Metrological assurance of the characteristics of electric drives at the design stage

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Abstract. The article is devoted to the study of determining the quality indicators of the controlled electric drives that determine the characteristics of metal-cutting machine tools, robocars, industrial robots and other automatic equipment. The main trends in the development of electric drives are highlighted. Special attention is paid to the technical requirements for the controlled electric drives. A mathematical model of an electric drive with a valve motor is presented, using which it is possible to determine the main metrological characteristics of the electric drive specified in GOST even at the design stage, using a mathematical device. The use of the presented mathematical model makes it possible to make changes to the planned operating modes of the electric drive, select the parameters of the speed and current regulators, and study the influence of non-linearities. The model reflects all the features of the circuit design of the regulators and the power amplifier. The work presents tachograms for determining the coefficients of uneven rotation and frequency bandwidth. The analysis of the obtained tachograms makes it possible to theoretically determine the range of speed control of the electric drive. The results of an experimental study of a test sample of the controlled electric drive under consideration are presented, illustrating the correctness of the calculations performed.

1. Introduction

At present, flexible production systems [1], in which automated electric drives are the energy basis, are the most widely used in industry. At the same time, the most common type of automated electric drive is a controlled electric drive (a drive closed in terms of the frequency of rotation of the shaft of the executive motor).

The most famous developers of electric drives are “BOSCH”, “INDRAMAT”, “Lenze”, “Siemens” (Germany); “Teiricu Trading” (Japan); “ABB” (Sweden), “SOPREL” (Italy); “Artech” (Bulgaria), “Triol” (Russia).

At the same time the following is observed:
- the electric drives with DC motors continue to be used in equipment where high technical characteristics are the main requirement, and reliability requirements are not decisive;
- still the most widely used today are drives with asynchronous motors, both uncontrolled (but with controlled start) and speed-controlled;
electric drives with valve motors have become increasingly widespread in automatic equipment, which is due to their good technical characteristics and high reliability.

2. Materials and methods
Due to the fact that the characteristics of automatic equipment are determined by the quality indicators of a controlled electric drive, the issues of their improvement and regulation are given serious attention. So now there is a GOST, which regulates the characteristics of electric drives [2] and describes how to determine them. From the total number of technical requirements for a controlled electric drive, the following parameters should be noted: the speed control range, the coefficient of uneven rotation of the shaft of the executive motor and the frequency bandwidth.

In practice, the speed control range of the electric drive is determined by the ratio of the maximum to the minimum value of the motor rotation speed, while observing the permissible fluctuations.

The coefficient of uneven rotation is defined as the doubled ratio of the difference between the maximum and minimum values of the instantaneous speed of rotation of the engine to their sum. The coefficient of uneven rotation at the minimum speed should not exceed 25% (this mode is the most difficult and indicative for controlled electric drive).

The bandwidth of a variable speed drive is determined by the maximum frequency of the input signal, at which the signal lag from the feedback sensor from the input does not exceed a quarter of the period, or in which the reduction in the drive transmission ratio does not exceed 30%.

To determine the real quality indicators of the developed and manufactured controlled electric drives, rather complicated and expensive stands are used [3]. Such stands, in addition to imitating the required operating modes, must create certain thermal conditions. In addition, the task of processing the received data is not an easy task [4]. Therefore, an urgent and important task is the development of a mathematical and software tools that make it possible to analyze the quality indicators of a controlled electric drive at various stages of development, manufacture and operation [5].

In this work, the characteristics of a controlled electric drive are determined and analyzed, which consists of a test sample servo amplifier, a valve motor and a pulse speed sensor. This controlled electric drive is constructed according to a typical scheme similar to EPS-B1-0D75AA (Germany), SER13-1R5-10-3ABYR (Hong Kong), etc. [6].

![Figure 1. Functional diagram of controlled electric drive.](image)
various VM models are used both three-phase and two-phase. The authors have chosen a three-phase model.

The functional diagram of controlled electric drive is shown in figure 1.

