STABILITY AND ACCURACY OF THE ROBUST SYSTEM FOR STABILIZING THE ROTOR FLUX-LINKAGE OF AN ASYNCHRONOUS ELECTRIC DRIVE AT RANDOM VARIATIONS OF THE UNCERTAIN PARAMETERS WITHIN THE SPECIFIED BOUNDARIES

Purpose. The aim is to investigate the stability and the accuracy of a robust system for stabilizing the rotor flux-linkage of an asynchronous electric drive at random variations of the uncertain parameters of the object and the regulator within the specified boundaries. Methodology. To make the research, the mathematical model of the rotor flux-linkage channel of the vector control system of an asynchronous electric drive with parametric uncertainty was applied. The transfer function of the $H_{\infty}$-suboptimal regulator was calculated using the mixed sensitivity method. This transfer function was used to construct the regulator structural scheme in the form of a connection of proportional and integrating links and several adders. Analytical dependences of the coefficients of the regulator's transfer function on the parameters of links of such a connection are determined. These dependences served to researching the influence of uncertain parameters of the regulator links and the object on the stability of the robust system and the accuracy of flux-linkage stabilization. Results. Investigations of the robust system stability and the accuracy of flux-linkage stabilization in the Robust Control Toolbox are done. The curves of the flux-linkage transient processes and the Bode diagram for the open system at random variations of the indeterminate parameters of the object and the regulator links within the specified boundaries are constructed. A choice of variable parameters was carried out by the Monte Carlo method. By the scatter of the obtained curves of the transient processes, the accuracy of flux-linkage stabilization was determined, and according to the Bode diagram, stability reserves in the amplitude and the phase of the robust system were determined. A high accuracy of flux-linkage stabilization (deviation less than 1%) in fairly wide ranges of changing the uncertain parameters of the object and the regulator, while maintaining the stability of the system with permissible reserves in amplitude and phase, is established. Originality. For the first time, analytical dependences of the coefficient of the regulator's transfer function on the parameters of links of such a connection are determined. These dependences served to researching the influence of uncertain parameters of the regulator links and the object on the stability of the robust system and the accuracy of flux-linkage stabilization. References 10, figures 3.

Key words: electric drive, vector control, flux-linkage channel, stabilizing robust system, stability, accuracy.

Цель. Целью работы является исследование устойчивости и точности робастной системы стабилизации потокосцепления ротора асинхронного электропривода при случайных вариациях неопределенных параметров объекта и регулятора в заданных границах. Методология. Для проведения исследований применялась математическая модель канала потокосцепления ротора системы векторного управления асинхронного электропривода с параметрической неопределенностью. Рассчитывалась передаточная функция $H_{\infty}$-субоптимального регулятора по методу смешанной чувствительности. Эта передаточная функция использовалась для построения структурной схемы регулятора в виде соединения пропорциональных и интегрирующих звеньев и нескольких сумматоров. Определялись аналитические зависимости коэффициентов передаточной функции регулятора от параметров звеньев такого соединения. Эти зависимости служили для исследования влияния неопределенных параметров звеньев регулятора и объекта на устойчивость робастной системы и точность стабилизации потокосцепления. Результаты. Проведены исследования устойчивости робастной системы и точности стабилизации потокосцепления в пакете Robust Control Toolbox. Построены кривые переходных процессов потокосцепления и диаграмма Боде для разомкнутой системы при случайных вариациях неопределенных параметров объекта и звеньев регулятора в заданных границах. Выбор варьируемых параметров осуществлялся по методу Монте-Карло. По разбросу полученных кривых переходных процессов определялась точность стабилизации потокосцепления, а по диаграмме Боде – запас устойчивости по амплитуде и фазе робастной системы. Установлена высокая точность стабилизации потокосцепления (отклонение менее 1%) в достаточно широких диапазонах изменения неопределенных параметров объекта и регулятора при сохранении устойчивости системы с допустимыми запасами по амплитуде и фазе. Новизна. Впервые получены аналитические зависимости коэффициентов передаточной функции $H_{\infty}$-субоптимального регулятора от параметров его структурной схемы, представленной в виде соединения пропорциональных и интегрирующих звеньев. Построена методика расчета устойчивости системы робастного управления потокосцепления и точности ее стабилизации при случайных вариациях неопределенных параметров объекта и звеньев регулятора в заданных границах. Практическое значение. Использование предложенной методики позволяет в процессе конструирования регулятора обеспечить выбор его элементов из стандартных рядов.

