FREQUENCY METHOD FOR DETERMINING THE PARAMETERS OF THE ELECTROMAGNETIC BRAKES AND SLIP-TYPE COUPLINGS WITH SOLID MAGNETIC CIRCUITS

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16. Abstract

The possibility of the equivalent representation of such brakes and couplings by lumped circuits is investigated. Analytical equations are derived for relating the indices of the transients to the parameters of the equivalent circuits for the arbitrary rotor speed. A computer algorithm is given for the calculations.

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FREQUENCY METHOD FOR DETERMINING THE PARAMETERS OF THE ELECTROMAGNETIC BRAKES AND SLIP-TYPE COUPLINGS WITH SOLID MAGNETIC CIRCUITS

F. G. Guseynov and E. M. Abbasova

The important characteristic of electrical machines with solid magnetic circuits is the fact that, when acting as a magnetic circuit, their solid parts simultaneously perform the role of an alternating current distributed winding. In solid magnetic circuits the current and flux are complex functions of magnetic permeability and frequency. /44*

A rigorous investigation of the processes in machines with solid magnetic circuits must be conducted in accordance with Maxwell's equations. If saturation and end effects are taken into account, these processes are very complex and have not been studied adequately. To undertake a number of practical tasks such as the investigation of the reaction of machines with solid magnetic circuits to external disturbances, the determination of the operating parameters and the /45 characteristics of the machines, etc., it is not necessary to study the processes occurring inside the machines; it is sufficient merely to examine the effects which result from these processes.

Under such a set-up, solid magnetic circuits can be compared to lumped magnetically coupled circuits. The establishment of the

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*Numbers in the margin indicate pagination in the original foreign text.

equivalence of solid magnetic circuits of synchronous and asynchronous machines to one or more lumped circuits and the determination of their parameters and characteristics is examined in detail in [1 - 4].

It should be emphasized that the ability to feed three-phase alternating current to the stator winding of these machines is a great convenience in the experimental determination of the equivalent parameters of solid magnetic circuits and in the design of the corresponding characteristics of the machines.

Considerable interest is manifested in the establishment of the equivalence of electromagnetic brakes and slip-type couplings having solid magnetic circuits with lumped circuits and in the determination of their parameters and characteristics. A distinctive feature of these machines is the fact that only the terminals of the field winding are accessible and the excitation of the current is fixed and does not depend on slipping and the magnitude of the armature current. The methods worked out in [1 - 4] for determining the parameters are not suitable for these special machines.

In the present article, we show that the solid magnetic circuits of electromagnetic brakes (EMB) and slip-type electromagnetic couplings (SEC) are equivalent to lumped circuits and we determine the parameters of these circuits by the frequency method.

Equivalence and Mathematical Modeling for EMB and SEC. Structurally, EMB and SEC consist of a solid steel stator and a salient-pole inductor. The cores of the poles are also solid.

We replace the armature current by the equivalent lumped circuit currents with respect to the axes d and q.

The body of a pole in the transient modes is equivalent in its action to a damper winding; therefore the poles of EMB and SEC are equivalent to the short circuit D along the longitudinal axis.

It should be observed that there exists in fact a damping action of the pole along the transverse axis Q also. However, in view of the absence of a clearly expressed transverse circuit, the presence of large magnetic resistance on the path of the transverse flux, and considering the slow rate of change of the flux, we neglect the equivalent transverse circuit.

Thus EMB and SEC with a solid armature and solid poles are equivalent to the four lumped circuits b, d, D, q (Figure 1).

The parameters of these circuits can be determined provided the follow- criteria for equivalence are observed:

invariance of the reactance effect of the armature;

invariance of the electromagnetic power (torque) of the EMB and SEC fore and after their equivalence.

