Energy Characteristics of Electric Drive of Oscillatory Motion at the Shock-Free Start

L A Payuk[1], N A Voronina[1] and O V Galtseva[2]

[1]Senior Lecturer, Institute of Power Engineering, Tomsk Polytechnic University, Tomsk, Russian
[2]Associate Professor, NDT Institute, Tomsk Polytechnic University, Tomsk, Russian
E-mail: lubapa81@mail.ru

Abstract. The peculiarity of operation of oscillatory electric drive with doubly-fed motor at realization of algorithm of shock-free start was considered. The method of evaluating of energy parameters of such motors operating at the resonance mode with учетом of quantitative and qualitative components of the process of energy conversion by an electric motor (doubly-fed motor) is proposed. The calculation of energy characteristics of electric drive of this type was made, the results of calculation show an increase of energy efficiency (an average, generalized efficiency coefficient η_E increased by 10 %), which confirms the practical significance of the research object.

1. Introduction

The modern concept of analysis and design of electric drives of oscillatory motion (*EDOM*) is based on the principles of energy and resource efficiency, and this is reflected in methods of analysis and synthesis. *EDOM* widely used in modern industry: from vibration systems for inspection of electrical equipment to the ventilation systems and human life [1–4]. Oscillations measured from a few microns to meters [1, 5]. In each case it is necessary to consider the difference between these types of drives from industrial. For example, the nonsinusoidal supply voltage, the harmonic composition of the currents in the windings of the stator and rotor of the control motor, the double frequency in the electromagnetic torque. Consequently, the generally accepted criteria of efficiency of electric drives for this type of drive are not suitable, as it does not take into account their specificity.

It is therefore proposed to use the method of evaluating the energy characteristics of controlled *EDOM* on the base on serial asynchronous motor by scheme of doubly-fed motor (*DFM*). Its oscillatory mode is excited by periodic soft reverse [6]. A distinctive feature of this method is an account of harmonic content of supply voltage, and, as a consequence, of resulting electromagnetic torque, angular velocity of rotation and law of motion of movable element of motor of drive with allowance of distortion and asymmetry.

It is known that the highest power consumption at operating of any electric drive happens at its start due to the occurrence of inrush currents and torque, which may differ from the nominal value by several times. Therefore, we proposed a method of providing of shock-free start by current and torque of *EDOM* with *DFM*. According to [7, 8] the phase correction of supply voltages reduces the magnitude of shock value of stator current on 30 % and the electromagnetic torque – in to 3 times.

2. Research object and method

The analysis of free components of inrush currents showed that the following condition is necessary to suppress the shock values of current of *DFM* [3]:

$$\begin{aligned} &\omega_1 \cos(\alpha`) - \alpha_1 \sin(\alpha`) = 0; \\ &\alpha_3 \cos(\beta`) + \omega_2 \sin(\beta`) = 0. \end{aligned} \tag{1}$$

The formation of supply voltage of windings of excitation (*WE*) and control (*WC*) of stator (*S*) and rotor (*R*) of executive engine (doubly-fed motor) occurs in the following laws, respectively:

$$\begin{aligned} &U_{WES} = U_m \gamma_1 \sin(\omega_1 t + \alpha`); \\ &U_{WCS} = U_m \gamma_2 \sin(\omega_1 t + \beta` + \Omega t); \\ &U_{WER} = U_m \gamma_3 \sin(\omega_1 t + \gamma) \cos(\chi) - U_m \gamma_4 \sin(\omega_1 t + \varphi + \Omega t) \sin(\chi); \\ &U_{WCR} = U_m \gamma_3 \sin(\omega_1 t + \varphi + \Omega t) \cos(\chi) + U_m \gamma_4 \sin(\omega_1 t + \gamma) \sin(\chi), \end{aligned} \tag{2}$$

where U_m – peak values of supply voltage of windings of stator and rotor; α, β, γ, φ – initial phases of voltage on motor windings (*rad*); ω_1, ω_2 – angular supply frequencies of stator and rotor $\omega_2=\omega_1+\Omega$, γ_i – coefficients of signals.

Expressions for starting currents and torque shall not give here; we note only conditions of shock-free start by current and torque, based on the conditions of Table 1 (α_i – attenuation coefficients of free components of stator and rotor currents of *DFM*, which were previously found as the roots of characteristic equations upon condition of retardation of shaft of executive motor) [3].

