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CALCULATION OF TRANSIENT PROCESSES DURING THE START-UP OF AN ELECTRIC DRIVE WITH AN ASYNCHRONOUS MOTOR CONNECTED DIRECTLY TO THE NETWORK

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Abstract: This article calculates the transient processes occurring during the start-up of an electric drive using a system of equations describing the mathematical expression of an asynchronous motor electric drive in an open-loop control system. The calculations take into account the mathematical expression of the speed control system of an asynchronous motor electric drive, which ensures the invariance of the stator flux linkage, the nonlinearity of the voltage dependence on the frequency, and the nonlinearity of the system itself. The article also analyzes the equations that provide the relationships between voltages, currents, and flux linkages in the form of phase vectors, as well as the equations that determine the electromagnetic torque of an asynchronous motor. The calculation equations additionally include the equations of the mechanics of the electric drive and the equations that relate the angular frequency of the supply voltage to the engine speed and the angular frequency of the rotor electric driving force.

Keywords: Open adjustment system, transient process, stator current flow, space vector, flow application, electromagnetic torque.

1. Introduction

There are two different but related approaches to the mathematical representation of an asynchronous motor.

In the first approach, a sinusoidal voltage is applied to one of the stator phase windings or one of the rotor windings, and it is assumed that the currents and flux linkages in these windings are generated by these currents. The relationships between such variable quantities are determined in a stationary (steady) mode, that is, when the motor is powered by a constant voltage source and operates at a constant speed (ω=const and $d\omega/dt=0$). Usually, a symbolic method is used to calculate such variable quantities. The graphical interpretation of such an approach is the commutation diagram of an asynchronous motor, and the principle of constructing an asynchronous motor electric drive control system, called a U/f-control system, a variable or scalar module control system, is based on this.

The second type of approach is based on the representation of a three-phase system of voltages, currents and flux linkages in the form of phase vectors. In it, the electromagnetic processes occurring in alternating current motors are described on the basis of phase vectors.

When mathematically expressing the electromagnetic processes occurring in asynchronous

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motors, the following conditional requirements must be met:

1.the three-phase system is symmetrical, there is no zero current in it, the sum of the instantaneous values of the phase currents is zero: $i_{1A}+i_{1B}+i_{1C}=0$;

2.the current flowing through each phase winding creates a magnetic induction force distributed sinusoidally along the circumference of the motor air gap;

3.the sum of the magnetic induction forces in the individual windings creates a total magnetic induction distributed sinusoidally along the motor air gap;

4.the magnetization characteristic of the motor is linear.

Assuming that the relative magnetic permeability of the stator and rotor magnetic conductors is infinitely large, the magnetic field of the motor can be assumed to consist of a main field and a leakage field. The main field corresponds to the main harmonic components of the induction distribution in the air gap. It can be imagined as two fields that are stationary relative to each other: the main field of the stator, which is generated by the currents in all phase windings of the stator, and the main field of the rotor, which is generated by the currents in all phase windings of the rotor. In turn, the main field of the stator and the main field of the rotor can be imagined as the sum of the main fields generated by the individual phases of the stator and rotor. The leakage magnetic field is also generated by the stator and rotor phase currents, but does not participate in the formation of the main magnetic field.

The main flux coupling of the winding is based on the formation of a coupling between the fields of both windings of the motor through the air gap. The leakage flux coupling in the coil is related only to the part of the magnetic field that is coupled to a given coil. The sum of the main magnetic flux coupling and the leakage flux coupling gives the total flux coupling of the coil.

For the sake of generality, let us assume that in the first stage of the problem under consideration, the motor has a phase rotor and that both the stator coil and the rotor coil are energized.

To construct the commutation circuit, it is necessary to write equations for the instantaneous values of the voltage, current, and flux couplings. To do this, we assume that the rotor coil is close to the stator, the magnetic system is not saturated, the magnetic driving forces generated by the phase currents are distributed sinusoidally in the air gap, and the operating mode of the motor is symmetrical and, therefore, there are no zero-sequence currents. This allows us to write the equilibrium equation of the voltage for one phase of the stator and one phase of the rotor. We denote the variables related to the stator by the number 1 and those related to the rotor by the number 2.

