Mechanical characteristics of the doubly-fed machine and its use in the hoist electric drive

V Yu Ostrovlyanchik, I Yu Popolzin and D A Marshev
Siberian State Industrial University, 42 Kirova street, Novokuznetsk, 654007, Russia

E-mail: eidoline@yandex.ru

Abstract. Currently, a large number of existing mine hoisting units use the electric drive based on asynchronous motor with a rotary station. Despite the fact that such drives have a large overload capacity and linear (within the working areas) mechanical characteristics, they have drawbacks, first of all, significant energy losses. The promising way of their modernization, as well as design of new drives based on a phase-wound rotor motor, is the use of the scheme of a doubly-fed electric machine. The paper outlines the requirements for the electric drive of a mine hoisting unit, in particular, for its mechanical characteristics; the analysis of the mechanical characteristics of the doubly-fed machine in asynchronous and synchronous modes, as well as changes in the active resistance of the rotor was carried out; the working sections of characteristics are indicated; the operating modes of the machine are compared to the sections of the speed diagram of the hoisting unit; the rationale for the combined control of the machine with the change in operating modes directly during operation is shown.

1. Introduction
Most hoisting systems are equipped with electric drives with asynchronous motors with a phase rotor and a rotor station. The main disadvantages of these electric drives are significant losses of electrical energy in the rotor station, as well as dynamic overloads in the mechanical part of the drive that arise during the switching of the station stages. Therefore, the work related to the elimination of these shortcomings in existing hoisting systems is relevant.

When upgrading mine hoisting systems (MHS), it is promising to use the mode of a doubly-fed machine (DFM) for phase-wound rotor motors, in which an additional voltage from the frequency converter is added to the rotor circuit of the motor. In this case, frequency converters are used in the rotor circuit, which are able to consume the slip energy, to recuperate it into the network and to feed the engine, that is, to work both in the forward and reverse directions. The advantage of this scheme, in particular, is the possibility of recuperation of slip energy into the electricity network.

2. Modes of operation of the mine hoisting unit and the doubly-fed machine
For the MHS, five main characteristic modes (sections of the speed diagram) should be identified [1].

- Torque control on the looked motor. It is necessary to exclude the reverse stroke of the machine drum when removing the mechanical brake and starting;
- Movement at speed when exiting curves or in the mode of “Revision”;
- Acceleration to the set speed;
- Movement at a given speed;
- Slowing down.
The main criterion determining the working areas of mechanical characteristics is constant stiffness 
\[ \beta = \frac{d\omega}{dM} = \text{const} \] (where \( \omega \) – the angular velocity, \( M \) – the moment of the electric drive) and the 
required overload capacity \( \lambda = \frac{M_{cr}}{M} \) (where \( M_{cr} \) – the critical moment on the specified characteristic).

Let us consider the possible modes of DFM operation and compare them with the speed diagram of 
the hoisting unit. The mode of DFM operation depends on the relation between the frequency of 
the internal rotor EMF and the frequency of the additional voltage introduced into the rotor circuit.

If the frequency of the auxiliary voltage is equal to the frequency of the eigen EMF, then this mode 
of operation is called asynchronous [2-4], if the frequency of the additional voltage does not depend 
on the load and rotor speed – the mode is called synchronous [2, 3, 5]. In asynchronous mode, the 
frequency of the auxiliary voltage is a parameter dependent on the speed, and in the synchronous 
mode – the independent parameter determining the speed [2], [4].

3. DFM mechanical characteristics in asynchronous mode

The equation of DFM mechanical characteristics for an asynchronous mode was obtained in [2] and 
[4]. It is written as:

\[
M = \frac{3}{2} z_p \frac{k_S^2 U_S^2}{\omega_0 \sigma L_R} \frac{s_{cn}s}{s_{cn}^2 + s^2} \left[ 1 - \frac{U_R^*}{s} \left( \cos \delta + \frac{s}{s_{cn}} \sin \delta \right) \right], \tag{1}
\]

where \( k_S \) – the stator coupling coefficient; \( L_R \) – rotor inductance; \( z_p \) – the number of the machine 
pole pairs; \( M \) – electromagnetic moment of the machine; \( \omega_0 \) – speed of the ideal idle motion of the 
machine; \( \sigma = 1 - \frac{L_\mu}{L_S L_R} \) – the scattering coefficient (\( L_\mu \) – the mutual inductance of the stator and the 
rotor, \( L_S \) – the inductance of the stator); \( k_S \) – the coupling factor of the stator; \( s_{kn} = \frac{R_R}{\sigma_0 \omega_0 L_R} \) – rated 
critical slip of the machine on the natural mechanical characteristic (\( R_R \) – rated rotor active resistance; 
\( X_{kn} \) – rated X-reactance of the machine short-circuit); \( s = \frac{\omega_0 - \omega}{\omega_0} \) – current slip; \( \omega \) – current rotational 
speed of the machine rotor; \( U_R^* = \frac{U_R}{k_S U_S} \) – relative value of the voltage amplitude on the rotor (\( U_R, U_S \) 
– the effective values of the voltages on the rotor and stator, respectively); \( \delta \) – phase shift between the 
additional voltage on the rotor and the voltage on the stator.