Table 1. Conditions for calculation of shock-free start by current and torque for *EDOM*.

Shock-free start of *EDOM* with *DFM*	
by current	by torque
$\alpha` = \text{arctg}\left(\frac{\omega_1}{\alpha_1}\right)$; $\beta` = \text{arctg}\left(\frac{-\omega_2}{\alpha_3}\right)$	$\alpha` = \text{arctg}\left(\frac{\omega_1}{\alpha_2}\right)$; $\beta` = \text{arctg}\left(\frac{-\omega_2}{\alpha_4}\right)$

Valuation of indicators of quality of designed system is produced by method of discrete synthesis at different frequency nutrition of *DFM* of *EDOM*. The energy quality indicators can be divided into two groups: first group determines the quality of process of electromechanical energy conversion of *EDOM*; the second group determines the comprehensive quantitative assessment of process of electromechanical energy conversion efficiency by motor and *EDOM*.

The consumption or generation of reactive power occurs at the work of electromechanical energy converters in dynamic modes except consumption of active power [6]. In this case, the total power consumption of motor is characterized by the power of distortion and asymmetry. Therefore power factor (K_P), shear factor (K_S), factor of distortion (K_D) and asymmetry (K_A) characterize the ratios between active and reactive powers and power of distortion and asymmetry. Feature of this approach to evaluating of energy characteristics allow evaluate the quality of energy consumption of *EDOM.*

Power factor K_P is determined by the formula:

$$K_{Pi} = \frac{P_i}{S_{iAV}} = \frac{P_i}{\sqrt{P_i^2 + Q_{iAV}^2 + T_{iAV}^2}}, \tag{3}$$

where P_i, Q_{iAV}, T_{iAV} – active power, average values of reactive and total power of distortion of *i* phase for the period.

The shear factor K_S describes the relationship between active and reactive power of phase and it is determined by the formula:

$$K_{Si} = \sqrt{\frac{P_i^2}{P_i^2 + Q_{iAV}^2}} . \tag{4}$$

The distortion factor K_D determines the degree of distortion of power consumption and it is calculated by the expression:

$$K_{Di} = \sqrt{\frac{P_i^2 + Q_{iAV}^2}{P_i^2 + Q_{iAV}^2 + T_{iAV}^2}} . \tag{5}$$

The factor of asymmetry is calculated according to the expression:

$$K_A = \frac{S}{S_M} . \tag{6}$$

The generalized efficiency coefficient refers to the quantitative assessment criteria and it determines the useful portion of the consumed power diverted from the network:

$$\eta_E = \frac{P_{\text{mech}}}{S} = \sqrt{\frac{P_{\text{mec,a}}^2 + P_{\text{mec,r}}^2 + P_{\text{mec,d}}^2}{S^2}} , \tag{7}$$

where $P_{mec,a}$, $P_{mec,r}$, $P_{mec,d}$ – active, reactive mechanical power and power of distortion of drive motor, respectively; S – total conditional power consumption of motor.

The mechanical power of the electric motor in an oscillatory mode of operation includes power distortion $P_{mec,d}$, active $P_{mec,a}$, and reactive $P_{mec,r}$ components. Any of these components of mechanical power are involved in useful work depending on the target of drive and nature of load. The generalized efficiency coefficient considers the qualitative (K_P) and quantitative (η) aspects of process. Therefore its maximum value is necessary to retain during operation of machine in the oscillatory mode (for providing of resonant mode).

This expression is used for determination of mechanical power of *DFM* at the feeding of windings of stator and rotor by currents of frequencies ω_1 and ω_2 at the first approximation:

$$P_{mec} = \frac{M_{EL.T}\omega_m \sin(\varphi - \alpha)}{2} \cdot \left[1 + \cos 2(\Omega t + \alpha)\right] + \frac{M_{EL.T}\omega_m \cos(\varphi - \alpha)}{2} \cdot \sin 2(\Omega t + \alpha) , \tag{8}$$

where $\Omega = \omega_2 - \omega_1$ – oscillation frequency of movable element of the executive motor; α, φ – initial phases of the first harmonic components of the motion law and electromagnetic torque of *DFM*.

