Engineering of Machine tool’s High-precision electric drives

E S Khayatov, M E Korzhavin and N I Naumovich

Privodnaya Tekhnika, 19, 40-letya Oktyabrya, Chelyabinsk, 454007, Russia

E-mail: 74uc1@mail.ru

Abstract. In the article it is shown that in mechanisms with numerical program control, high quality of processes can be achieved only in systems that provide adjustment of the working element’s position with high accuracy, and this requires an expansion of the regulation range by the torque. In particular, the use of synchronous reactive machines with independent excitation control makes it possible to substantially increase the moment overload in the sequential excitation circuit. Using mathematical and physical modeling methods, it is shown that in the electric drive with a synchronous reactive machine with independent excitation in a circuit with sequential excitation, it is possible to significantly expand the range of regulation by the torque and this is achieved by the effect of sequential excitation, which makes it possible to compensate for the transverse reaction of the armature.

1. Introduction

In electric drives of mechanisms with numerical program control, high quality of processes can be achieved only in systems that ensure the regulation of the working body’s position with high accuracy. In this case, the speed control range in the zone of small deviations of variables can reach 100 000:1. With large deviations, this range becomes smaller, but traditional electric drives still can not provide it. This is due to the low values of the motor torque overloads (usually no more than 2) [1]. In these conditions, it is necessary to pay attention to new types of contactless electric drives, which make it possible to significantly expand the range of regulation by the electromagnetic moment [2]. One of which is an electric drive with a synchronous machine of independent excitation. Since in the existing technical literature this electric drive is described poorly, it is useful to give a technique for synthesizing the power part and the control system, and to confirm the adjustment capabilities of the system by overfilling at the stage of physical simulation.

2. Stages of electric drive’s synthesis with the SSERM

At the first stage, the electromagnetic calculation of the synchronous self-excited reactive motor (SSERM) SSERM was performed. The main dimensions of the machine were chosen according to the machine constant for SSERM. Taking into account the magnetic system’s degree of saturation, the magnitude of the pole gap was chosen equal to 0.66 [3].

At the next stage models of machines on the basis of induction motors (in the body of the corresponding machines) were manufactured. These machines have a different number of poles, which makes it possible to compare the corresponding versions of the SSERM [4].

Furthermore, as a scheme of power circuits, individual sources of phase stator windings were selected, which allows one to estimate the specific parameters of the electromechanical converter with the simplicity of the control circuit.

The control of the frequency converter is performed out of the phase current generating unit
The load of the observed engine’s shaft was created by a hard-wired DC electric machine with independent excitation (type P-41U4, $P_n = 3.2$ kW, $U_n = 220$ V, $n_n = 1500$ rpm, $J = 0.037$ kg/m$^2$). The excitation winding of the machine was connected to a single-phase uncontrolled rectifier. The current of the loader (torque on the motor shaft) was maintained by the armature’s current control circuit and adjusted by the current regulator [5].

To implement the motor mode of the observed machine, the loading machine was turned on in the opposite direction, i.e. so that the machines (load and test), that are individually plugged in the network, would rotate in different directions. At the same time, the load machine operated in the regenerative braking mode [6].

Regenerative braking mode for SSERM was realized with the consistent connection of the load and the examined machines. In this case, the load machine worked in the motor mode.

In the study of the torque-limiting part of the SSERM’s mechanical characteristic the load machine was put into a speed-keeping mode.

3. Mathematical and physical modeling of the electric drive

The most objective assessment of the computational model for the established operating modes of the electric drive is the comparison of the calculated and experimental characteristics. As a calculation model, a detailed structural [7] diagram was adopted.

The characteristics of the electric drive in the schemes: independent, sequential excitation and two-zone speed control make the practical interest.

In the calculated model, let us neglect the finite time of commutation of the armature current, although this circumstance can always be taken into account by the proportionality coefficient of the electromagnetic moment to armature current $C_M$.

In Figure 1 the experimental dependence of the speed on the control signal, which coincides with the calculated one is shown [8].

Let us define stator current components $I_a$, $I_e$. The magnitude of the armature current is connected to the moment on the shaft according to expression:

$$I_a = \frac{M_{LM} + M_L}{C_M},$$  \hspace{1cm} (1)

where $M_{LM}$ is the moment of static load created by the loader; $M_L$ is the moment of idling loss.

In Figure 2 the calculated curve of armature current (5) as a function of speed is shown. Here the experimental curve (4) is given [9].

Analysis of the curves in Figure 3 shows that in the speed range from 0 to 70 rad/s the error between the calculated and experimental values does not exceed 15%. At velocities above 70 rad/s, this error increases and at a rate of 75 rad/s - corresponds to 40%, which is explained by the effect of the finite speed of the stator current control circuit [10]. Indeed, as the speed increases, the relative fraction of time during which the current in the armature winding has a negative sign relative to the preset increases, which leads to a considerable distortion of the field of excitation, and hence to a greater demagnetizing effect of the transverse reaction of the armature [11].