The expression for the mechanical characteristic (1) can be divided into two components:

a) \( M = \frac{3}{2} z_p \frac{k_S^2 U_S^2}{\omega_0 \sigma L_R} \frac{s_{cn}s}{s_{cn}^2 + s^2} \) – equation of the natural mechanical characteristic of the phase-wound 
rotor motor (in the absence of additional voltage source in the rotor circuit);

b) \( k_y = 1 - \frac{U_R^*}{s} \left( \cos \delta + \frac{s}{s_{cn}} \sin \delta \right) \) – component (coefficient) describing the change in the natural 
mechanical characteristic of the machine when an additional voltage is introduced into the rotor 
circuit.

This component depends on the amplitude of additional voltage and its phase. In [7] the condition 
for maximizing this component with respect to the phase shift of the additional voltage was obtained. 
According to [7], to ensure the maximum value of the moment at a given speed, it is necessary to 
control the phase of the additional voltage on the rotor according to the law.
\[ \delta = \arctg \left( \frac{s}{s_{cm}} \right). \tag{2} \]

Under condition (2), the MDP mechanical characteristics have the longest sections with negative stiffness (working areas).

The speed control in the asynchronous mode is performed by changing the relative amplitude of the additional voltage on the rotor \( U^*_R \). As follows from (1), an increase in the amplitude of the additional voltage on the rotor reduces the speed of the machine at a constant load moment. This also reduces the speed of ideal idle motion on the artificial characteristics of the machine, the critical slip and the critical moment due to the fact that when \( U^*_R \) increases \( k_y \) decreases.

![Figure 1. Family of DFM mechanical characteristics in the asynchronous mode depending on the relative amplitude of the additional voltage on the rotor (the working sections of the characteristics are marked with bold lines).](image)

The family of DFM mechanical characteristics with the maximization of the moment by condition (2) is shown in figure 1.

As it can be seen from the family of mechanical characteristics shown in figure 1 that when the amplitude of the additional voltage on the rotor increases, the speed of the machine decreases, but at the same time the overload capacity of the machine drops and the working section of mechanical characteristics decreases (a section with negative stiffness). Also the speed regulation in the DFM asynchronous mode with constant load torque is inappropriate below the speed of \( 0.6\omega_0 \), since the overload capacity of the machine becomes unsatisfactory. The given family of characteristics is constructed for the experimental DFM based on the crane engine, the working section of the natural mechanical characteristic of which has relatively low stiffness. Since the MHS uses powerful asynchronous motors with low nominal slip (and, therefore, with a greater stiffness of the working areas), the lower limit of the speed control of the DFM-based hoisting system can be estimated as \( 0.5\omega_0 \).

Thus, the DFM in asynchronous mode at the nominal load moment can operate only in the speed range \( 0.5\omega_0 < \omega \leq \omega_0 \), and the speed control range in this mode does not exceed 2:1 down from the rated speed of the machine. Consequently, the asynchronous mode is suitable only for MHS running at a constant maximum speed or for acceleration/deceleration in the speed range \( 0.5\omega_0 < \omega < \omega_0 \).
4. DFM Mechanical characteristics in synchronous mode

The synchronous operating mode takes place when the frequency of the auxiliary voltage is independent of the frequency of the eigen EMF of the rotor [2, 3, 5]. The rotor speed in this mode is constant and is determined by the expression:

\[ \omega = \omega_0 \frac{f_S - f_R}{f_S} = \omega_0 s, \]

where \( f_S, f_R \) – the stress frequencies on the stator and the additional voltage on the rotor, respectively. The parameter \( s \) in this case has the meaning of the relative voltage frequency on the rotor.

An expression for the mechanical characteristic of a DFM operating in synchronous mode was obtained in [5] and [7]. It has the following form:

\[ M = \left( \frac{L_\mu}{L_S} \right)^2 \frac{3sR_RU_S^2}{\omega_0 (R_R^2 + X_s^2 s^2)} + \frac{L_\mu}{L_S} \frac{3U_SU_R}{\omega \sqrt{R_R^2 + X_s^2 s^2}} \sin \gamma, \]

where \( R_R \) – the value of the rotor’s active resistance adjusted to the stator; \( \gamma = \theta + \arctg \frac{sX_{sc}}{R_R} \) – phase shift between the stator field and the rotor field, \( \theta \) – load angle, defined similarly to the load angle of the synchronous machine, \( X_{sc} \) – reactive short circuit resistance of the machine.

