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Mechanical characteristics of a double-fed machine in asynchronous mode and prospects of its application in the electric drive of mining machines

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Abstract. The concept of a double-fed machine as an asynchronous motor with a phase rotor and a source of additional voltage is defined. Based on the analysis of a circuit replacing the double-fed machine, an expression is derived relating the moment, slip, amplitude and phase of additional voltage across the rotor. The conditions maximizing the moment with respect to amplitude and phase of additional voltage in the rotor circuit are also obtained, the phase surface of function of machine electromagnetic moment is constructed. The analysis of basic equation of electric drive motion in relation to electric drive of mine hoisting installations and the conclusion about the necessity of work in all four quadrants of coordinate plane "momentslip" are made. Family of mechanical characteristics is constructed for a double-fed machine and its achievable speed control range in asynchronous mode is determined. Based on the type of mechanical characteristics and the calculated range of speed control, the conclusion is made about the suitability of using a dual-fed asynchronous machine for driving mine mechanisms with a small required speed control range and the need for organizing a combined operating mode for driving mine hoisting installations and other mechanisms with a large speed control range.

1. Introduction

Currently, most alternating current drives are built according to the scheme of asynchronous motors with a phase rotor and a rotor station. The use of these drive systems is due to their relative simplicity and good overload capacity. At the same time, the used electric drives with a phase rotor have low energy efficiency. These disadvantages are not typical for electric drive systems with frequency control of asynchronous motors, but the use of frequency control for existing asynchronous motors designed for an unchanged frequency of the supply voltage 50 Hz is associated with such problems as significant deterioration of machine mechanical characteristics at a underfrequency, steel overheating, reduction of efficiency rate and power factor [1]. Thus, to ensure acceptable energy and control characteristics of already existing motors with a phase rotor, it is optimal to use them in the dualsupply mode [2, 3]. The article is devoted to the study of characteristics of a dual-fed machine in an asynchronous mode and consideration of the expediency of using this scheme in electric drives of mine installations.

2. Methods of research

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For the preparation of the present article, the following research methods were used: the method of a generalized two-phase electrical machine; method of equivalent circuits; method of partial derivatives; method of mathematical modeling.

3. Results and discussion

A double-fed machine (DFM) is a circuit of switching on an asynchronous motor with a phase rotor, in which an additional voltage is supplied to the rotor from an external power source, which usually is a frequency converter [4, 5]. The most important characteristics of a DFM are its mechanical characteristics. They determine the suitability of its application in the electric drive and the operating modes of the machine.

Depending on the method of generating the additional voltage, two modes of DFM operation are distinguished: asynchronous and synchronous. In asynchronous mode, the frequency of the additional voltage is equal to the frequency of rotor emf [6, 7], in synchronous mode – the frequency of additional voltage is set independently [8]. Let us consider the asynchronous operation mode of DFM.

To do this, let us turn to the T-shaped circuit of machine replacement [4, 9] (figure 1).



Figure 1. Circuit of DFM replacement in asynchronous mode.

The following designations are adopted on the equivalent circuit:

 \overline{U}_{S} - complex value of voltage across the stator; \overline{I}_{S} - complex current value of the stator; E_{S} - complex value of emf induced by a rotating field in the stator; $X_{\sigma S}$ - intrinsic inductive resistance of stator scattering; I_{μ} - magnetizing current of the machine; X_{μ} - inductive resistance of the magnetizing circuit; $X_{\sigma R}$ - intristic inductive resistance of the rotor scattering, is determined from the expression $X_{\sigma R} = 2\pi f_{S} L_{\sigma R} \frac{\omega_{0} - \omega}{\omega_{0}}$, where f_{S} - voltage frequency applied to the stator; R_{S} - active stator resistance;

 R_R – active rotor resistance; \overline{E}_{res} – complex value of the total (resulting) emf acting in the rotor; $\overline{E}_{R_{sc}}$ – emf of the rotor in short-circuit mode; $s - \operatorname{slip}_{s} = \frac{\omega_0 - \omega}{\omega_0}$; ω_0 – angular rotation speed of the stator

magnetic field; ω – angular rotation speed of the rotor; \overline{U}_R – complex voltage value applied to the rotor.

