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Mathematical Models and Algorithmic Scheme of Frequency Controlled Electric Drives for General Industrial Mechanisms

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ABSTRACT: The article presents a generalized mathematical model and a block diagram of the engine with a variable control frequency in a coordinate system rotating in space with an arbitrary angular velocity. Mathematical relations and corresponding schemes of two-phase-three-phase phase conversion and vice versa are considered. The resulting algorithmic scheme, being a dynamic model of the engine, reflects its dynamic properties.

KEY WORDS: mathematical models, algorithmic scheme, frequency-controlled electric drives, general industrial mechanisms, asynchronous motor, frequency start

I. INTRODUCTION

General industrial mechanisms: pumps, fans, turbochargers, conveyors, feeders, mining excavators, etc. are machines of mass use in industry, mining and metallurgical industry, energy, agriculture and utilities, etc. The power of general industrial mechanisms lies in a very wide range - from one to tens of thousands of kilowatts.

Among the reasons hindering the mass introduction of an adjustable electric drive, it should be noted that there is insufficient propaganda and information about the technical and economic advantages and performance of an adjustable electric drive.

Currently, the most modern and economical way to regulate electric drives is the frequency method based on changing the frequency and magnitude of the supply voltage at the input of the drive motor [1-4] .

The article considers the features of the characteristics of general industrial mechanisms (on the example of turbomechanisms) as load machines of electric drives [5-9]. The differential equations of a three-phase asynchronous motor in real phase quantities are described, which are quite difficult to solve, have periodic coefficients and nonlinearities in the form of a product of variables. To obtain a simplified system of differential equations, an idealized two-phase asynchronous machine is considered, which is a mathematical model that allows one to study transient processes in a real three-phase machine.

Electromechanical transients have a significant impact on both the operation of an electrical machine and the operation of a working mechanism. The rotating electromagnetic moment and currents arising during transient processes can reach very large values; in an unfavorable case, the electromagnetic torque can reach 15 times the nominal torque, and the current can reach three times the steady-state short-circuit current [10-13]. Operating experience shows that most accidents and outages occur during transients.

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II. RESEARCH PROBLEM AND METHOD

Differential equations of electromechanical processes in AC machines have periodic coefficients and nonlinearities in the form of a product of variables. Therefore, the system of equations of a three-phase asynchronous machine, written in real phase values of currents and flux links, is subjected to transformations, thanks to which it is possible to obtain a system of equations with constant coefficients.
Generalized equations and principles of two-phase and three-phase coordinate transformations are the mathematical basis for the construction of special control computers that provide automatic control of processes in the system of an asynchronous electric drive with frequency control [2].

Experience shows that analytical studies of transient processes, performed on the basis of an idealized machine, give results that agree well enough with the results of experiments, which allows them to be used for practical purposes [3].
To simplify the system of differential equations of a three-phase asynchronous motor (IM), written in phase quantities, we represent them in a coordinate system (U, V) rotating in space with an arbitrary angular velocity ω_k .

The equivalent stator voltages (U_{U1},U_{V1}) in the coordinate system (U,V) are related to the phase voltages (U_A, U_B, U_C,) of a three-phase IM by the following relations [4]

$$\left.\begin{aligned} U_{U1} &= \frac{2}{3}\left[U_A \cos\omega_k t + U_B \cos\left(\omega_k t - 120^\circ\right) + U_C \cos\left(\omega_k t + 120^\circ\right)\right], \\ U_{V1} &= -\frac{2}{3}\left[U_A \sin\omega_k t + U_B \sin\left(\omega_k t - 120^\circ\right) + U_C \sin\left(\omega_k t + 120^\circ\right)\right]. \end{aligned}\right\} \tag{1}$$

Similar relationships connect the equivalent values of currents and motor flux links with the corresponding phase values of the variables.