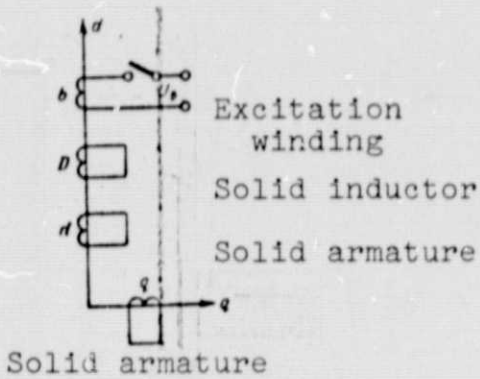

Figure 1

On the basis of these criteria for equivalence, it is possible to work out a procedure for determining the parameters of lumped circuits. One such method, for example, is to determine the parameters of lumped circuits from the field current build-up or attenuation curve. Here the equivalence criteria are satisfied in an natural fashion, since the parameters of lumped circuits are found from the invariance condition imposed on the build-up or attenuation curve $i_b = f(t)$ for a real machine with solid magnetic circuits and the equivalent machine with lumped circuits.

This method of determining the parameters was used.

The presence of a constant field current, the reactions of the armature under load and the structural similarity of EMB and SEC to a synchronous machine make it possible to apply to them the well-developed theory of transients in synchronous machines.

As opposed to the usual synchronous machines in which the circuit parameters are assumed constant, in machines with solid magnetic circuits the parameters of the equivalent armature circuits are variable and depend on the field current and the speed of rotation.

Using the Park-Gorev equations, it is possible to obtain analytic relations which determine the parameters of solid magnetic circuits with respect to the indices of the transients.

The problem of determining the parameters of equivalent circuits with respect to transient indices was solved for synchronous machines in [3 - 5, et al]. However, by these methods, the input inductance is determined when $\omega = 0$. Moreover, when these methods are used, it is impossible to determine the resistance and inductance of all equivalent circuits of EMB and SEC. We present an algorithm for calculating the parameters of equivalent circuits for EMB and SEC with respect to transients.

The Park-Gorev system of equations for EMB on SEC has the form:

$$\left.\begin{aligned} U_B &= (r_B + pL_B) i_B + pMi_d + pMi_D; \\ 0 &= (r_D + pL_D) i_D + pMi_d + pMi_B; \\ 0 &= (r_d + pL_d) i_d + pMi_B + pMi_D + \omega L_q i_q; \\ 0 &= (r_q + pL_q) i_q - \omega Mi_B - \omega Mi_D - \omega L_d i_d. \end{aligned}\right\} \quad (1)$$

Here the notation is generally accepted and requires no explanation.

The coefficients in the equations are the parameters of the equivalent circuits for a given rotor speed and a given field current fed to the field winding. The excitation for U_B applied to the field winding must be small so that the condition of constant speed and constant field current is not violated. This can be achieved by applying a small increment ΔU_B close to the given stable value U_B corresponding to the specified state of saturation. /46

Under these conditions, the parameters of the equivalent circuits are constant, corresponding to the specified speed and field current. Therefore, the equations in System (1) are linear.

Due to the powerful surface effect, the resistance of the lumped circuits r_d and r_q are large at high frequencies. The losses in these resistances determine the electromagnetic output and the moment of the brakes and the couplings. Therefore these resistances cannot be neglected.

<u>The Analytic Relations Between the Circuit Parameters and the Indices of the Frequency Characteristic</u>. The analytic relations for the special cases $\omega = 0$ and $\omega = \omega_H$ with specified tolerances are derived in [7]. Let us consider a more general and more precise case for any value of the speed ω.

Calculation of the transients reduces to the solution of the system of equations (1) and the determination of the excitation current:

$$i_{\text{в}} = \frac{D_{\text{в}}}{D},$$

where

$$D = r_{\text{в}} r_d r_D r_q (a_0 p^4 + a_1 p^3 + a_2 p^2 + a_3 p + a_4); \tag{2}$$