In asynchronous mode, the frequency of this voltage is equal to the self-frequency of rotor emf: $f_R = sf_s$.

We shall write down the equations of electric equilibrium of the machine for T-shaped analogue circuit, expressing the self-emf of windings through the flux-linkages of windings, and the electromagnetic moment will be defined as a function of the vector product of flux-linkages of the stator and rotor windings:

$$\begin{cases} \overline{U}_{s} = j\omega_{0}\overline{\Psi}_{s} + \overline{I}_{s}R_{s}, \\ \overline{U}_{R} = j\omega_{0}s\overline{\Psi}_{R} + \overline{I}_{R}R_{R}, \\ M = -\frac{3}{2}z_{P}\frac{L_{\mu}}{L_{P}L_{P}-L^{2}}\left[\overline{\Psi}_{s}\times\overline{\Psi}_{R}\right], \end{cases}$$
(1)

where $\overline{\Psi}_S$ – complex value of stator flux-linkage; $\overline{\Psi}_R$ – complex value of rotor flux-linkage; L_{μ} – magnetization inductance; L_S – stator inductance; L_R – inductance of the rotor; z_P is the number of machine pole pairs.

To facilitate further transformations, we shall neglect the stator active resistance and its inductive scattering resistance. We shall also assume that the complex value of voltage is defined as $\overline{U}_R = U_R e^{j\delta}$ [4].

The scattering coefficient of the machine is determined by the expression:

$$\sigma = 1 - \frac{L_{\mu}^2}{L_S L_R} \tag{2}$$

Let us write down the expressions for the current coupling and flux-linkage of the machine windings taking into account (2):

$$\begin{cases} \overline{I}_{S} = \frac{1}{\sigma L_{S}} \overline{\Psi}_{S} - \frac{k_{R}}{\sigma L_{S}} \overline{\Psi}_{R} \\ \overline{I}_{R} = -\frac{k_{S}}{\sigma L_{R}} \overline{\Psi}_{S} - \frac{1}{\sigma L_{R}} \overline{\Psi}_{R}, \end{cases}$$
(3)

where k_S , k_R – are the stator and rotor coupling coefficients, respectively.

Substituting the expressions for currents (3) into system (1), we obtain:

$$\begin{cases} \overline{U}_{S} = \left(\frac{R_{S}}{\sigma L_{S}} + j\omega_{0}\right) \overline{\Psi}_{S} - \frac{R_{S}k_{R}}{\sigma L_{S}} \overline{\Psi}_{R}, \\ \overline{U}_{R} = -\frac{R_{R}k_{S}}{\sigma L_{R}} \overline{\Psi}_{S} + \left(\frac{R_{R}}{\sigma L_{R}} + j\omega_{0}s\right) \overline{\Psi}_{R}', \\ M = -\frac{3}{2} p_{P} \frac{L_{\mu}}{L_{S}L_{R} - L_{\mu}^{2}} \left[\overline{\Psi}_{S} \times \overline{\Psi}_{R}\right] \end{cases}$$

$$(4)$$

Let us consider system (4). Obviously, it is universal and can describe both an asynchronous motor (at $\overline{U}_R = 0$) and a dual-fed machine (at $\overline{U}_R \neq 0$). The product σL_R , called the equivalent machine inductance, is determined by the following relationship: $\sigma L_R = L_S$, where $\sigma L_R = L_S$ – the machine inductance in the short-circuit mode.

At $\overline{U}_R = 0$ and nominal conditions of inductance L_S corresponds reactive short circuit resistance X_S :

$$X_{S} = 2\pi f_{C} L_{S} = X_{S|fc} + X_{R|fc},$$

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where f_C – nominal voltage frequency of the power mains; $X_{S|f_C}$ – reactance of the stator at the nominal voltage of the power mains; $X_{R|f_C}$ – rotor reactance at the nominal voltage of the power mains.