The equations that provide the connections between the voltages, currents and flux linkages in the form of spatial vectors, as well as the equations that determine the electromagnetic torque of

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an asynchronous motor, were analyzed. If we add to these equations the equations of the mechanics of the electric drive and the equations that connect the angular frequency of the supply voltage with the motor speed and the angular frequency of the rotor electric driving force, these expressions can be used to mathematically represent the electric drive in the form of structural diagrams in an open-loop system. We make the following changes to these expressions:

1.we write the differential equations in normal form;

2.leaving the definitions unchanged, we proceed to the description of the variables in Laplace's form and introduce the transformation $d/dt=p$;

3.we consider a short-circuited motor and assume that $\tilde{U}_2=0$;

4.By successively eliminating $\tilde{I}_2$ from the third equation of the system of equations and $\tilde{I}_1$ from the fourth equation, we describe the stator and rotor currents as a function of the flux linkage.

Then, the initial equations mathematically representing the electric drive with an asynchronous motor can be expressed in the following form:

$$p\tilde{\Psi}_1=\tilde{U}_1-R_1\tilde{I}_1-j\omega_{0эл}\tilde{\Psi}_1;$$

$$p\tilde{\Psi}_2=-R_2\tilde{I}_2-j\omega_p\tilde{\Psi}_2;$$

$$\tilde{I}_1=\frac{1}{\sigma L_1}\left(\tilde{\Psi}_1-k_2\tilde{\Psi}_2\right);$$

$$\tilde{I}_2=\frac{1}{\sigma L_2}\left(\tilde{\Psi}_2-k_1\tilde{\Psi}_1\right);$$

$$M_д=\frac{3}{2}p_п L_m Im\left[\tilde{I}_1\dot{I}_2\right];$$

$$p\omega=\frac{1}{Jp}\left(M_д-M_c\right);$$

$$\omega_p=\omega_{0эл}-p_п\omega,$$

where $J-$ is the moment of inertia of the electric drive; M_c- is the load torque, which includes the load torque on the shaft and the wasted torque during engine rotation.

2. Discussion of transients occurring during the start-up of an electric drive with an

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asynchronous motor connected directly to the mains

Using the structural scheme of an asynchronous motor, in the stepwise distribution of the frequency, when ω_{0el}=314 rad/sek and $I_1=u_{1\alpha}=\sqrt{2}\cdot 220=311$ $V(u_{1\beta}=0)$ at the value of the speed from zero to 157 rad/sek in the ideal normal operation mode, the start of the synchronous motor we present the results of calculations.

In this problem, an asynchronous motor with a short-circuited rotor with a power of P_n=1,1 kW was chosen. Nominal phase voltage and armature current (effective values): $U_{1n}=220$ V; $I_{1n}=2{,}73$ A; nominal frequency of supply voltage f=50 Gts ($\omega_{0el.n}=314$ rad/s); number of pairs of poles p_p=2 (synchronous speed $n_{0n}=1500$ rpm; synchronous angular speed $\omega_0=157$ rad/s).

Moment of inertia of the engine $J_d=0{,}0026$ $kg{\cdot}m^2$. In further calculations, the sum of torques of the engine and working body is assumed to be $J=J_d+J_{i.o}=0{,}026$ $kg{\cdot}m^2$. The value in relative units of the parameters of the switching circuit given in the references: active resistances of the stator and rotor phases: $\overline{R}_1=0{,}118$; $\overline{R}_2=0{,}07$; inductive resistance of the magnetization circuit $\overline{x}_m=1{,}74$; stator and rotor inductive leakage resistances, respectively $\overline{x}_{1\sigma}=0{,}144$; $\overline{x}_{2\sigma}=0{,}113$. These values base resistance to switch in absolute units must be multiplied by $Z_b=U_{1b}/I_{1b}=220/2{,}73=80{,}59$ Ohm. As a result, $R_1=9{,}50$ Ohm; $R_2=5{,}64$ Ohm; $x_m=140{,}4$ Ohm; $x_{1\sigma}=11{,}6$ Ohm; $x_{2\sigma}=149{,}5$ Ohm will be. Inductive resistances are calculated at nominal frequency. Therefore, when determining the inductance, the value of the inductive resistance should be divided by the nominal value of the angular frequency $\omega_{0el.n}$ and as a result we will have the following: $L_m=0{,}447$ Gn; $L_{1\sigma}=0{,}037$ Gn; $L_{2\sigma}=0{,}029$ Gn; $L_1=L_m+L_{1\sigma}=0{,}484$ Gn; $L_2=L_m+L_{2\sigma}=0{,}476$ Gn.

