Precision increase in electric drive speed loop of robotic complexes and process lines

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Abstract. The article presents the principles of synthesis of control structures for high-precision electric drives of robotic complexes and manipulators. It has been theoretically shown and experimentally confirmed that improved characteristics of speed maintenance in the zone of significant overloads are achieved in systems of series excitation. They are achieved due to the redistribution of control signals both in the zone of setting the armature current and in the excitation currents. At the same time, the characteristic of the electromagnetic torque becomes linear because the demagnetizing effect of the armature response is compensated by the setting of the excitation current. It is recommended in those cases when it is necessary to extend the range of speed control with a significant reduction in load to apply structures with two-zone speed control. The regulation of the weakening of the excitation flow is more convenient as a function of the voltage in the armature windings.

1. Introduction
The powerful mechanisms of robots and manipulators are working in technological chains of metallurgical production facilities. The electric drives of these robots have an increasing requirement for the accuracy of speed maintenance, not only at idle speed, but also in overload zones [1]. Such characteristics can only be obtained by control systems with motors that implement high torque overloads and with appropriate control laws [2]. Synchronous reluctance machines are the most promising, but improved accuracy characteristics are obtained with special control laws [3]. Therefore, the task is to select rational control structures, which provides improved accuracy characteristics.

2. Materials and methods
When the controlled object is poorly understood, the interest in frequency-topological models of the developed drive systems is increased, especially in those cases where there is equipment for determining the experimental frequency characteristics of real objects [4].

The linear and linearized control systems have frequency analysis and synthesis methods, which allow a simple relationship of the frequency response with the structure and parameters of the circuit and its links. The possibility of experimental determination of frequency characteristics eliminates the need to determine the exact mathematical description of links [5]. The experimental frequency characteristics of the links and drive systems are complex, integral estimates and take into account the real relationships in the system.
3. Statement of the problem
Let us choose characteristics of FRRM, which must be taken into account in the synthesis of the regulatory structure [6]:
- part of the stator winding of FRRM is located above the interpolar gap. It forms an equivalent excitation winding, and the other is the equivalent armature winding, which is located above the pole [7];
- currents are flowing along the excitation winding. They create an excitation field. Armature currents create an armature response field;
- the electromagnetic torque is formed as a result of the interaction of the field of excitation created by an equivalent excitation winding and armature conductors;
- commutation of currents in equivalent excitation windings and an armature must be performed as a function of the rotor position.

In order to regulate the electromagnetic torque, it is necessary to be able to change the values of the excitation flux and the armature currents in the FRRM [8]. By analogy with the DC electric drive, the motor torque can be controlled by acting on the motor armature at a constant flow, i.e., regulating the current of the armature winding with the unchanged excitation current.

The electromagnetic torque is formed by individual sources of phase currents similarly to the scheme of a DC drive of series excitation. At the same time, one of the significant drawbacks of DC drive control systems of series excitation can be avoided - the complexity of implementing brake modes and the reverse of the drive [9]. The requirements of the technological process for the AC drive remain basically the same as for the DC drive [10]. That is why, static operation modes can be generalized in the form of the usual rectangular or almost rectangular mechanical characteristic containing two sections (Figure 1):

![Figure 1. The mechanical characteristic of a controlled electric drive.](image)

- Section 1 is the maintaining of set speed in the range of allowable changes in workloads.
- Section 2 is the limiting of the torque for the overloads of the electric drive on the side of the working mechanism.

As in DC drives, the most common control structure in AC drives remains a subordinate regulation system. The internal torque control loop is covered by an external speed control loop. Such structure has a number of advantages [11]:
- the universality of the scheme;
- simplicity of calculation and adjustment;
- the lowest sensitivity in comparison with other schemes to the change in the parameters of the links of the power section.

The subordinate control schemes have the following disadvantages [12]: inconsistent conditions for adjusting the contours, the possibility of the occurrence of unrecoverable oscillations under "large" influences. However, these schemes are simple for the calculation and adjustment. Therefore they have received the widest distribution in domestic and foreign electric drives. That is why, when synthesizing the control structure of an electric drive, one will be guided by the typical structures of a
DC electric drive.