$$D_{\text{в}} = r_d r_D r_q (b_0 p^3 + b_1 p^2 + b_2 p + b_3); \tag{3}$$

$$\left.\begin{aligned}
a_0 &= T_{\text{в}} T_D T_d T_q (\sigma_{Dd} - \mu_{\text{в}D}\sigma_d - \mu_{\text{в}d}\sigma_D);\\
a_1 &= T_{\text{в}} T_D T_q \sigma_{\text{в}D} + T_{\text{в}} T_d T_q \sigma_{\text{в}d} + T_D T_d T_q \sigma_{Dd} +\\
&\quad + T_{\text{в}} T_D T_d (\sigma_{Dd} - \mu_{\text{в}D}\sigma_d - \mu_{\text{в}d}\sigma_D);\\
a_2 &= T_{\text{в}} T_D \sigma_{\text{в}D} + T_D T_d \sigma_{Dd} + T_{\text{в}} T_d \sigma_{\text{в}d} + T_{\text{в}} T_q +\\
&\quad + T_D T_q + T_d T_q + \omega^2 T_{\text{в}} T_d T_D T_q (\sigma_{Dd} -\\
&\quad - \mu_{\text{в}D}\sigma_d - \mu_{\text{в}d}\sigma_D);\\
a_3 &= T_{\text{в}} + T_D + T_d + T_q + \omega^2 (\sigma_{Dd} T_D T_d T_q +\\
&\quad + \sigma_{\text{в}d} T_{\text{в}} T_d T_q);\\
a_4 &= 1 + \omega^2 T_d T_q.
\end{aligned}\right\} \tag{4}$$

$$\left.\begin{aligned}
b_0 &= \sigma_{Dd} T_D T_d T_q;\\
b_1 &= \sigma_{Dd} T_D T_d + T_d T_q + T_D T_q;\\
b_2 &= T_D + T_d + T_q + \omega^2 \sigma_{Dd} T_D T_d T_q;\\
b_3 &= 1 + \omega^2 T_d T_q.
\end{aligned}\right\} \tag{5}$$

Returning to the original equation, we obtain:

$$i_{\text{в}}(t) = \frac{U_{\text{в}}}{r_{\text{в}}} - i' e^{-\frac{t}{T'}} - i'' e^{-\frac{t}{T''}} - i''' e^{-\frac{t}{T'''}} -$$

$$- i^{IV} e^{-\frac{t}{T^{IV}}}, \tag{6}$$

where

$$\left.\begin{aligned}
i' &= \frac{T_{в} + \sigma_{вd} T_{в} T_{d} T_{q} \omega^2}{T_{в} + T_{D} + T_{d} + T_{q} + \omega^2 (\sigma_{вd} T_{в} T_{d} T_{q} + \sigma_{Dd} T_{d} T_{D} T_{q})} \frac{U_{в}}{r_{в}};\\
i'' &= \frac{T_{D} + T_{d} + T_{q} + \omega^2 \sigma_{Dd} T_{D} T_{d} T_{q}}{T_{в} + T_{D} + T_{d} + T_{q} + \omega^2 (\sigma_{вd} T_{в} T_{d} T_{q} + \sigma_{Dd} T_{d} T_{D} T_{q})} \times\\
&\times \frac{T'' - T''_0}{T'' - T'''} \frac{U_{в}}{r_{в}};\\
i''' &= \frac{T_{D} + T_{d} + T_{q} + \omega^2 \sigma_{Dd} T_{D} T_{d} T_{q}}{T_{в} + T_{D} + T_{d} + T_{q} + \omega^2 (\sigma_{вD} T_{в} T_{d} T_{q} + \sigma_{Dd} T_{d} T_{D} T_{q})} \times\\
&\times \frac{T''_0 (T''' - T'''_0)}{T'' (T''' - T^{IV})} \frac{U_{в}}{r_{в}};\\
i^{IV} &= \frac{T_{D} + T_{d} + T_{q} + \omega^2 \sigma_{Dd} T_{D} T_{d} T_{q}}{T_{в} + T_{D} + T_{d} + T_{q} + \omega^2 (\sigma_{вd} T_{в} T_{d} T_{q} + \sigma_{Dd} T_{d} T_{D} T_{q})} \times\\
&\times \frac{T''_0 (T'''_0 - T^{IV})}{T'' (T''' - T^{IV})} \frac{U_{в}}{r_{в}}.
\end{aligned}\right\} \tag{7}$$