Time constant of stator phase currents $T_1=L_1/R_1=0{,}0509$ s; the time constant of the rotor phase currents $T_2=L_2/R_2=0{,}0844$ s. Engine dispersion coefficient $\sigma=1-k_1k_2=0{,}133$ ($k_1=L_m/L_1=0{,}923$; $k_2=L_m/L_2=0{,}939$).

The results of calculations performed in the MATLAB Simulink environment are presented in Figure 1. The figure shows two transient processes. The first is to start the electric drive by connecting the motor directly to the power source. Before this process began, all variables were equal to zero, that is, there was an initial zero condition. The first is to start the electric drive by connecting the motor directly to the power source. Before this process began, all variables were equal to zero, that is, there was an initial zero condition. At the moment of time t=1, the loading moment suddenly reaches M_s=4 N·m, which causes the formation of the second transient process. By the time this second transient occurs, the motor speed, current, and current have reached their nominal values, and these values define the initial zero condition for the second transient. In this case, there was no need to define these two processes separately because both processes were calculated within the same problem and the initial condition for the second process was automatically determined.

If the calculation of the second transient process is considered as an independent problem, then it is necessary to calculate the initial zero condition that existed before its initiation. For this, the following must be present: the initial voltage on the stator, the frequency of rotation of this voltage and the initial value of the rotation frequency of the rotor electroabsorbing power. The initial value of the rotation frequency of the rotor electroabsorbing power can be determined from the value of the mechanical characteristics of the engine to the increase in the value of the load torque (in this problem, the initial frequency of the rotor electroabsorbing power was $\omega_{0el.n}=0$).

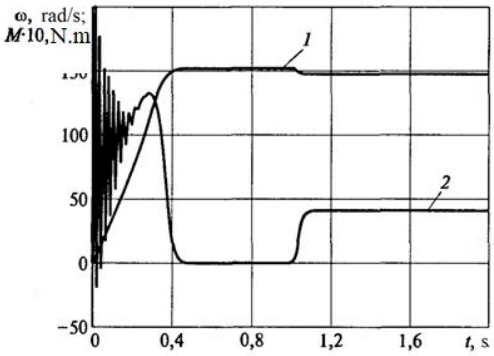

Figure 1. The results of the calculation of transient processes in the case of a sudden increase in torque during the direct start of an electric drive with an asynchronous motor:

1 – speed curve; 2 – torque curve

As a result of the calculations, the initial values of the stator and rotor currents should come out. It is more convenient to determine them by solving the matrix equation written in the following form based on the first three expressions of the system of equations when $p=0$:

$$\mathbf{Ax=u}; \qquad (1)$$

$$\mathbf{A}=\begin{bmatrix} 1/(\sigma T_1) & -\omega_{0эл} & -k_2/(\sigma T_1) & 0 \\ \omega_{0эл} & 1/(\sigma T_1) & 0 & -k_2/(\sigma T_1) \\ -k_1/(\sigma T_2) & 0 & 1/(\sigma T_2) & -\omega_{\text{р}} \\ 0 & -k_1/(\sigma T_2) & \omega_{\text{р}} & 1/(\sigma T_2) \end{bmatrix};$$

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$$\mathbf{x}=\begin{bmatrix}\psi_{1\alpha}\\ \psi_{1\beta}\\ \psi_{2\alpha}\\ \psi_{2\beta}\end{bmatrix};\quad \mathbf{u}=\begin{bmatrix}U_1\\ 0\\ 0\\ 0\end{bmatrix}.$$

The column matrix of the initial values of the flux is calculated by the inverse matrix of coefficients $\mathbf{A}^{-1}$:

$\mathbf{x}=\mathbf{A}^{-1}\mathbf{u}$.

In the given problem, the initial values of flow interactions before the moment of time t=1 with ω_r=0 are as follows: $\psi_{1\alpha бош}=0{,}062$; $\psi_{1\beta st}=-0{,}986$; $\psi_{2\alpha st}=0{,}057$; $\psi_{2\beta st}=-0{,}91$;Vb.

3. Calculation of the response of a synchronous motor to a change in load torque

Below are the results of several transient calculations performed in the MATLAB Simulink environment to explain the specific nature of the synchronous motor electric drive operation.