Substituting in (1) expressions of real phase voltages

$$\left.\begin{aligned} U_A &= U_m \cos(\omega_0 t + \gamma), \\ U_B &= U_m \cos(\omega_0 t - 120^\circ + \gamma), \\ U_C &= U_m \cos(\omega_0 t + 120^\circ + \gamma), \end{aligned}\right\} \tag{2}$$

one can obtain expressions for the stress components in the equivalent two-phase coordinate system in the form

$$\left.\begin{aligned} U_{U1} &= U_m \cos\left[\left(\omega_0 - \omega_k\right)t + \gamma\right], \\ U_{V1} &= U_m \sin\left[\left(\omega_0 - \omega_k\right)t + \gamma\right], \end{aligned}\right\} \tag{3}$$

where U_m - the amplitude value of the phase voltage; $\omega_0 = \omega_{0\,эл.н}\ F / P_n$ - angular frequency of rotation of the stator field, $\omega_{0\ эл.н} = 2\pi\ f_н$ - nominal angular frequency of the motor supply voltage, F = $f/f_н$ - relative control frequency, f and $f_н$ - current and nominal values of the control frequency; P_n - the number of motor pole pairs; γ - the initial voltage phase of phase A of the motor.

Omitting intermediate calculations, the expressions for the main parameters of a two-phase machine in the coordinate system (U, V) with a variable control frequency will be obtained [5,6].

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III. RESULT AND DISCUSSION

The stator and rotor voltages along the U and V axes will be

$$\left.\begin{aligned} U_{U1} &= \frac{d\psi_{U1}}{dt} - \omega_k \psi_{V1} + r_1 i_{U1}, \\ U_{V1} &= \frac{d\psi_{V1}}{dt} - \omega_k \psi_{U1} + r_1 i_{V1}, \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} O &= \frac{d\psi_{U2}}{dt} - (\omega_k - p_n\omega)\ \psi_{V2} + r_2 i_{U2}, \\ O &= \frac{d\psi_{V2}}{dt} - (\omega_k - p_n\omega)\ \psi_{U2} + r_2 i_{V2}, \end{aligned}\right\} \qquad (5)$$

where, $\omega = \omega_{\text{он}}(F-\beta)$ - the angular velocity of rotation of the IM rotor, $\beta = FS$ - the absolute slip parameter, S - the slip; r_1, r_2 - active resistance of the phase of the stator and rotor windings.

The currents of the stator and rotor windings along the U and V axes will be:

$$\left.\begin{aligned} i_{U1} &= \frac{\omega_{\text{он}}}{x_{SH}\,\sigma}(\psi_{U1} - \psi_{U2} k_r), \\ i_{V1} &= \frac{\omega_{\text{он}}}{x_{SH}\,\sigma}(\psi_{V1} - \psi_{V2} k_r), \end{aligned}\right\} \qquad (6)$$

$$\left.\begin{aligned} i_{U2} &= \frac{\omega_{\text{он}}}{x_{\text{rн}}\,\sigma}(\psi_{U2} - \psi_{U1} k_s), \\ i_{V2} &= \frac{\omega_{\text{он}}}{x_{\text{rн}}\,\sigma}(\psi_{V2} - \psi_{V1} k_s), \end{aligned}\right\} \qquad (7)$$

where $k_s = x_{\mu\text{н}} / x_{s\text{н}}$, $k_r = x_{\mu\text{н}} / x_{r\text{н}}$, $\sigma = 1 - k_s k_r$ - the scattering coefficient of IM at F=1.

Substituting (6) into (4) and (7) into (5), we obtain

$$\left.\begin{aligned} U_{U1} &= \frac{d\psi_{U1}}{dt} - \omega_k \psi_{V1} + \frac{\omega_{\text{он}} r_1}{x_{s\text{н}}\sigma}\psi_{U1} - \frac{\omega_{\text{он}} r_2}{x_{s\text{н}}\sigma} k_r \psi_{U2}, \\ U_{V1} &= \frac{d\psi_{V1}}{dt} + \omega_k \psi_{U1} + \frac{\omega_{\text{он}} r_1}{x_{s\text{н}}\sigma}\psi_{V1} - \frac{\omega_{\text{он}} r_2}{x_{s\text{н}}\sigma} k_r \psi_{V2}, \end{aligned}\right\} \qquad (8)$$

$$\left.\begin{aligned} O &= \frac{d\psi_{U2}}{dt} - (\omega_k - p_n\omega)\psi_{V2} + \frac{\omega_{\text{он}} r_2}{x_{r\text{н}}\sigma}\psi_{U2} - \frac{\omega_{\text{он}} r_2}{x_{r\text{н}}\sigma} k_s \psi_{U1}, \\ O &= \frac{d\psi_{V2}}{dt} + (\omega_k - p_n\omega)\psi_{U2} + \frac{\omega_{\text{он}} r_2}{x_{r\text{н}}\sigma}\psi_{V2} - \frac{\omega_{\text{он}} r_2}{x_{r\text{н}}\sigma} k_s \psi_{V1}. \end{aligned}\right\} \qquad (9)$$