From Equation (6) it is clear that the field current has four free components, each of which attenuates with its own time constant:

$$T' = -\frac{1}{p_1};\; T'' = -\frac{1}{p_2};\; T''' = -\frac{1}{p_3};\; T^{IV} = -\frac{1}{p_4}.$$

From the properties of the roots of the characteristic equation:

$$a_0 p^4 + a_1 p^3 + a_2 p^2 + a_3 p + a_4 = 0 \tag{8}$$

the following equations are obtained:

$$\begin{aligned}
\frac{a_0}{a_4} &= T' T'' T''' T^{IV};\\
\frac{a_1}{a_4} &= T' T'' T''' + T' T'' T^{IV} + T'' T''' T^{IV} + T' T''' T^{IV};\\
\frac{a_2}{a_4} &= T' T'' + T' T''' + T' T^{IV} + T'' T''' + T'' T^{IV} + T''' T^{IV};\\
\frac{a_3}{a_4} &= T' + T'' + T''' + T^{IV}.
\end{aligned}$$

Analogously, we have for Equation (3):

$$\frac{b_0}{b_3} = T'_0 T''_0 T'''_0;\quad \frac{b_1}{b_3} = T'_0 T''_0 + T'_0 T'''_0 + T''_0 T'''_0;$$
$$\frac{b_2}{b_3} = T'_0 + T''_0 + T'''_0.$$

When the rotor is stationary, the problem is somewhat simplified, since the generator emf linking the longitudinal circuit with the transverse circuit vanishes. In this case, the characteristic equation has the form:

$$A_0 p^3 + A_1 p^2 + A_2 p + A_3 = 0, \tag{9}$$

where

$$\left. \begin{aligned} A_0 &= T_{\text{в}0} T_{D_0} T_{d_0} (\sigma_{Dd_0} - \mu_{\text{в}d_0} \sigma_{D_0} - \mu_{\text{в}D_0} \sigma_{d_0}); \\ A_1 &= T_{\text{в}0} T_{d_0} \sigma_{\text{в}d_0} + T_{D_0} T_{d_0} \sigma_{Dd_0} + T_{\text{в}0} T_{D_0} \sigma_{\text{в}D_0}; \\ A_2 &= T_{\text{в}0} + T_{D_0} + T_{d_0}; \ A_3 = 1. \end{aligned} \right\} \tag{10}$$

The subscript "0" signifies that the parameters of the circuits pertain to the case $\omega = 0$.

The constant attentuation times of the free current components are expresssed as follows in terms of the coefficients of the characteristic equation (9): /47

$$\tau' \tau'' \tau''' = A_0, \tag{11}$$

$$\tau' \tau'' + \tau' \tau''' + \tau'' \tau''' = A_1, \tag{12}$$

$$\tau' + \tau'' + \tau''' = A_2.$$

In this case the expression for the field current takes the form:

$$i_{\text{в}_0}(t) = \frac{U_{\text{в}}}{r_{\text{в}0}} - i'_0 e^{-\frac{t}{\tau'}} - i''_0 e^{-\frac{t}{\tau''}} - i'''_0 e^{-\frac{t}{\tau'''}} \tag{13}$$

where

$$D_{\text{в}_0} = r_{d_0} r_{D_0} (B_0 p^2 + B_1 p + B_2).$$

In Equation (13),

$$\left. \begin{aligned} i'_0 &= \frac{U_{\text{в}}}{r_{\text{в}0}} \frac{U_{\text{в}0}}{T_{\text{в}0} + T_{d_0} + T_{D_0}}; \\ i''_0 &= \frac{U_{\text{в}}}{r_{\text{в}0}} \frac{T_{D_0} + T_{d_0}}{T_{\text{в}0} + T_{d_0} + T_{D_0}} \frac{\tau' - \tau''_0}{\tau'' - \tau'''}; \\ i'''_0 &= \frac{U_{\text{в}}}{r_{\text{в}0}} \frac{T_{D_0} + T_{d_0}}{T_{\text{в}0} + T_{d_0} + T_{D_0}} \frac{\tau''_0 - \tau'''}{\tau'' - \tau'''}. \end{aligned} \right\} \tag{14}$$

