restoration error, which affect the dynamic properties of the electric drive.

3. For the parametric surveillance device, which is a significantly nonlinear object, the dependences of tuning coefficients on the dynamic parameters of induction motors with a power range of up to 90 kW were obtained for the first time. This allows to calculate the values of transmission coefficients and time constants of the observer (for the design and adjustment of asynchronous electric drives with vector control) in order to give it the necessary dynamic properties without direct measurement of flux linkage. The connection between the adjustment coefficients and the main dynamic parameters of the induction motor was established, which allows to synthesize a closed

system of vector control of the speed of the electric drive.

4. It was established that the use of a combined surveillance device that adapts to changes in motor parameters while simultaneously adapting the control system to changes in induction motor parameters leads to an increase in the quality of transient processes and a reduction in the error of restoration of the flux linkage of the induction motor rotor. The error of restoration of the rotor flux linkage, when adjusting the angular speed down from the nominal, is less than 0.5%, and when adjusting the angular speed up from the nominal, it does not exceed 3%.

5. It is proposed to determine the angle between a stationary coordinate system and a coordinate system that rotates synchronously with the rotor flux linkage vector using surveillance devices. When using this method, the accuracy of the angle recovery is almost independent of the power of the electric drive and is determined by the accuracy of the recovery of parameters and coordinates of the electric drive when using a combined surveillance device.

6. It is proposed to use a correction device with a variable structure to take into account the changes in the induction motor parameters that occur when the steel of the asynchronous machine is saturated. Control between channels is carried out as a function of the rotor flux linkage amplitude. In case of small deviations of flow linkage, corrective elements are used, in case of large deviations (by more than 5%) – information about the parameters of the object is obtained with the help of a parametric surveillance device.

7. For a two-mass electromechanical system, it was established that the accuracy of restoration of the rotor flux linkage depends on the stiffness of the elastic connection between the motor shaft and the mechanism. The limits ($J_2 \leq 8J_1$) of the change in the moment of inertia of the mechanism J_2 in relation to the moment of inertia of the motor J_1, in which the accuracy of restoration of the rotor flux linkage does not depend on the stiffness of the elastic connection between the motor shaft and the mechanism were defined. The most unfavorable conditions (increasing the error of restoring the rotor flux linkage) occur when the moment of inertia of the mechanism exceeds the

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moment of inertia of the motor by more than 8 times.

8. When working in stable modes, in order to take into account the change in the parameters of the induction motor, which occurs when the steel is saturated, it is necessary to use corrective devices. In transient modes, the use of a parametric surveillance device ensures a higher accuracy of parameter recovery than corrective elements. In stable modes, higher accuracy is provided by the correcting elements. The construction of the corrective device according to the principles of a system with a variable structure allows to obtain the best dynamic indicators in transient and stable modes.

9. The introduction of a combined surveillance device into the vector control system to restore the flux linkage of the rotor and motor parameters does not lead to a deterioration in the stability of the electric drive.