The switching of the armature winding sections is carried out by a brush-collector contact in the DC drive (the collector performs the function of a mechanical inverter in the motor mode and is simultaneously a rotor position sensor). The current switching of the FRRM stator windings is performed by the switch converter by the signals from rotor position sensor [13].

The requirement for the accuracy of the position sensor is determined by the number of phases of the machine, for example, in the six-phase FRRM the required accuracy is 30 electric degrees.

The dynamic properties of the controlled object are considered with the use of experimental LFR, the variants of the functional schemes of the electric drive being studied, the synthesis of the control structure is described. According to the technical specification, the prototype of the electric drive was made, on which the static characteristics of the drive were investigated [14]; its dynamic characteristics of the electric drive and asynchronous frequency-controlled electric drives of the alternating current were compared [15].

4. Static characteristics of the scheme with sequential excitation of the electric drive

Here one will be interested primarily in static characteristics with a constant speed reference signal and a change in the moment of resistance.

As in the DC drive, the equalities of the excitation current and the armature are performed in the whole range of load changes. The moment will depend on the current in the square in a linear magnetic system. However, when one has to take into account the demagnetizing effect of the transverse armature reaction, this dependence approaches a linear one [16].

Calculation of phase current \( I_p = I_{ex} = I_a \) is an iterative process. First, by assuming some value of the saturation coefficient of magnetic system \( k_{\mu}(I_{ex}) \), let us calculate the current by (1) and (2). Next, let us refine \( k_{\mu}(I_{ex}) \). The dependence of coefficient \( k_{\mu}(I_{ex}) \) is obtained by calculating the magnetization curve of the magnetic system from stator MDS [17]. Then, again according to (1), (2), the phase current is determined and the calculation procedure is repeated.

The calculation of the electromagnetic moment is carried out by expression:

\[
T = 3.56 \cdot B_\delta \cdot I_a ,
\]

where 3.56 is the constructive coefficient.

The induction in the gap is determined on the basis of the expression:

\[
B_\delta = \mu_0 \cdot \frac{(1-\alpha_\delta)}{4p \cdot \delta \cdot k_{\mu}(I_e)} \cdot I_e \cdot N ,
\]

where \( \mu_0 \) is the magnetic permeability of vacuum; \( \alpha_\delta \) is the pole-arc coefficient; \( p \) is the number of pairs of poles; \( \delta \) - calculated air gap value; \( N \) is the number of stator conductors.

The results of calculating the phase current are shown in Figure 2 (curve 1). Analysis of the calculated phase current curve and the experimental curve of its armature component shows their satisfactory coincidence (Figure 2, curve 2), (the error is not more than 20%). A significant discrepancy between the phase current (curve 1) and its excitation component (Figure 2, curve 3) obtained in the course of the experiment is related to the finite operating time of the current control loop [18].

Calculation of the armature component of the voltage is:

\[
U = \sqrt{\left(I_r \cdot I_e \right)^2 \cdot \frac{1}{3} + \left( B_\delta \cdot w_\phi \cdot D \cdot l_\delta \cdot \omega_{mech} \right)^2 \cdot \frac{2}{3} } ,
\]

where \( B_\delta \) is the mean value of the induction in the gap; \( l_\delta \) - the length of the rotor; \( w_\phi \) is the number of phase turns; \( D \) is the diameter of the rotor; \( \omega_{mech} \) - the mechanical speed of the rotor.
As in a DC drive, the calculated voltage curve, as a function of the load, resembles the magnetization curve [19]. Comparison of the calculated (1) and experimental (2) curves (Figure 3) of the armature voltage shows that the discrepancy between them does not exceed 20%.

Figure 3. The calculated (1) and experimental (2) curves of the armature voltage in a circuit with sequential excitation.

5. Static characteristics of the scheme with two-zone speed control of the electric drive
The basic structure of the electric drive scheme with a two-zone speed control at rotational speeds of the smaller rotor will work as in the case of a constant-drive electric drive [20]. Therefore, the static characteristics of the system at speeds below the main one do not differ from the characteristics of the circuit with a constant excitation [21].