Analytical expressions for determination of electromagnetic torque and angular speed of rotation were determined previously [7, 9]. We give final versions for their determination. Electromagnetic torque of motor in expression (8) defined by formula:

$$M_{EL.T} = k\left[M_{ST} + M_{DE} \cdot \frac{d\chi}{dt}\right],$$

where k – coefficient of proportionality, which takes into account the specificity of motor; M_{ST}, M_{DE} – starting and damping electromagnetic moments of motor.

Angular speed of rotation ω_m in expression (8) defined by formula:

$$\omega_m = \int \left(\frac{1}{J_\Sigma} \left(L_m \left(i_{\beta s} i_{\alpha r} - i_{\alpha s} i_{\beta r} \right) - R_g \omega - C_m^{-1} \chi - M_c \right) \right) dt ,$$

where R_g – coefficient of damping load torque; C_m^{-1} – coefficient of positional load torque; M_c – torque of static load on the motor shaft, χ – coordinate of movable element of motor; J_Σ – total inertia moment, which consists of the inertia moment of motor J_m and load J_l.

Instant consumption power of electric circuit AC at different frequency feeding is defined as

$$P_n(t) = U_n(t) \cdot i_n(t), \tag{9}$$

where *n* takes on the values 1, 2, 3, 4, which correspond to the phase currents and voltages.

Next we substitute the expressions (1) and the expressions for the currents of stator and rotor [7, 8] in (9):

$$\begin{gathered} i_1(t) = i_{\alpha s}(t);\ i_2(t) = i_{\beta s}(t);\ i_3(t) = i_{\alpha r}(t);\ i_4(t) = i_{\beta r}(t); \\ U_1(t) = U_{\alpha s}(t);\ U_2(t) = U_{\beta s}(t);\ U_3(t) = U_{\alpha r}(t);\ U_4(t) = U_{\beta r}(t). \end{gathered} \tag{10}$$

Instant values of phase currents for specified functions of regulating are defined by the formula (10); for example, the expression of instant power of phase α_s can be written in the form:

$$P_{\alpha s}(t) = P_1[1 - \cos 2(\omega_1 t + \alpha)] - Q_1 \sin 2(\omega_1 t + \alpha) - T_1 \ . \tag{11}$$

The total active and reactive power along the axes α and β are defined as

$$P_\alpha = P_{\alpha s} + P_{\alpha r}\ ;\ Q_\alpha = Q_{\alpha s} + Q_{\alpha r}\ ;\ P_\beta = P_{\beta s} + P_{\beta r}\ ;\ Q_\beta = Q_{\beta s} + Q_{\beta r}$$

Functional scheme of electric drive of oscillatory motion with potentially - phase modulation and ability of realization of shock - free start is presented in figure 1.