According to the finite speed of the excitation current’s control circuit, the experimental excitation current curve (see Figure 2, curve 1) in the velocity function decreases from the preset value by 12% (with a speed change from 0 to 70 rad/s) [12].

In Figure 2 the calculated 3 and experimental 2 dependences of the current value of the current on the speed are shown. The error between the calculated and experimental values does not exceed 20% in the whole investigated range of rotor speed [13].

Let us consider the dependence of the voltage on the armature winding as a function of speed. If one neglects the EMF of the armature’s winding self-induction ($e = L_a \cdot \frac{dI_a}{dt}$), then the equation of balance of the voltages on the armature winding will have the form:
\[ U_a = E + I_a \cdot r \] (2)

where \( E \) is the rotation EMF induced in the armature winding; \( I_a \) - current in the anchor winding, \( r \) - resistance of the armature winding [14].

**Figure 1.** Dependence of the electric drive’s speed on the control voltage at a constant moment of static load \( M_s = 6 \, \text{N}\cdot\text{m} \) and given excitation current \( I_e = 8 \, \text{A} \).

**Figure 2.** Dependences of the excitation current’s real (1), experimental (4) and calculated (5) values of armature current, experimental (2) and the calculated (3) phase current of the SSERM on the speed.

With constant excitation and speed, the average value of the rotation EMF varies linearly (Figure 2).

Analysis of the experimental curve \( U_a = f(U_{\text{con}}) \) (see Figure 3, curve 2) shows that the error (from 0 to 70 rad / s) between the calculated and experimental values does not exceed 15%. With a further increase in speed, this error increases, which is due to an error in the determination of the armature current, the inconstancy of the excitation flux and the disregard of the self-induction EMF [15].

The considered mechanical characteristic will be valid for any control structure (independent, sequential, two-zone control), and is determined only by the operation of the outer speed counter [16].

Armature current, as in a DC electric drive, depends linearly on the electromagnetic moment (calculated curve 1 is shown in Figure 4) [17]. The actual current curve (see Figure 4, curve 2) in the
load range from – 6 to + 11 N-m differs from the calculated curve by no more than 20%. A significant increase in armature current at a load greater than 12 N-m is explained by the demagnetizing influence of the armature reaction [18].

Figure 3. The calculated (1) and experimental (2) voltage curves on the armature winding as a function of speed.

With a constant reference to excitation, the experimental excitation current curve increases (by 20%) with an increase in the load (in the motor mode) [19], which is due to the following circumstances: for large loads, the armature current is greater than the excitation current, and when passing from the anchor zone to the excitation zone the sign does not change, therefore, taking into account the finite speed of the current loop, the average value of the excitation current is somewhat larger than the preset value. At low loads, the armature current is less than the excitation current, so the average value of the excitation current is less than the preset value [20].

The effective value of the phase current (Figure 5) was calculated using the expression [21]:

$$I_{qav} = \sqrt{\left(I_a^2 \cdot m_\eta + I_e^2 \cdot m_d\right) \cdot \frac{1}{m}}.$$  

Armature voltage was determined from the ratio [22]:

$$U_a = C_e \cdot \omega + I_a \cdot r.$$  

The anchor voltage variation curve contains two sections with the change in the moment: at the first, corresponding to the regime of maintaining the specified speed in the working load zone, it will increase since with constant speed, the EMF induced in the anchor windings increases insignificantly, and the increase in the moment of resistance and, therefore, in the armature current requires an increase in the armature voltage. The experimentally taken external characteristic $U_a = f(I_a)$ (Figure 6, curve 2) differs by no more than 15% in the range of the electromagnetic moment's variation from – 8 to +13 N-m. In the second segment (the moment limiting section), the decrease in speed causes a decrease in voltage $U_a$.

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Figure 4. The calculated (1), experimental (2) curves of the armature current and the excitation current (3) as a function of the load on the motor shaft.

Figure 5. The calculated (1) and experimental (2) phase current of the SSERM versus the load.

4. Conclusion
1. In electric drives with numerical control software, precision values with a large range of moment variation can be achieved only in systems with large overload moments. In most cases, these are synchronous contactless electric drives.
2. In the electric drive with a synchronous reactive machine with independent excitation in a circuit with sequential excitation, it is possible to significantly expand the range of regulation by the torque and this is achieved by the effect of sequential excitation, which makes it possible to compensate for the transverse reaction of the armature.
Figure 6. The calculated (1) and experimental (2) armature voltage versus load.

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