Key words: электропривод, векторное управление, канал потокосцепления, робастная система стабилизации, устойчивость, точность.

Introduction. In [1] the method of structural synthesis is constructed and the structure of the stabilizing robust $H_{\infty}$-suboptimal regulator is obtained in the form of a connection of proportional and integrating links for the flux-linkage channel of the vector control system of an
asynchronous electric drive with parametric uncertainty of the control object. However, when designing such a regulator from analog devices (operational amplifiers and RC-circuit) there are rounding errors of its gain factors and time constants due to the selection of elements (resistors, capacitors) of these devices from standard series. The consideration of such rounding errors in the calculation model of the regulator with parametric uncertainty of the object is of fundamental importance for ensuring the stability of the robust system and the necessary accuracy of flux-linkage stabilization.

Robust systems of stabilizing the parameters of asynchronous electric drives are engaged in a number of domestic and foreign scientists [2-9]. They solved many problems both in the development of mathematical methods of research, and in studying the stability, accuracy of regulation, and the speed of systems with a given uncertainty of the object. However, the problem of the influence of the parametric uncertainty of the robust regulator on the stability and accuracy of the flux-linkage stabilization system was not considered. In this connection, the study of the stability of a robust system and the accuracy of stabilizing the rotor flux-linking parametric uncertainty of the robust regulator on the systems with a given uncertainty of the object.

The goal of the work is study of the stability and accuracy of a robust system for stabilizing the rotor flux-linkage of an asynchronous electric drive at random variations of uncertain parameters within given boundaries.

Methods and results of research. The paper [1] contains a system of equations of state of an object consisting of a frequency converter and stator and rotor windings in the normal operator form:

\[ px_1 = \frac{1}{T_2} x_1 + \frac{L_{12} I_n}{T_2} x_2 ; \]
\[ px_2 = \frac{1}{T_{1eq}} x_2 + \frac{E_n}{R_{1eq} T_{1eq}} x_3 ; \]
\[ px_3 = \frac{1}{T_{fc}} x_3 + \frac{K_{fc} U_n}{T_{fc} E_n} u , \]

where

\[ x_1 = \frac{V}{L}; \quad x_2 = \frac{1}{I_n}; \quad x_3 = \frac{E_n}{U_n}; \quad u = \frac{U}{U_n}; \]

\( p \) is the Laplace operator; \( E \) is the frequency converter’s EMF; \( U \) is the control action; \( I \) is the current in the rotor flux-linkage channel; \( \Psi \) is the rotor flux-linkage vector’s module; \( T_{fc} \) is the time constant of the frequency converter; \( T_{1eq} = I_{1eq} / R_{1eq} \) is the electromagnetic time constant of the stator winding, where \( R_{1eq} = R_1 + (k \sigma) R_2 \) and \( L_{1eq} = \sigma L_1 \) are its equivalent resistance and the leakage inductance; \( R_1, R_2 \) are the active resistances of the stator and rotor windings; \( T_{2eq} = L_2 / R_2 \) is the electromagnetic time constant of the rotor winding; \( L_1, L_2 \) are the inductances of the stator and rotor windings; \( L_{12} \) is the mutual inductance of the stator and rotor windings; \( \sigma = 1 - (L_{12} / L_1 L_2) \) is the coefficient of magnetic field scattering; \( k_{\sigma} = L_1 / L_2 \).

In this paper, this system of equations, together with the undefined parameters \( K_{fc}, R_{1eq}, R_2, L_1, L_2 \) and \( L_{12} \) of the object, is used to construct a mathematical model for the stability and accuracy of a robust system for stabilizing the rotor flux-linkage of an asynchronous electric drive at random variations of uncertain parameters within given boundaries.

To construct such a model, the system of equations (1) is reduced to the canonical form [1]:

\[ px = Ax + B_1 w + B_2 u ; \]
\[ z = C_1 x + D_{11} w + D_{12} u ; \]
\[ y = C_2 x + D_{21} w + D_{22} u , \]