The figure shows: RS – speed regulator; RPa, RPh, RPc – regulators currents in the phase windings; TWG – periodic signal generator; PWM – pulse width modulator; CC – coordinate converter; ISO – galvanic isolation device; SPa, SPb, SPc – current sensors in phase windings; PR – mains rectifier; M – valve motor; HS – Hall sensor, which determines the position of the rotor; SS – speed sensor; Q1 - Q6, D1 - D6 – power amplifier elements; Urs, Urm – speed and moment setting reference signals; Uss – speed sensor output signal; UT WG – periodic signal; Urp – signal from the rotor position sensor; Uca, Ucb, Ucc – control signals; Upa, Upb, Upc – signals for setting currents in phase windings; Usa, Usb, Usc – output signals from current sensors; Upwm – modulated control signal; UQ1–UQ6 – power transistor control signals.

The mathematical model of the valve motor has the following form [7]:

\[
U\varphi a(t) = R \times I\varphi a(t) + L \times \frac{dI\varphi a(t)}{dt} + F_{0a}(t) \times V(t) \tag{1}
\]

\[
U\varphi b(t) = R \times I\varphi b(t) + L \times \frac{dI\varphi b(t)}{dt} + F_{0b}(t) \times V(t) \tag{2}
\]

\[
U\varphi c(t) = R \times I\varphi c(t) + L \times \frac{dI\varphi c(t)}{dt} + F_{0c}(t) \times V(t) \tag{3}
\]

\[
M_a(t) = I\varphi a(t) \times F_{0a}(t) \tag{4}
\]

\[
M_b(t) = I\varphi b(t) \times F_{0b}(t) \tag{5}
\]

\[
M_c(t) = I\varphi c(t) \times F_{0c}(t) \tag{6}
\]

\[
M_D(t) = [M_a(t) + M_b(t) + M_c(t)] \times K_m \tag{7}
\]

\[
M_D(t) - M_R(t) = J \times \frac{dv}{dt} \tag{8}
\]

\[
V = \frac{dP}{dt} \tag{9}
\]

\[
U_{\varphi a}(t) = U_a(t) \times \sin(Z \times P) \tag{10}
\]

\[
U_{\varphi b}(t) = U_b(t) \times \sin(Z \times P - 120^0) \tag{11}
\]

\[
U_{\varphi c}(t) = U_c(t) \times \sin(Z \times P - 240^0) \tag{12}
\]

\[
F_{0a}(t) = F_0 \times \sin(Z \times P) \tag{13}
\]

\[
F_{0b}(t) = F_0 \times \sin(Z \times P - 120^0) \tag{14}
\]

\[
F_{0c}(t) = F_0 \times \sin(Z \times P - 240^0) \tag{15}
\]

where \(U_{\varphi a}(t), U_{\varphi b}(t), U_{\varphi c}(t)\) – phase voltage; \(I_{\varphi a}(t), I_{\varphi b}(t), I_{\varphi c}(t)\) - phase currents; \(F_{0a}, F_{0b}, F_{0c}\) – phase magnetic fluxes; \(R\) – active resistance; \(L\) – inductance of phase winding; \(M_a(t), M_b(t), M_c(t)\) – moment components caused by currents in phase windings; \(M_D\) – total moment of the electric motor; \(K_m\) – moment coefficient; \(M_R\) – external moment of resistance; \(J\) – rotor inertia moment; \(V\) – angular speed of the engine; \(Z\) – number of pole pairs; \(U_a(t), U_b(t), U_c(t)\) – voltage amplitudes of phase windings; \(P\) – rotor position; \(F_0\) – constant magnetic flux.

Taking into account the above material, a block diagram of a controlled electric drive was developed. It is shown in figure 2.
Figure 2. Mathematical model of controlled electric drive.

In figure 2 D Model – model of a valve motor; \( W_{RS}(S) \) – speed regulator transfer function; \( W_{RP}(S) \) – current regulator transfer function for each phase; \( K_{SPa}, K_{SPb}, K_{SPc} \) – transmission ratios of phase current sensors; \( F_1, F_2 \) – signal limiting nonlinearities; \( F_3 \) – nonlinearity of the pulse width modulator; \( K_{HS} \) – transmission coefficient of the rotor position sensor; \( K_{SS} \) – transmission coefficient of the speed sensor; \( T_{PWM}, T_{P_{\text{PWM}}} \) – amplitude and frequency of the pulse-width modulator; \( Usr \) – speed regulator output signal; \( Ucr \) – current regulator output signal; \( Uu \) – signal at the output of nonlinearity \( F_2 \).