τ'_0 and τ''_0 are determined from the expressions:

$$\tau'_0 \tau''_0 = B_0, \ \tau'_0 + \tau''_0 = B_1 \quad \text{where} \quad B_2 = 1.$$

Algorithm for Calculating the Parameters and the Characteristics of EMB and SEC. An analysis of (4), (7), (10), and (14) shows that these equations express the relation between the indices of the transients and the parameters of the equivalent circuits. These systems of equations are nonlinear; moreover, the nonlinearity is expressed in the form of the product of many unknown parameters and the quotient is obtained from their division. There is no analytic solution for such equations; even a numerical solution involves great difficulties.

To simplify the task of solution, certain of the parameters are determined by other methods. Thus, for example, the parameters of the field winding r_b and M_{ad_0} can be determined from design data or experimentally. In an example cited in [8], M_{ad_0} was found by experiment, and r_b — by direct measurement.

Calculation of the parameters of the equivalent circuits for EMB or SEC when the rotor is stationary is carried out according to the following algorithm:

1. A_0 and A_1 are determined from (11) and (12).

2. Just as in the case of a synchronous machine [3], the parameters of the excitation winding are determined from the indices of the transients:

$$\left.\begin{aligned} L_{\text{в}0} &= r_{\text{в}0}\frac{i'_0\tau' + i''_0\tau'' + i'''_0\tau'''}{i_{\text{уст}}}; \\ L_{\text{в}s} &= L_{\text{в}0} - M_{ad_0}; \quad T_{\text{в}0} = \frac{L_{\text{в}0}}{r_{\text{в}0}}. \end{aligned}\right\} \qquad (15)$$

3. After substitution of the parameters determined above and the corresponding transformations, the system of equations (10) and (14) assume the following form:

$$\tau' - T_{\text{в}_0} = T_{D_0} + T_{d_0}; \qquad (16)$$

$$\tau''_0\tau'_0 = \left(1 - \frac{M^2_{ad_0}}{L_{D_0}L_{d_0}}\right)T_{d_0}T_{D_0}; \qquad (17)$$

$$\frac{A_0 \tau_{в0}}{B_0}(L_{D_0} L_{d_0} - M^2_{ad_0}) = L_{в0} L_{D_0} L_{d_0} + 2M^3_{ad_0} + \quad (18)$$
$$+ M^2_{ad_0}(L_{d_0} + L_{D_0} + L_{в0});$$

$$-T_{в0} \frac{M^2_{ad_0}}{L_{в0}} \left(\frac{T_{d_0}}{L_{d_0}} - \frac{T_{D_0}}{L_{D_0}} \right) = A_1 - \tau'_0 \tau''_0 - T_{в0}(T_{D_0} + T_{d_0}), \quad (19)$$

where the unknowns are the parameters of the equivalent circuits of the solid stator L_{d_0} and T_{d_0}, and of the solid fields of the rotor L_{D_0} and T_{D_0}.

Equations (16) and (18) are solved for the unknowns L_{d_0} and T_{d_0} and the results are substituted in (17) and (19). Thus we obtain a system of two quadratic equations in two unknowns T_{D_0} and L_{D_0}:

$$\left.\begin{aligned} &(d_1 T_{D_0} - d_0 T^2_{D_0} + d_2) L^2_{D_0} + (b_0 T^2_{D_0} + \\ &+ b_1 T_{D_0} + b_2) L_{D_0} + (c_1 T_{D_0} - c_0 T^2_{D_0}) = 0; \\ &(d'_2 - T_{D_0} d'_1) L^2_{D_0} + (b'_2 - b'_1 T_{D_0}) L_{D_0} + \\ &+ c'_1 T_{D_0} = 0. \end{aligned}\right\} \quad (20)$$

From the simultaneous solution of these two equations, a single equation in the unknown L_{D_0} is obtained:

$$C_0 L^6_{D_0} + C_1 L^5_{D_0} + C_2 L^4_{D_0} + C_3 L^3_{D_0} + C_4 L^2_{D_0} + C_5 L_{D_0} = 0. \quad (21)$$

The coefficients in Equation (21) are known and are expressed in terms of the previously determined parameters for the equivalent circuits of the EMB and the indices of transients. On solving Equation (21), we determine L_{D_0}.