The electromagnetic torque of the motor as a function of the stator and rotor currents along the U and V axes will be:

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$$M = \frac{3}{2}\frac{x_{\mu\,н}}{\omega_{о\,н}}\, p_n\left(i_{U2}i_{V1} - i_{U1}i_{V2}\right) \tag{10}$$

or in the flux linkage function

$$M = \frac{3}{2}\frac{\omega_{\hat{\imath}\ \acute{\imath}}}{\tilde{o}_{SH}\sigma} k_r\ p_n\left(\psi_{U2}\psi_{V1} - \psi_{U1}\psi_{V2}\right). \tag{11}$$

The equations of motion of the engine in a single-mass mechanical system has the form

$$M - M_C = \frac{I}{p_n}\frac{d\omega}{dt} = \frac{I\omega_{он}}{p_n}\left(\frac{dF}{dt} - \frac{d\beta}{dt}\right), \tag{12}$$

where I and M_C are the total moment of inertia reduced to the motor shaft and the load resistance moment on the motor shaft.

For the convenience of analyzing expressions (8) and (9), we solve with respect to the first derivatives of the flux linkages:

$$\left.\begin{aligned}
\frac{d\Psi_{U1}}{dt} &= U_{U1} - \frac{\omega_{он}r_1}{x_{SH}\sigma}\Psi_{U1} + \frac{\omega_{он}r_1}{x_{SH}\sigma}\ k_r\ \Psi_{U2} + \omega_k\Psi_{V1},\\
\frac{d\Psi_{V1}}{dt} &= U_{V1} - \frac{\omega_{он}r_1}{x_{SH}\sigma}\Psi_{V1} + \frac{\omega_{он}r_1}{x_{SH}\sigma}\ k_r\ \Psi_{V2} - \omega_k\Psi_{U1},\\
\frac{d\Psi_{U2}}{dt} &= -\frac{\omega_{он}r_2}{x_{rн}\sigma}\Psi_{U2} + \frac{\omega_{он}r_2}{x_{rн}\sigma}\ k_s\ \Psi_{U1} + (\omega_k - p_n\omega)\Psi_{V2},\\
\frac{d\Psi_{V2}}{dt} &= -\frac{\omega_{он}r_2}{x_{rн}\sigma}\Psi_{V2} + \frac{\omega_{он}r_2}{x_{rн}\sigma}\ k_s\ \Psi_{V1} - (\omega_k - p_n\omega)\Psi_{U2}.
\end{aligned}\right\} \tag{13}$$

Of considerable interest is the solution of the equations of transient processes of IM at $\omega = const$ or $\omega = 0$, for example, when analyzing the initial section of the frequency start of the engine. When $\omega = const$ the equation (10-13) allows analytical solutions, since the equation of motion (12) drops out of consideration. For $\omega = 0$, $F = const$ and $F = \text{var}$ analytical solutions are possible [7-9].

A good choice of value ω_k , i.e. coordinate system, greatly facilitates the analysis of the equations of transient processes of IM at a variable control frequency.

When $\omega_k = 0$ the coordinate system is fixed relative to the motor stator winding. The axes of this coordinate system are denoted by (α, β). This coordinate system has the advantage that in it the current is equal to the phase current of one of the stator phases.

The use of this coordinate system is expedient in the analysis of a frequency control system with a scalar frequency control.

On fig. 1 shows an algorithmic (structural) diagram of a frequency-controlled IM, built on the basis of equations (4-7) and (10.11-13) at $\omega_k = 0$ (α, β).