The calculations were performed for an electric drive with the following parameters:

$$\bar{x}_{1d}=2;\quad \bar{x}_{1q}=0{,}83;\quad 1-\sigma_f=0{,}87;\quad \mu_D=0{,}86;\quad 1-\sigma_q=0{,}77;$$

$$1-\sigma_D=0{,}87;\ T_D=0{,}13;\ T_Q=0{,}08;\ T_f=1{,}64;\ T_M=1\ c.$$

As the initial mode $\overline{U}_{1st}=1$; $\bar{u}_{1st}=1{,}5$; $\overline{M}_{sst}=0$; When $\theta_{st}=0$ ideal salt operation mode is adopted. The result of calculation of the given matrix gives the following values of current:

$\overline{\psi}_{1dst}=1$; $\overline{\psi}_{1qst}=0$; $\overline{\Psi}_{fst}=1{,}065$; $\overline{\Psi}_{Dst}=0{,}9$; $\overline{\Psi}_{Qst}=0$.

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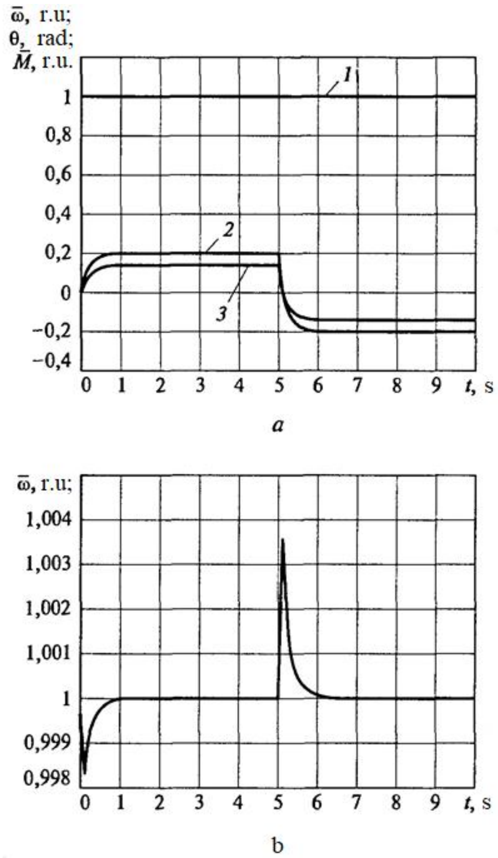

Figure 2. The reaction of the electric drive with a synchronous motor to the load change when $\overline{M}_s<\overline{M}_{max}$:

a – curves of speed, electromagnetic torque and load angle; 1 – speed; 2 – electromagnetic torque; 3 – loading angle; b – instantaneous values of the engine speed in the transient process

The results of calculation of transient processes in electrical conduction are shown in figure 2,a in the form of an oscillogram. It shows the response of the electric drive to the change of the load torque value from zero to a small value ($\theta<\theta_{max}$) than the permissible value. The limit value of the loading angle is equal to θ_{max}=1,059 rad and $\overline{M}_{dmax}$ when $\theta=\theta_{max}$.

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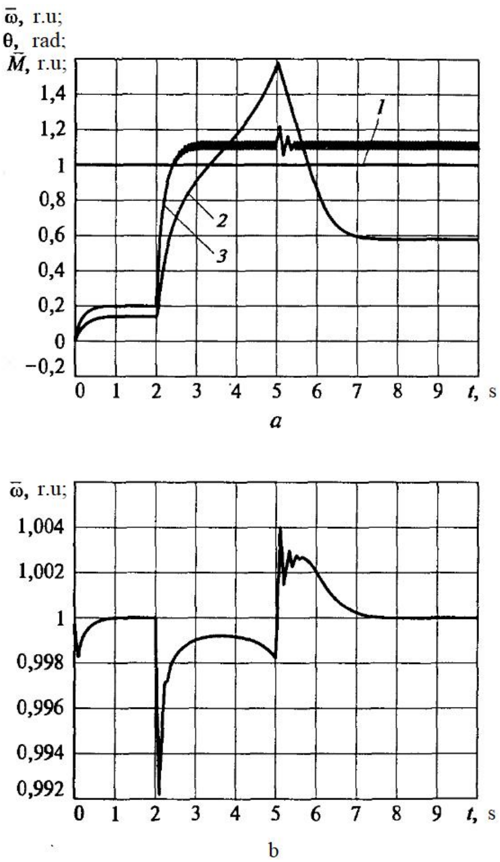