We propose a simpler engineering method for solving the system of equations (20). Since the unknown quantities in this system of equations are circuit parameters — T_{D_0} is the time constant and L_{D_0} is the inductance of the equivalent circuit for the EMB or SEC under study — the roots of each equation in the System (2) individually are accordingly equal.

The equality of the roots justifies the conclusion that the coefficients in the equations of (20) are proportional. From this property we obtain the equations:

$$(c_0d'_1+d_0c'_1)T^2_{D_0}-(c_0d'_2+c_1d'_1+d_1c'_1)T_{D_0}+$$
$$+(c_1d'_2+d_2c'_1)=0;$$
$$(b_0c'_1-b'_1c_0)T^2_{D_0}+(b_1c'_1+c_0b'_2+c_1b'_1)T_{D_0}+$$
$$+(b_2c'_1-c_2b'_1)=0,$$

from which T_{D_0} is determined.

4. T_{d_0} is determined by substituting the known quantity T_{D_0} into (16).

5. L_{D_0} is determined from any of the equations in (20).

The inductance of stray currents in the equivalent circuit for a solid pole is determined analogously to the corresponding determination in the case of the excitation circuit:

$$L_{D_{\sigma 0}}=L_{D_0}-M_{ad_0}.$$

6. L_{d_0} is found by substituting L_{D_0} into Equation (18) /48

7. The resistances of the equivalent circuits r_{d_0} and r_{D_0} are determined by means of known relationships in terms of the time constants and the inductance of the circuits.

The algorithm for calculating the parameters of the equivalent circuits by means of the associated equations differs from that presented above when the rotor is revolving. It consists of the following steps:

1. The parameters of the excitation winding L_B and T_B are determined by means of the indices for the transients associated with the attenuation of the field current when $\omega \neq 0$. A formula analogous to (15) is used which takes into account the four free components of the field current.

In contrast to synchronous machines, in machines with solid magnetic circuits the mutual induction flux is completed through the solid parts in which the depth of penetration of the magnetic flux and the current vary with the speed of rotation, and therefore the reluctance for the flux varies. Hence the coefficient of mutual induction M_{ad} and the inductance of the circuits of EMB and SEC differ for various values of ω from the corresponding quantities when $\omega = 0$, and they are determined for each speed of rotation of the rotor, since:

$$M_{ad} = L_{\text{в}} - L_{\text{в}s}.$$

For stray currents of the excitation winding, the inductance does not change with changes in the rotation speeds of the rotor, since the rotors of EMB are provided with large air gaps, so that the flux of stray currents is completed in the air and has constant reluctance.

2. The inductance of the equivalent circuit for a solid pole is determined by means of the formula:

$$L_D = L_{D_s} + M_{ad}.$$

The resistance of a solid pole r_D does not depend on ω and is assumed equal to the resistance when the rotor is stationary — corrected for the temperature at which the experiment is conducted.