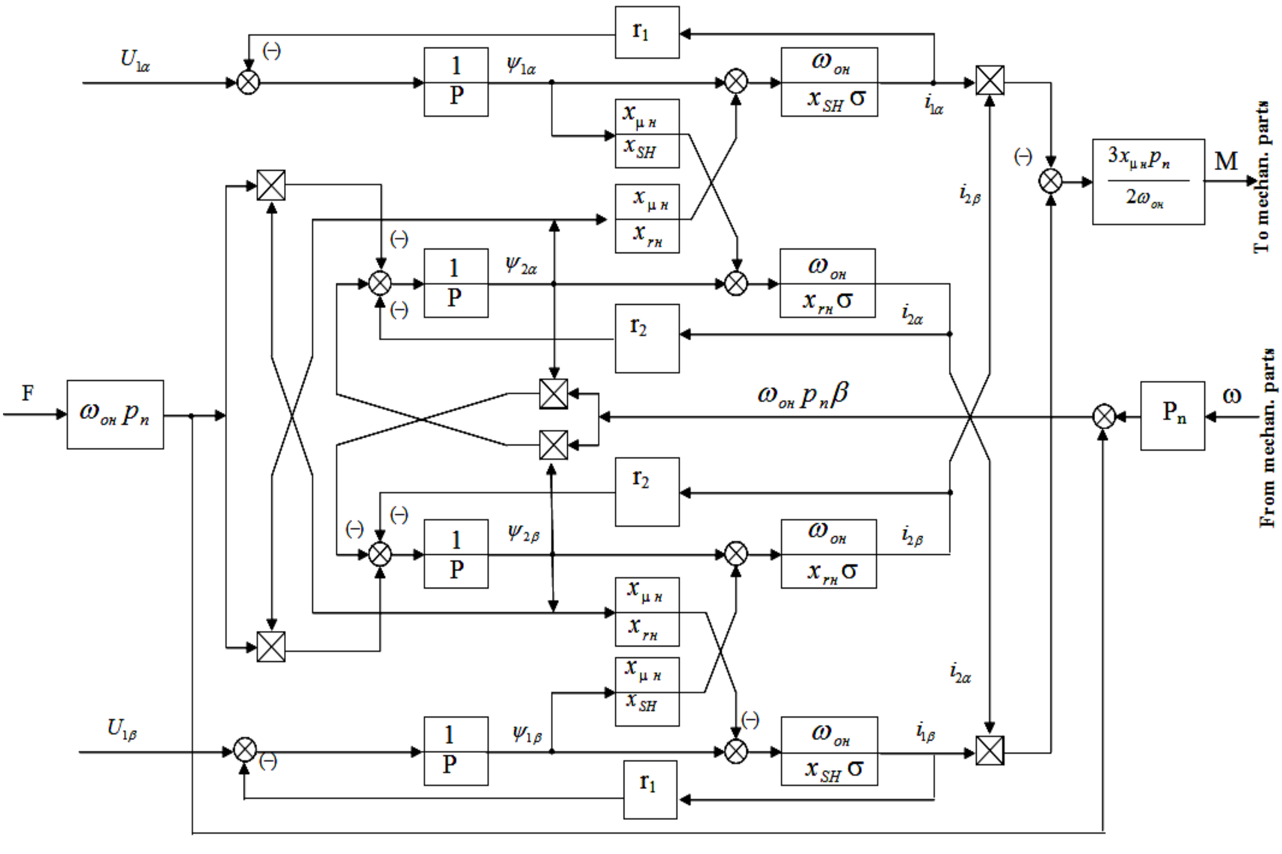

Fig.1. Algorithmic scheme of a frequency-controlled IM in a fixed coordinate system (α, β)

IV. CONCLUSION

A generalized mathematical model and a block diagram of the engine with a variable control frequency in a coordinate system rotating in space with an arbitrary angular velocity are presented. Similar mathematical models and block diagrams are given in the coordinate systems of the stator field that is stationary relative to the stator winding and rotates with the angular velocity of the stator field. Mathematical relations and corresponding schemes of two-phase-three-phase phase conversion and vice versa are considered. The resulting algorithmic scheme, being a dynamic model of the engine, reflects its dynamic properties. It shows what elementary links it consists of, the algorithmic scheme, how they are interconnected, the presence of internal direct, reverse cross-links, as well as control and disturbing influences. They provide an opportunity to create general research methods.

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