where

\[ A = \begin{bmatrix} -\frac{R_{2n}}{L_{2n}} & \frac{R_{1n}}{L_{1n}} & 0 \\ 0 & -\frac{R_{1eq}}{L_{1eq}} & \frac{R_{1eq}}{L_{1eq}} \\ 0 & 0 & -\frac{1}{T_{fc}} \end{bmatrix} ; \]
\[ B_1 = \begin{bmatrix} \frac{R_{2n}}{L_{2n}} & \frac{R_{1n}}{L_{1n}} & 0 \\ \frac{R_{1eq}}{L_{1eq}} & \frac{R_{1eq}}{L_{1eq}} & 0 \\ 0 & \frac{R_{1eq}}{L_{1eq}} & 0 \\ -\frac{R_{2n}}{L_{2n}} & \frac{R_{1n}}{L_{1n}} & 0 \end{bmatrix} ; \]
\[ C_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} ; \quad C_2 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} ; \]
\[ D_{11} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} ; \quad D_{12} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} ; \]
\[ D_{21} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} ; \quad D_{22} = \begin{bmatrix} 0 \end{bmatrix} ; \]
\[ x = (x_1, x_2, x_3)^T \] is the phase vector; \( y \) is the one-dimensional output vector which closes the feedback; 
\[ z = (z_1, z_2, \ldots, z_i)^T, \ w = (w_1, w_2, \ldots, w_i)^T \] are, respectively, the input and output uncertainty vectors interconnected by the matrix expression \( w(p) = \Delta(p)z(p) \) in which the uncertainty matrix \( \Delta(p) \) has a diagonal form.

The written canonical form of equations (2) together with the weight functions [10] for control the quality of the robust stabilization system, allows in the Robust Control Toolbox to calculate the transfer function of the \( H_s \)-suboptimal regulator for the nominal object. This transfer function can be represented in the form

\[ K(p) = \frac{p^2 + b_1 p + b_2}{p^3 + a_1 p^2 + a_2 p + a_3}, \quad (3) \]

where \( k, a_1, a_2, a_3, b_1, b_2 \) are the regulator parameters.

We assume that the transfer function of the regulator (3) retains its form for random variations of the parameters \( k, a_1, a_2, a_3, b_1, b_2 \).

Then, expanding (3) into a continued fraction by the Euclidean algorithm, we obtain the block diagram of the regulator shown in Fig. 1. It contains the block diagram of the \( H_s \)-suboptimal regulator for the nominal object. This transfer function can be represented in the form

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Then, expanding (3) into a continued fraction by the Euclidean algorithm, we obtain the block diagram of the regulator shown in Fig. 1. It contains the block diagram of the \( H_s \)-suboptimal regulator for the nominal object. This transfer function can be represented in the form

\[ K(p) = \frac{p^2 + b_1 p + b_2}{p^3 + a_1 p^2 + a_2 p + a_3}, \quad (3) \]

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where \( k, a_1, a_2, a_3, b_1, b_2 \) are the regulator parameters.
Undefined parameters of the object varied in the ranges ±90 %, and the parameters of the regulator $k_1$, $k_2$ – in the ranges ±3 %, $k_3$, $T_1$, $T_2$ in the ranges ±20 % of their nominal values.

Fig. 2 shows 20 curves of transients of the rotor flux-linkage corresponding to random variations of the undefined parameters of the object and the regulator selected within the prescribed boundaries by the Monte Carlo method. They are obtained in the packages of the MATLAB application for a single step change in the control action.

As can be seen, the curves of the transients shown in Fig. 2 do not exceed the limits of 1 % of the tube.

Fig. 3 shows the Bode diagram with 20 generated curves of amplitude $L(\omega)$ and 20 phase $\varphi(\omega)$ frequency characteristics with the same uncertain parameters as in the previous case.

From the amplitude $L(\omega)$ and phase $\varphi(\omega)$ characteristics presented in this diagram, it is seen that the system is stable, since the amplitude characteristic crosses the abscissa axis before the phase characteristic, finally decaying, goes over the value of the angle –180°. In this case, the calculated value of the stability reserve in amplitude is 19.9 dB, and in phase – 47.9° for nominal values of the object and regulator parameters for variance of random curves not exceeding 4 dB for amplitude and 15° for phase frequency characteristics.

Thus, the results of the calculations confirm the expediency of using the proposed method for constructing robust $H_\infty$-suboptimal regulators from elementary links.

Conclusions.

1. For the first time, analytical dependences of the coefficients of the transfer function of the $H_\infty$-suboptimal regulator from the parameters of its structural scheme represented as a combination of proportional and integrating links are obtained.

2. A method is developed for calculating the stability and accuracy of a robust system for stabilizing the rotor flux-linkage of an asynchronous electric drive at random variations of the indeterminate parameters of the object and the regulator within given boundaries.

3. The results of the calculations show a high accuracy of flux-linkage stabilization (deviation less than 1 %) and a low sensitivity of the robust stabilization system to random variations of uncertain parameters within given wide enough boundaries.

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