3. After the pertinent transformations are carried out and all the previously determined quantities are substituted in (4) and (7), a system of equations is obtained for the relation between the indices of the transients and the equivalent circuits when $\omega \neq 0$:

$$a_0 = T_{\text{в}} T_D T_d T_q (\sigma_{Dd} - \mu_{\text{в}d} \sigma_D - \mu_{\text{в}D} \sigma_d); \qquad (22)$$

$$a_3 = T_{\text{в}} + T_D + T_d + T_q + \omega^2 (\sigma_{\text{в}d} T_{\text{в}} T_d T_q + \sigma_{Dd} T_D T_d T_q); \qquad (23)$$

$$a_4 = 1 + \omega^2 T_d T_q; \qquad (24)$$

$$i' = \frac{U_{\text{в}}}{r_{\text{в}}} \frac{T_{\text{в}} + \omega^2 T_{\text{в}} T_d T_q \sigma_{\text{в}d}}{T' a_4}. \qquad (25)$$

4. L_d is determined from (22); then from (25), a_4, the coefficient of the characteristic equation, is found.

5. T_d and T_q are found by solving (23) and (24) simultaneously.

6. The relation $L_q/L_d = k$ is considered known from design or experimental data. The resistances r_d and r_q of the equivalent circuits for a solid stator are determined by the known quantities L_d and L_q, T_d and T_q.

Thus by means of the algorithms introduced, it is possible to calculate the parameters of EMB and SEC for arbitrary values of the field current and any rotation speed of the rotor, using the corresponding indicators of the transients associated with the build-up and attenuation of the excitation current.

By means of the known equivalent parameters of EMB and SEC, it is possible to calculate their mechanical characteristics from the equation:

$$M = \frac{i_d^2 r_d + i_q^2 r_q}{\omega} p,$$

where i_d, i_q are the currents in the solid armature which are found from the system of equations (1) as applied to the steady-state mode:

$$i_d = \frac{U_B}{r_B} \frac{\omega^2 T_d T_q M}{L_d(1 + \omega^2 T_d T_q)}; \quad i_q = \frac{U_B}{r_B} \frac{\omega M}{r_q(1 + \omega^2 T_q T_d)}.$$

Error estimates for the parameters can be found by means of analytic expressions which relate the desired parameters to the initial information [9]. These expressions were derived by using a method which is based on an estimate of the random errors in the calculated quantity in terms of the root-mean-square errors in measurements [10].

Appendix 1. Determination of the parameters and characteristics of a prototype model EMB. The data for the prototype model EMB under study is as follows: M = 40 kgm, n = 1500 rpm, U_{BH} = 24 V, i_{BH} = 12 a p = 8.

The EMB stator is solid, made of mark "40" steel, and has a diameter D_a = 306 mm. The rotor is of armored type with staggered poles made of "steel-10". The poles are trapezoidal in form. The length of a pole is l_p = 140 mm, and the pole division is τ = 59 mm.

The excitation winding of coil type is located under the poles, and the number of windings w = 285. The air gap δ = 3 mm.

Attenuation tests of the excitation current were conducted with a stationary rotor, and also at various rotation speeds (n = 180, 320, 510, 565, 890, and 1410 rpm) for various excitation current values (i_B = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5 i_{BH}).

A program for calculating the parameters of EMB on the digital computer "Ural-3" according to the proposed algorithm was worked out and the parameters were calculated for all the rotation speeds of the rotor and field currents mentioned above.

The calculations carried out make it possible to construct the functions expressing the equivalent parameters of a solid armature in terms of the speed of rotation for various currents $L_d = f(\omega)$, $L_q = f(\omega)$ (Figures 2, 3). /49

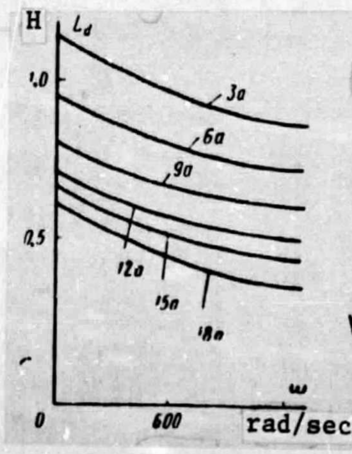

Figure 2

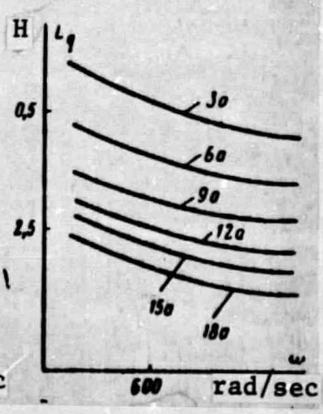

Figure 3

Using the computed values of the parameters for the EMB under study, we constructed its mechanical characteristics for various field currents by the analytical method. It is clear from Figure 4 that the mechanical characteristics obtained by calculation practically coincide with those found by experiment, using a tensometer.