Let us divide both sides of the second equation of system (4) by ω_0 :

$$\frac{\overline{U}_R}{\omega_0} = -\frac{R_R k_S}{\omega_0 \sigma L_R} \overline{\Psi}_S + \left(\frac{R_R}{\omega_0 \sigma L_R} + js\right) \overline{\Psi}_R.$$

With the assumption about the equivalent inductance and nominal operating conditions of the machine, the equality will be fulfilled:

$$\frac{R_R}{\omega_0 \sigma L_R} \approx \frac{R_{Rn}}{X_{Sn}} = S_{CRn} , \qquad (5)$$

where R_{Rn} – nominal rotor active resistance; X_{Sn} – nominal short-circuit reactance of the machine; s_{CRn} is the nominal critical slip of the machine on its natural mechanical characteristic (under the condition $\overline{U}_R = 0$).

We shall neglect the stator active resistance, and write down the first two equations of system (4) taking into account (5) in the form:

$$\begin{cases} \overline{\Psi}_{S} = \frac{\overline{U}_{S}}{j\omega_{0}}, \\ \overline{\Psi}_{R} = \frac{\overline{U}_{R}}{\omega_{0}} \frac{1}{s_{CRn} + js} + \frac{\overline{U}_{S}k_{S}}{j\omega_{0}} \frac{s_{CRn}}{s_{CRn} + js}, \\ M = -\frac{3}{2} p_{P} \frac{L_{\mu}}{L_{S}L_{R} - L_{\mu}^{2}} \left[\overline{\Psi}_{S} \times \overline{\Psi}_{R} \right] \end{cases}$$

$$(6)$$

In the obtained system (6) there is an implicit connection between the moment developed by the machine and the rotor rotation speed (in the form of slip). This relationship is expressed through the machine flux-linkage. The direct computation of the moment according to (6) is difficult, since it requires a complete identification of the flux-linkages of machine windings (finding their current effective values and phases), which is a non-trivial task even with Hall sensors installed into the steel of the machine.

Turning to the method of generalized two-phase electrical machine and performing the necessary transformations [4], we obtain the following expression for the moment of the machine:

$$M = \frac{3}{2} z_P \frac{k_s^2 U_s^2}{\omega_0^2 \sigma L_R} \frac{s_{CRn} s}{s_{CRn}^2 + s^2} \left[1 - \frac{U_2^*}{s} \left(\cos \delta + \frac{s}{s_{CRn}} \sin \delta \right) \right].$$
(7)

Under $\overline{U}_R = 0$ and other nominal conditions, the following relationship is satisfied:

$$M_{CRn} = \frac{3}{2} z_P \frac{k_s^2 U_s^2}{\omega_0^2 \sigma L_R},$$
(8)

where M_{CRn} – nominal critical moment of the machine on its natural mechanical characteristic.

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Substituting (8) in (7), we obtain an expression relating the moment developed by the machine, slip, phase and relative amplitude of the voltage in the rotor circuit:

$$M = \frac{2M_{CRn}}{s_{CRn}/s + s/s_{CRn}} \left[1 - \frac{U_R^*}{s} \left(\cos \delta + \frac{s}{s_{CRn}} \sin \delta \right) \right], \tag{9}$$

where U_R^* is determined in accordance with the expressions:

$$U_{ROTH} = \frac{U_R}{U_S},$$
$$U_R^* = U_{ROTH} / k_S$$

where U_{ROTH} – relative voltage across the rotor, U_R^* – refined relative voltage across the rotor.

It should be noted that the critical slip and critical moment values in (9) correspond to their nominal values on the natural mechanical characteristic. The critical values of slip and moment on artificial characteristics when the additional voltage source is included into the rotor circuit are not equal to those of the natural characteristic and depend on the parameters of the additional voltage, as will be shown below.

It follows from expression (9) that a change in the amplitude and phase of the additional voltage in the rotor circuit makes it possible to adjust the moment developed by the motor and the speed of rotor rotation [10].