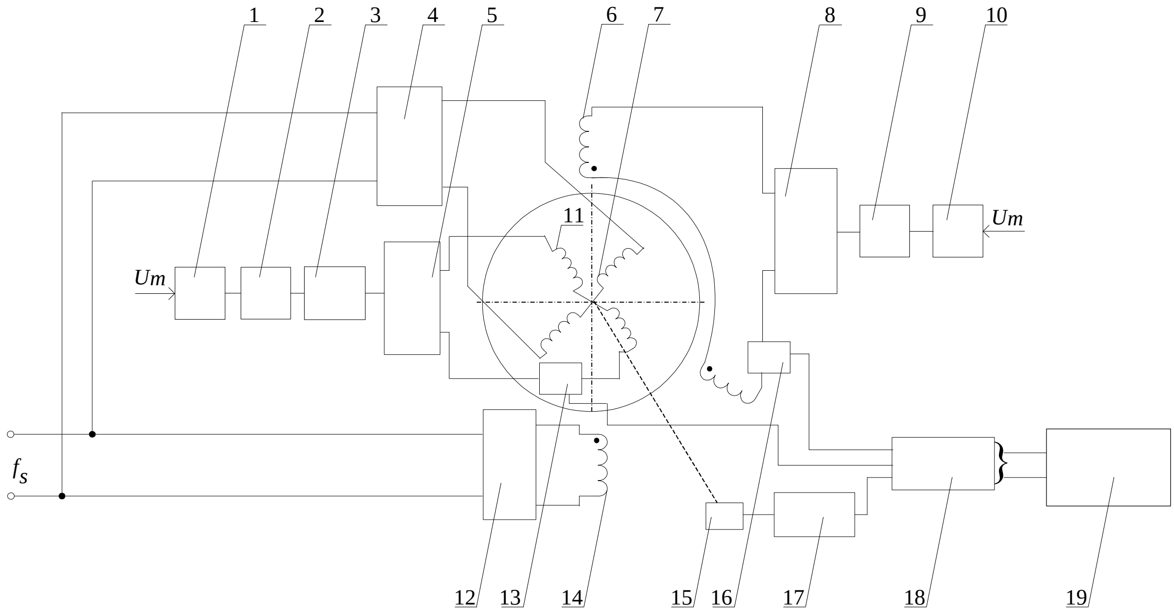

Figure 1. Functional scheme of *EDOM* with potentially - phase modulation: 1 – driving generator 2; 2 – modulator of frequency 2; 3 – phase - shifting device; 4 – linear autotransformer 2; 5 – autonomous voltage inverter 2; 6 – control winding of stator; 7 – excitation winding of rotor; 8 – autonomous voltage inverter 1; 9 – modulator of frequency 1; 10 – driving generator 1; 11 – control winding of rotor; 12 – linear autotransformer 1; 13 – current sensor 2; 14 – excitation winding of stator; 15 – speed sensor; 16 – current sensor 1; 17 – differentiator (integrator); 18 – sensor unit; 19 – personal computer.

EDOM (figure 1) consists of control system of stator and rotor of DFM realized on the basis of the asynchronous motor with slip-ring rotor, sensor unit (18) with system for converting analog signal to digital, IBM – compatible personal computer with built-in board with input-output data, providing feedback of speed and current. Control systems of stator and rotor of *DFM* consists of frequency converters with DC links, which specify the modulation frequency of linear autotransformers (4, 12), signal amplification unit and autonomous voltage inverters (5, 8), switched - on from stator and rotor side with the carrier frequency f_1 = 50 *Hz* and the modulation frequency f_2 = 55 *Hz*.

The signals from the frequency modulators (2, 9) are fed on autonomous voltage inverters (5, 8) through the windings of stator and rotor respectively, signals U_m come on them from driving generators (1, 10). The signal from the phase-shifting device (3) comes to the input (5); this signal provides realization of algorithm of shock - free start of *DFM* in the composition of *EDOM*.

Electric machine of alternating current of type *MTN* - 011-6*U*1with the following parameters was used as *DFM*: P_n=1400 *W*, nominal voltage U_n =220 *V*, nominal current of stator I_n=3.35 *A*, η=76 *%*, $\cos\ \varphi_н$ = 0.78, nominal frequency of rotation n_n=1250 *rev/min* [8–9]. At calculation of energy indicators the following values for the components of the load were adopted (all values are given in relative units): at shock-free start by torque R_g=1.35, C_m^{-1}=1.3, M_c= 0.2, J_Σ=1.25; at shock-free start by current R_g=0.54, C_m^{-1}=0.45, M_c=0.08, J_Σ= 1.25.

Results of calculation of energy indicators of *EDOM* (expressions (3) – (7)) are shown in Table 2.

Table 2. Calculated energy indicators of the electric drive of oscillatory motion.

Indicators	Shock - free start by current of *EDOM*	Shock - free start by torque of *EDOM*	Standard start of *EDOM*
K_P	0.5	0.53	0.56
K_S	0.55	0.5	0.64
K_D	0.35	0.37	0.4
K_A	0.45	0.4	0.5
η_E, %	73.5	77	65

4. Summary

1. Analysis of the energy characteristics of *EDOM* at the realization of shock - free start by current and torque has shown that the generalized efficiency coefficient η_E increased by 10 *%* at the use of this method an average; power factor K_P decreased by 0.4 relative units; shear factor K_S decreased by 0.8 relative units; factor of distortion K_D decreased by 0.035 relative units; factor of asymmetry K_A decreased by 0.055 relative units. The harmonic composition of the supply voltage improves and affects on final consumption of active and reactive power.

2. The largest increase of the generalized efficiency coefficient η_E (by 12 %) and the largest decrease of the factor of asymmetry (by 0.1 relative units) occur at the realization of shock - free start by torque. This suggests that the process of energy consumption occurs with the best of quantitative and qualitative indicators at the realization of algorithm of shock - free start by torque.

3. The dependences (3) – (7) allow one to accurately assess the energy characteristics of the electric drive of oscillatory motion (of any periodic movement) and to get an adequate result and to analyze the efficiency of the designed electric drives.

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