The settings of the current and speed loops are standard (technical and symmetrical optima) [8], which makes it easy to determine the transfer functions of the corresponding regulators.

Therefore, one can write:

\[
W_{RP_i}(S) \times \frac{1}{(R + L S)} \times \frac{K_A}{1 + T_A S} \times K_{SP_i} = \frac{1}{2\tau_1 S (1 + T_A S)} \quad i = 3
\]

where \( \tau_1 = T_A \); \( K_A, T_A \) – power amplifier parameters, from where:

\[
W_{RP_i}(S) = \frac{(R + L S) - K_{SP_i} S}{2\tau_1 T_A K_{SP_i} S} = \frac{(R + L S) - K_{SP_i} S}{2\tau_1 T_A K_{SP_i} S} \quad i = 3
\]

Then

\[
W_{Ci}(S) = \frac{1}{K_{SP_i} (1 + 2 T_A S)}
\]

\[
W_{M}(S) = \frac{K_m}{K_{SP_i} (1 + 2 T_A S)}
\]

where \( W_{Ci}(S) \) – transfer function of the closed i-th current loop, \( W_{M}(S) \) – transfer function of the moment loop.

\[
W_{RS}(S) \times \frac{1}{(1 + 2 \tau_2 S)} \times K_M \times \frac{1}{S} \times K_{SS} = \frac{(1 + 4 \tau_2 S)}{8 T_A S^2 (1 + 2 \tau_2 S)}
\]

where \( \tau_2 = 2 \times T_A \), from where:

\[
W_{RS}(S) = \frac{J (1 + 4 \tau_2 S)}{2 K_M S (1 + 2 \tau_2 S)} = \frac{K_{RS} (1 + 4 T_A S)}{32 T_A S^2}
\]
The following should be noted:
When determining the transfer functions of speed and current controllers, a real power amplifier based on a generator and three comparators was described by the transfer function of an aperiodic link with a time constant equal to:

\[ T_A = \frac{1}{f_A} \tag{22} \]

where \( f_A \) – pulse-width modulation frequency.

Model parameters: \( R = 3 \) Ohm; \( L = 30 \) mH; \( J = 0.0008 \) kg×m\(^2\); \( K_m = 1 \) N×m/A; \( Z = 1 \); \( U_{TWG} = 10 \times \sin(20000 \times t) \); \( K_{SS} = 0.06 \) V/s/rad; \( K_{SPa} = K_{SPb} = K_{SPc} = 3 \) V/A; \( K_{HS} = 1 \); \( f_A = 3 \) kHz.

3. Results
We will carry out mathematical modeling of controlled electric drive in accordance with the requirements and methodology set out in GOST 27803-91 [3]:
- to define the tachograms in a controlled electric drive after the signals \( U_r(t) = +/- 0.001 \) V, \( U_r(t) = +/- 10 \) V are fed to its input;
- to determine the coefficients of uneven rotation by the obtained tachograms;
- to define tachograms in the controlled electric drive after sending signals to its input \( U_r(t) = 0.1 \times \sin(62.8 \times t) \), \( U_r(t) = 0.1 \times \sin(628 \times t) \);
- to determine the frequency bandwidth from the received tachograms.

The simulation results are presented in figures 3–6.

![Figure 3](image1.png)
**Figure 3.** Tachogram at \( U_r(t) = +/- 10^{-3} \) V.

![Figure 4](image2.png)
**Figure 4.** Tachogram at \( U_r(t) = +/- 10 \) V.

![Figure 5](image3.png)
**Figure 5.** Tachogram at \( U_r(t) = 0.1 \times \sin(62.8 \times t) \).

![Figure 6](image4.png)
**Figure 6.** Tachogram at \( U_r(t) = 0.1 \times \sin(628 \times t) \).

4. Conclusion
Analysis of the obtained tachograms allows to draw the following conclusions:
- the range of speed control of the considered electric drive is 10,000;
- the coefficient of non-uniformity of rotation frequency does not exceed 25%;
• the frequency bandwidth is 100 Hz.

It should be noted that experimental studies of the test sample of the controlled electric drive under consideration have confirmed the correctness of the calculations: the range of regulation of the electric drive speed was 10,000, but the frequency bandwidth exceeds 100 Hz.

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