As it was mentioned above, in asynchronous mode the amplitude of the voltage applied to the rotor and its phase can be independently set, and its frequency is always equal to the current slip frequency (the frequency of the self-emf of the rotor). Thus, with the values of U_2^* and δ and substituting them into expression (9), it is possible to construct mechanical characteristics of the machine.

To determine the optimal parameters of voltage applied to the rotor (amplitudes and phases), we shall analyze expression (9). In accordance with (9), the moment developed by the machine is a function of three variables: slip, voltage amplitude across the rotor and its phase. Analysis of the function of three variables is difficult, therefore we shall consider the slip s as a parameter, and, accordingly, (9) as a function of two variables with the parameter:

$$M = f(U_{R}^{*}, \delta) = \frac{2M_{CR}}{s_{CR_{n}}/s + s/s_{CR_{n}}} \left[1 - \frac{U_{R}^{*}}{s} \left(\cos \delta + \frac{s}{s_{CR_{n}}} \sin \delta \right) \right].$$
 (10)

The analysis of (10) shows that this function is periodic in the variable δ with a period of 2π , which allows us to focus only on one period of its variation for this function. From considerations of physical realizability, it is enough to study the interval of phase variation $[-\pi \le \delta \le \pi]$.

In expression (10), we can distinguish two parts:

1) The part describing the natural mechanical characteristic of asynchronous motor with a phase rotor, to the rotor of which no additional voltage is applied $\frac{2M_{CR}}{s_{CRn}/s + s/s_{CRn}}$;

2) The part describing the change in the mechanical characteristic of the machine when the voltage source is connected to the rotor $\left[1 - \frac{U_R^*}{\cos \delta} + \frac{s}{\sin \delta}\right]^2$.

The part
$$\left[1 - \frac{U_R^*}{s} \left(\cos \delta + \frac{s}{s_{CR_n}} \sin \delta\right)\right]$$
 includes two parameters of voltage across the rotor –

amplitude (relative amplitude) and phase. Change in both parameters leads to a change of machine mechanical characteristic. Let us assume, as it was mentioned above, that for the voltage, directed counter to the self-emf of the rotor, U_R^* is positive, and when codirected – negative. Then it follows from expression (10) that the amplitude increase of counter directed voltage across the rotor leads to a decrease in electromagnetic moment with the same slip, and the increase in the amplitude codirected voltage leads to its increase. It is easily explained by referring to the machine replacement scheme (Figure 1). Indeed, the inclusion into the rotor circuit of a voltage source counter directed to the rotor self-emf, will lead to a decrease in the moment developed by the motor. Thus, the inclusion of the codirected voltage leads to an increase in the current of the rotor circuit and to the growth of the electromagnetic moment.

To find the values of the variables U_R^* and δ , for which the value (10) is maximal, it is necessary to determine the extremum points of function (10). Since (10) is a function of two variables and one parameter, the extremum points should be determined using partial derivatives with respect to the indicated variables. It suffices to consider the factor

$$k_{y} = 1 - \frac{U_{R}^{*}}{s} \left(\cos \delta + \frac{s}{s_{CRn}} \sin \delta \right).$$
(11)

Let us find the values of phase δ for which (11) takes the maximum values. To do this, we find the partial derivative (11) with respect to δ , taking s and U_R^* as constants, and equating it to 0:

$$\frac{\partial k_{y}}{\partial \delta} = 0,$$

$$-\frac{U_{R}^{*}}{s_{CRn}} \cos \delta + \frac{U_{R}^{*}}{s} \sin \delta = 0.$$
(12)

Solving equation (12) with respect to δ , we obtain a condition determining the maximum of (3.35) in phase:

$$\delta = \operatorname{arctg}\left(\frac{s}{s_{CRn}}\right) \tag{13}$$

Finding the derivative (12) with respect to the voltage amplitude, we can come to the conclusion that the expression has no extremum with respect to the voltage amplitude:

$$\frac{\partial k_y}{\partial U_R^*} = 0. \tag{14}$$

It follows from (11) - (14) that the maximum of the mechanical characteristic is determined by the value of voltage phase across the rotor, and its maximum value depends on the amplitude.