Figure 3. The reaction of the electric drive with a synchronous motor to the load change when $\bar{M}_s < \bar{M}_{max}$:

a – speed, loading angle and torque curves; 1 – speed; 2 – loading angle; 3 – electromagnetic torque; b - instantaneous values of engine speed on a larger scale

When $t=1$, a load torque $\bar{M}_s=0{,}2$ with a time constant of 0,2 sek is applied to the engine through an aperiodic link, resulting in a load angle of 0.1417 rad from zero. increases to a value of The engine runs in engine mode. A positive value of the angle θ corresponds to the fact that the spatial vector of the excitation current flow $\widetilde{\Psi}_f$ lags behind the stator current flow vector $\widetilde{\Psi}_1$. At $t=5$ sek, the sign of the load active moment has changed. At a negative value of the load value, the motor is switched to the generator mode, and this corresponds to the arrival of the rotor current vector before the stator current vector. Figure 2,b shows the variation of the instantaneous values of the engine speed in transient process modes on a larger scale.

Figure 3,a shows the response of the electric motor operating at the moment of time t=5 s when the load increases to a step-like $\bar{M}_s=1{,}1$, the excitation voltage $\bar{u}_v=1{,}5$ and the load torque $M_s=0{,}2$. At a given excitation current, such a load torque exceeds the permissible value. The

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increased load caused the motor to deviate from synchronism. This can also be seen by the sharp increase in the loading angle and the character of the speed change shown in Figure 3,b on a larger scale. In order to restore the synchronous mode at the moment of time t=5 s, the voltage in the excitation circuit is increased to $\bar{u}_v=3$. In this case, the permissible value of the torque is equal to $\bar{M}_{d.\max}=1{,}636$, and the limit value of the loading angle is equal to $\theta_{max}=0{,}568$.

As can be seen from figure 3,b, after the transient process ends, the motor starts working again at synchronous speed.

4. Comparison of the mechanical characteristics of the electric drive with an asynchronous motor calculated in the T-shaped and Γ-shaped switching schemes

Based on the calculation of the mechanical characteristics of the electric drive with an asynchronous motor with a power of 1.1 kW in the open control system, the error in the input of the magnetizing circuit is estimated based on the calculations of the T-shaped and G-shaped switching schemes. The parameters of the engine required for the calculations are given at the beginning of the article.

For this, given the value of the frequency in relative units and the corresponding voltage in volts, the value of the electromagnetic moment in newton-meters is calculated for a series of values of the relative frequency of the rotor $\bar{\omega}_r$. Calculations are made for engine mode. Therefore, the range of variation of the frequency of the rotor EIuK lies in the limit $0\leq\bar{\omega}_r\leq\bar{\omega}_0$. The angular speed of the motor is determined in rad/s according to the formula $\omega_{0el.n}(\bar{\omega}_0-\bar{\omega}_r)/\mathrm{p}_p$ in a series of values of the relative frequency of the rotor electric driving force and the corresponding motor torque. The nominal angular frequency in rad/s is related to the nominal frequency in Hz by the expression $\omega_{0el.n}=2\pi f_n$.

Calculations in the proportional change of voltage to frequency $U_1/\bar{\omega}_0 = U_{1n}/\bar{\omega}_{0n}$ ($U_{1n}=220$ V; $\bar{\omega}_{0n}=1$) four values of frequency $\bar{\omega}_0=1;0{,}7;0{,}4$ ва $0{,}1$ ($\bar{\omega}_0=314;220$ $125{,}6$ ва $31{,}4$ rad/s).

$U_{1n}=220\,V$ for T-shaped switching circuit; The results of calculations when $\bar{\omega}_0=1$ are presented in Table 1. The complete set of calculations is graphically illustrated in figure 4.