n, rpm	ω, rad/sec	i_s, A	r_s, O	L_s, H	T_s, sec	L_D, H	r_D, O	T_D, sec	L_d, H	r_d, O	T_d, sec	L_q, H	r_q, O	T_q, sec	M_{ad}, H	M_{aq}, H	M, kgm
0	0	11,9	2,28	0,875	0,334	1,035	4,14	0,2502	0,69	0,54	0,1055	—	—	—	0,672	0,336	0
180	153	12,1	2,06	0,772	0,374	0,936	4,04	0,225	0,668	7,12	0,094	0,334	4 771	$0,7 \cdot 10^{-4}$	0,569	0,284	22,2
320	267	12,0	2,25	0,745	0,331	0,847	4,11	0,206	0,646	10,6	0,061	0,323	6 050	$0,535 \cdot 10^{-4}$	0,551	0,275	28,4
510	428	11,8	2,26	0,732	0,324	0,831	4,14	0,201	0,631	12,1	0,052	0,315	8 730	$0,361 \cdot 10^{-4}$	0,538	0,269	31,1
565	468	12,0	2,3	0,728	0,315	0,826	4,3	0,192	0,626	14,0	0,0448	0,3087	10 580	$0,291 \cdot 10^{-4}$	0,534	0,266	31,5
890	748	11,9	2,33	0,72	0,309	0,818	4,42	0,185	0,617	17,05	0,0362	0,3085	14 950	$0,206 \cdot 10^{-4}$	0,526	0,267	33,2
1 410	1 180	12,0	2,1	0,708	0,338	0,804	4,08	0,177	0,604	24,6	0,0246	0,302	21 700	$0,139 \cdot 10^{-4}$	0,514	0,257	32,6

Applying the method of error determination discussed above, we calculated the errors in the parameters of the prototype model EMB for all values of the excitation current and speeds of rotation mentioned above. Under the assumption that the transient indices, which serve as underlying data, are determined with an error of 5%, the error of the desired parameters amounts to 3 - 5% when the parameters are found by the analytic method.

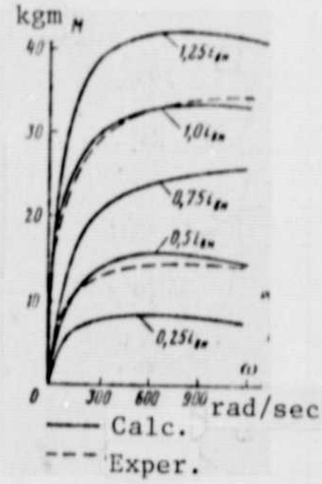

Figure 4

As an example, we present in the table the results of the calculation of the parameters of the EMB under study when $i_B = i_{BH} = 12$ a, and the speeds of rotation of the rotor are n = 0, 180, 320, 510, 565, 890, and 1410 rpm.

Appendix 2. Notation used.

i_B sts — steady state field current;

$i', i'', i''', i^{IV}, i'_0, i''_0, i'''_0$ — initial values of field current free components;

$T', T'', T''', T^{IV}, \tau', \tau'', \tau''', T'_0, T''_0, T'''_0, \tau'_0, \tau''_0$ — constant attenuation times of the free components of the field current;

$\sigma_{bd}, \sigma_{Dd}, \sigma_{bD}$ — coefficients of the stray currents between the circuits b and d, D and d, b and D, respectively;

μ_{bd}, μ_{bD} — coefficients of the relations between the circuits b and d, b and D;

p_1, p_2, p_3, p_4 — roots of the characteristic equation;

M — coefficient of mutual induction;

M — electromagnetic moment.

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