The phase surface of function (10) is shown in figure 2. As it can be seen from the constructed surface, the magnitude of electromagnetic moment of the machine is determined by the amplitude and

phase of the additional voltage, while for various combinations of amplitude and phase the machine can develop both a positive and a negative moment, and, therefore, work both in the motoring and in the braking modes.



The basic equation of drive motion (one of the forms of Lagrange equation following from D'Alembert principle) in the general case is written dowm as

$$\pm M \mp M_C = J \frac{d\omega}{dt}, \ (15)$$

where M, Mc – electromagnetic moment of the machine and the moment of loading, respectively; $\pm M \mp M_C = M_{dyn}$ – dynamic moment; *J* – the moment of inertia of the working mechanism reduced to the machine rotor.

Depending on the signs of $\omega \amalg M_{dyn}$, the machine can operate in different quadrants of mechanical characteristic. For example, let us consider the operation of a mine hoisting installation [11, 12], the force diagram and speed diagram of which are given in figure 3.



Figure 3. Typical tachogram and load diagram of the mine hoisting system.

Acceleration in sections 1, 5 is positive. In this case, expression (15) with regard to the sign of the speed takes the form:

$$\begin{cases} M_{MO} - M_C = J_{\Sigma} \frac{d\omega}{dt} > 0, \\ \omega > 0. \end{cases}$$
(16)

Acceleration in sections 3, 7 is negative, respectively, expression (15) takes the form:

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$$\begin{cases} -M_{MO} - M_C = J_{\Sigma} \frac{d\omega}{dt} < 0, \\ \omega > 0. \end{cases}$$
(17)

In this case, the engine operates in the braking mode in these sections. In sections 2, 4, 6 the acceleration is equal to 0, expression (17) takes the form:

$$\begin{cases} M_{MO} - M_C = 0, \\ \omega > 0. \end{cases}$$
(18)

In this case, the engine operates in the motoring mode in these sections.

It follows from expressions (15) - (18) that the electric drive must operate in different modes, to which correspond all coordinate quadrants of "speed-moment" plane.

The mechanical characteristics of experimental DFM based on the MTF-111 H6 engine are shown in figure 4.



Figure 4. Family of DFM mechanical characteristics based on MTF-111-H6 engine under the condition of maximizing the moment by condition (13).

The numbers in the characteristics indicate the value of the relative voltage across the rotor, at which the corresponding characteristic is obtained. According to the characteristics shown in Figure 3, it is evident that when the moment is maximized by condition (13) the working sections of the machine mechanical characteristics are practically parallel and the rigidity in their limits is preserved. According to the given mechanical characteristics (I and II quadrants) of DFM in asynchronous mode, it is seen that the range of speed control down at the nominal load moment in the motoring mode is limited by the maximum value of the amplitude of additional voltage across the rotor. In general, the range of speed control down depends on the type of natural mechanical characteristic of the asynchronous motor with a phase rotor, on the basis of which DFM is constructed; its maximum estimation is 1:2 - 1:2.5 [10]. As it was established by the authors, the conclusions drawn for quadrants I and II are valid for quadrants III and IV. To organize the operation of machine in these quadrants, it is necessary to change the direction of rotation of the stator magnetic field.

In addition, as it can be seen from figure 4, it is possible to start the machine by changing the amplitude of the additional voltage across the machine rotor.

Thus, the obtained expression for mechanical characteristics allows us to identify the DFM during its operation it and determine the required operating mode. It makes possible to organize digital control of the electric drive using the information-control system [13].

4. Conclusions

The achieved in asynchronous mode the range of DFM speed control is quite satisfactory for mechanisms that do not require deep speed control (fans, pumps, compressors). However, this range is unacceptably small for the electric drive of mine hoisting installations. To extend the range of DFM speed control, it is advisable to use a combined mode of DFM operation, which is a combination of asynchronous and synchronous operating modes of the machine in different sections of the speed diagram.

The resulting expression for the DFM mechanical characteristic is convenient to use in electric drive control systems.

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