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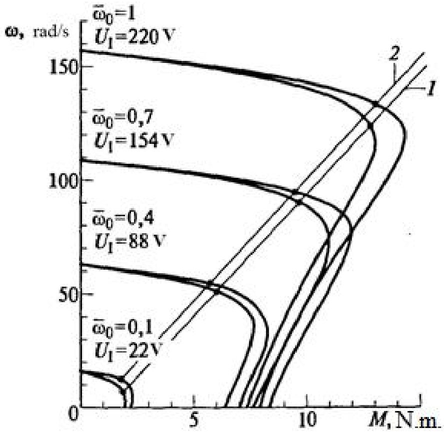

Figure 4. Mechanical characteristics of the asynchronous motor calculated according to the switching schemes:

1 – T-shaped; 2 – Γ-shaped

It can be seen that the error in determining the critical . from the T-shaped switching scheme to the Γ-shaped switching scheme is not very large. The error in determining the critical torque is 10% at the nominal frequency, and 20% at a 10-fold decrease in frequency.

We should also pay attention to the fact that in the considered motor with a nominal power of 1.1 kW, the change in the voltage in the stator proportional to the frequency does not ensure the invariance of the critical torque.

5. Calculation of the mechanical characteristics of an electric drive with an adjustable asynchronous motor in an open system that ensures the invariance of the critical torque

We calculate the mechanical characteristics of the open-system controlled 1.1 kW asynchronous motor in the load dependence of the stator and rotor fluxes in the stable mode and the $E_a/\varpi_0 = const$ frequency control law. The parameters of the engine required for the calculations are given at the beginning of the article. In addition, the effect of the heating of the coils on their resistance was taken into account, and R_1=1,23·9,5=11,68 Ohm; It is assumed that R_2=1,23·5,64=6,94 Ohm. The ratio E_a/ϖ_0 is determined based on the nominal mode of the engine:

$E_{a.n}=U_{1n}-I_{1n}R_1=220-2{,}23\cdot 11{,}68=188{,}1\ V$. Since $\varpi_0=\varpi_{0n}=1$ in nominal mode, $E_a/\varpi_0 = E_{a.n}/\varpi_{0n} = 188{,}1$ V.

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The effective value of the stator current interaction is defined as $\Psi_1 = 188{,}1/(1 \cdot 314) = 0{,}599$ Vb. The torque of the motor, depending on $\overline{\omega}_r$, is the rotor flux. The formula that determines the stator current is determined by the system of equations:

$$I_1 = \omega_{0el.n} \left(\Psi_1 x_2 - \Psi_2 x_m \right) / (x_1 x_2 \sigma) . \quad (2)$$

Calculation of static characteristic when $E_a/\overline{\omega}_r = 188{,}1\ V = const$

Value	$\overline{\omega}_p$	M	ω	Ψ_2	I_1
Unit of measure	*n.b.*	$N \cdot m$	*rad/s*	*Vb*	*A*
Value	0	0	157	0,55	1,28
	0,1	7,67	141,3	0,53	1,57
	0,2	12,49	125,6	0,48	2,3
	0,3	14,32	109,9	0,42	3,17
	0,4	14,35	94,2	0,36	4,05
	0,5	13,59	78,5	0,35	4,63
	0,6	12,59	62,8	0,28	5,22
	0,7	11,56	47,1	0,25	5,66
	0,8	10,61	31,4	0,22	6,09
	1	9,01	0	0,183	6,63

The results of the calculations are presented in table 2, and the graphical form of these results is shown in figure 5a. In the table, the speed value is calculated at the nominal frequency: $\omega = \omega_{0el.n}(\overline{\omega}_{0n} - \overline{\omega}_r)/p_p = \omega_{0el.n}(1 - \overline{\omega}_r)/p_p$ ($\omega_{0el.n} = 314\ rad/s$).

In the considered frequency adjustment law, the engine torque depends only on the value of the rotor electric power $\overline{\omega}_r$. This means that the frequency of the supply voltage $\overline{\omega}_0$ determines only the height of the mechanical characteristic relative to the abscissa axis (see fig. 5a).

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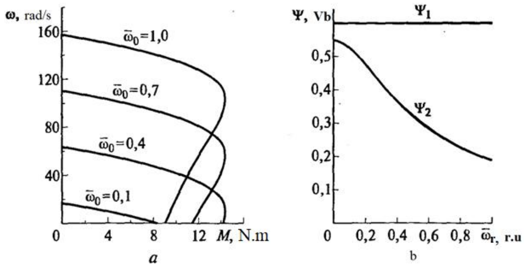

Figure 5. Mechanical characteristics (a) and the dependence of the stator and rotor current on the relative frequency of the rotor (b)

Figure 5b shows the dependence of the stator and rotor currents on the frequency of the rotor electric power (motor load).