Speed control above the main speed is performed by attenuating the flow. Therefore, with the speed reference for a velocity equal to two, the flux is attenuated by a factor of two [22]. In the area of maintaining the speed, the flow (excitation current) and the voltage at the armature winding remain constant. As the static load increases, the current of the armature winding increases. When the load is equal to half the nominal value, the speed controller of the SC saturates [23]. Further speed regulation occurs with constant power; now the increase in the electromagnetic torque is caused by the increase in the motor flow [24]. As soon as the static load torque reaches the limit value (in this case, unity), the drive switches to the operation mode on the stop, at which the armature current and excitation current are kept constant [25].

6. Static characteristics of DC electric drive with a single-channel subordinate control system
The results of the theoretical and experimental studies of the electric drive with FRRM require an assessment of the coincidence of the calculated and experimental curves [26]. The most objective assessment is the comparison of similar calculated and experimental static characteristics in a regulated electric drive, the design methodology is used. The most suitable, perhaps, is the electric drive of direct current, especially since it will be useful to compare its adjusting parameters and the characteristics of the electric drive with the FRRM.
The tested electric drive contained a constant-current motor of the P32 type (Pn = 2.2 kW, Un = 220 V, In = 12.2 A, n = 1600 rpm, J = 0.029 kgm², ra = 1.5 Ω), whose armature is connected to a two-component thyristor converter of TPE type 25/25 - 230 (Ud = 230 V, In = 25 A). The control system of the electric drive was designed as a two-circuit with an internal control loop of current, subordinated to the external speed loop [27]. The PI-type current controller adjusts the internal circuit. The external circuit has a PI-type speed controller with at the input the speed reference signal and the voltage of the speed sensor connected via a potentiometer to the tachometer. A load device - another DC electric drive created load on the shaft of the investigated machine.

As measuring devices, the magneto-electric system of type M45 of accuracy class 1 was used. The resistance moment was estimated from the value of armature current of the load machine [28].

The mechanical characteristics of the electric drive are of practical interest:

\[ I_a, U_a = f(M). \]

The armature current in the load function varies linearly with independent excitation, and it is related to the electromagnetic torque by coefficient kF, where k is the constructive coefficient. The experimental curve [29] when the static load torque varies from -10 to +8 Nm differs slightly from the calculated one. As the load increases, the discrepancy between the curves increases and at torque Mc = + 10 Nm reaches 20%, which is due to the demagnetizing effect of the transverse reaction of the armature. Indeed, the machines of the old series, in particular the P series, were designed without a compensation winding.

The voltage at the armature is determined by the motor's EMF and the voltage drop at the active resistance of the armature scheme:

\[ U_a = E + I_a \cdot r, \quad (4) \]

where E is the motor EMF, which is connected linearly with the speed with independent excitation; r is the active resistance of the armature scheme.

The speed of the electric drive in a system with a PI-speed controller is maintained with an error in the statics equal to zero. Therefore, as the load increases, when the drive is running at the speed maintaining section, the voltage at the armature will increase, in order to compensate for the voltage drop across the active resistance. [30] shows the experimental and calculated stress curves with the armature. The analysis of the armature voltage curves shows that the largest error (about 15%) is observed near the idling speed of the electric drive, determined by the intermittent currents of the converter.

7. Conclusion

The article presents the principles of synthesis of control structures for high-precision electric drives of robotic complexes and manipulators. It has been theoretically shown and experimentally confirmed that improved characteristics of speed maintenance in the zone of significant overloads are achieved in systems of series excitation and they are achieved due to the redistribution of control signals both in the zone of setting the armature current and in the excitation currents. At the same time, the characteristic of the motor's electromagnetic torque becomes linear, since the demagnetizing effect of the armature response is compensated by the setting of the excitation current. It is recommended in those cases when it is necessary to extend the range of speed control with a significant reduction in load to apply structures with two-zone speed control, with the regulation of the weakening of the excitation flow, which is more convenient as a function of the voltage in the armature windings.

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