6. Estimation of the effect of connecting and disconnecting the voltage vectors in the stator on the torque of the asynchronous motor and the value of the current in the stator during direct control of the torque

For a clearer picture of the effect of switching the voltage vectors on the value of the current and the motor torque, we analyze the result not at the moment of switching, but after some time Δt after the switching. For convenience, we use the voltage U_d normalized relative to the voltage in the DC link. Also, we assume that the value of the current is normalized to the base value of the current, and the base value of the time constant is equal to $\Psi_b = U_b T_b$ when $T_b = 1$ s. Then, if the current vector in relative units is $\overline{\overline{\Psi}}_{1st} = \overline{\psi}_{1xst} + j\overline{\psi}_{1yst}$ before connection, then the projection of the current vector after connection and after applying the stator voltage vector $\overline{\overline{U}}_1 = \overline{u}_{1x} + j\overline{u}_{1y}$ can be determined by the following equations:

$$\overline{\psi}_{1x} = \overline{\psi}_{1xst} + \overline{u}_{1x}\Delta t;$$

$$\overline{\psi}_{1y} = \overline{\psi}_{1yst} + \overline{u}_{1y}\Delta t, \qquad (3)$$

where $\overline{u}_{1x}$ and $\overline{u}_{1y}$ can take the following values: 0.5; -0.5; 0.866; -0.866 and 0.

We assume that the motor rotates in a counter-clockwise direction. Let us assume that at the initial moment of time, the vector $\widetilde{\Psi}_1 = \overline{\overline{\Psi}}_{1st}$, whose modulus is equal to one, is located in the sector $\alpha(1)$ and is turned by an angle $\theta_{1st} = 15^0$ relative to the x axis, i.e.

$$\overline{\psi}_{1xst}=\left|\overline{\overline{\Psi}}_{1st}\right|\cos\ \theta_{1st}=1\cdot\cos 15^0\approx 0{,}97;$$

$$\overline{\psi}_{1yst}=\left|\overline{\overline{\Psi}}_{1st}\right|\sin\theta_{1st}=1\cdot\sin 15^0\approx 0{,}26.$$

If the vector $\overline{\overline{U}}_{1-2}$ is placed at the instant of time Δt, then after Δt=0,1 s time (for a clearer picture, Δt is taken much larger than the real steps of calculations) in the case of formula (3) The final value of the vector projection will be:

$$\overline{\psi}_{1xst}=0{,}97+0{,}5\cdot 0{,}1=1{,}02;$$

$$\overline{\psi}_{1yst}=0{,}26+0{,}866\cdot 0{,}1=0{,}346.$$

The vector module was equal to $\left|\overline{\overline{\Psi}}_{1last}\right|=\sqrt{(1{,}02^2+0{,}346^2)}=1{,}077$, that is, increased. The new value of the rotation angle of the flow interaction vector relative to the x axis has increased to the value $\theta_1=arctg\left(\overline{\psi}_{1x}/\overline{\psi}_{1y}\right)=arctg(0{,}346/1{,}02)=18{,}7^0>\theta_{1st}$.

Thus, the introduction of the vector $\overline{\overline{U}}_{1-2}$ led to an increase in the modulus of the stator flux vector and a counterclockwise rotation of the vector (that is, in the direction of engine rotation).

Table 3

The response of the stator current vector to the switching of the voltage vectors

vector	$\overline{\overline{U}}_{1-2}$	$\overline{\overline{U}}_{1-3}$	$\overline{\overline{U}}_{1-5}$	$\overline{\overline{U}}_{1-6}$
$\bar{u}_{1x}$	0,5	-0,5	-0,5	0,5
$\bar{u}_{1y}$	0,866	0,866	-0,87	-0,87
$\overline{\Psi}_{1xlast}$	1,02	0,92	0,92	1,02
$\overline{\Psi}_{1ylast}$	0,346	0,346	0,173	0,173
$\left\|\overline{\overline{\Psi}}_{1last}\right\|$	1,077	0,983	0,983	1,035
θ_{last}	18,7	20,6	10,65	9,6

In the same way, it is possible to analyze the reaction of the stator current in the setting of voltage vectors $\bar{\bar{U}}_{1-3}$, $\bar{\bar{U}}_{1-5}$ and $\bar{\bar{U}}_{1-6}$. The results of these analyzes are presented in Table 3.

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