It follows from expression (2) that the DFM mechanical characteristic in synchronous mode has two components:

a) \( M_e = \left( \frac{L_\mu}{L_S} \right)^2 \frac{3sR_RU_S^2}{\omega_0 (R_R^2 + X_s^2 s^2)} \) – the component equivalent to the natural mechanical characteristic of the phase-wound rotor motor without a source of additional voltage in the rotor (asynchronous component);

b) \( M_c = \frac{L_\mu}{L_S} \frac{3U_SU_R}{\omega \sqrt{R_R^2 + X_s^2 s^2}} \sin \gamma \) – the component describing the electromechanical transformation of energy in the machine as a result of the stator field interaction and the winding of the rotor, over which the current flows due to the presence of an additional voltage source in the rotor circuit.

Since the relative frequency \( s \) in this mode depends only on \( f_R \), it is an independent parameter in (4) and does not depend on the moment on the machine shaft, its parameters and the amplitude of the stresses on the stator and rotor. In this case, the asynchronous component (4) is constant for a given value of the relative frequency, and the synchronous component depends only on angle \( \gamma \) conditioned by the internal load angle of the machine \( \theta \).

In practice, due to the limited speed of the frequency converter in the rotor circuit, the non-zero time of the transient processes in the rotor circuit when the frequency of the additional voltage is varied and the assumptions made when deriving expression (2), the machine speed in this mode depends on the load due to fluctuations in the additional voltage frequency, and the mechanical characteristics have a greater but finite stiffness. Nevertheless, for the purposes of this study, it can be assumed that the stiffness of mechanical characteristics is infinite, and the rotor rotation speed depends only on \( f_R \) and \( \gamma \).

Since the speed of rotor rotation does not depend on the load and is set forcibly, the load change leads to a change in the angles \( \theta \) and \( \gamma \). Thus, increasing the load on the shaft of the machine, the angle \( \gamma \) and the synchronous component of the moment \( M_c \) increase. The synchronous component of the moment is maximal at \( \gamma = \pi/2 \). When \( \gamma > \pi/2 \), the synchronous component of the moment begins to fall with increasing load, the machine falls out of synchronism and stops. Thus, the overload capacity of
the machine in synchronous mode is limited by the maximum possible value of the synchronous torque component. In this case, the synchronous component, as follows from (4), can be increased if to increase the amplitude of the additional voltage on the rotor.

The family of DFM mechanical characteristics corresponding to expressions (3) and (4) is shown in figure 2. The characteristics were obtained at the amplitude of additional rotor voltage 0.15US. The dashed lines show the areas of mechanical characteristics that correspond to the unstable operation of the machine after falling out of step.

Figure 2. The family of DFM mechanical characteristics in synchronous mode.

According to the characteristics shown in figure 2, it can be seen that the working sections of the DFM mechanical characteristics in the synchronous mode are stiff, and when the load moment exceeds the critical moment the machine “capsizes”, these parts of the mechanical characteristics have a positive stiffness, and the machine operation in this mode is unstable.

When the frequency of the auxiliary voltage on the machine rotor increases, the rotor speed decreases in accordance with (2). Taking into account the error in regulating the frequency at the output of the converter in the rotor circuit, it is advisable to take the maximum frequency of the additional voltage within 47.5–49 Hz, which corresponds to the relative rotation speed of the rotor 0.02–0.05.

In general, the DFM mechanical characteristics in synchronous mode are similar to the mechanical characteristics of a synchronous motor. However, the DFM overload capacity depends on the speed (figure 2). The greatest overload capacity is observed in the region of low velocities (below 0.5ω0). Besides, as the frequency of the additional voltage in the rotor decreases, the losses in the machine magnetic system increase (similar to a decrease in the stator voltage frequency [8]). Also, when the voltage frequency decreases, switching of the power valves of the frequency converter becomes difficult. Therefore, the frequency of the additional voltage in the DFM synchronous mode is reasonable to vary in the range 25 Hz – 47.5 Hz, which corresponds to the machine operation in the speed range 0.02 ÷ 0.05 ω ≤ ω ≤ 0.5ω0. Thus, the synchronous mode is suitable for the MHS operation in the specified speed range, including acceleration and deceleration.

5. DFM mechanical characteristics with a change in the rotor active resistance
As it follows from the above carried analysis of asynchronous and synchronous operation modes, none of these modes is suitable for MHS operation with a locked motor. In synchronous mode, the machine does not develop torque with the locked motor, and in asynchronous mode the overload capacity is too
low to realize the stable machine operation in the speed range. Therefore, to implement the MHS work, the mode of changing the rotor active resistance should be used. In this case, the equation of the DFM mechanical characteristic in this mode is analogous to one for the asynchronous motor with a phase rotor [9], and it can be written as:

\[
M = \frac{3U_s^2 k^2 R_{RS}}{\omega \Omega s \left( R_S + k^2 \frac{R_{RS}}{s} \right)^2 + X_{sc}^2},
\]

(5)

where \( R_{RS} \) – the total active resistance of the rotor chain; \( k \) – the transformation ratio of the machine. Since the moment is realized only by the active component of the rotor current, we can assume that in expression (5) \( X_R = 0 \) and write (5) in the form:

\[
M = \frac{3U_s^2 k^2 R_{RS}}{\omega \Omega s \left( R_S + k^2 \frac{R_{RS}}{s} \right)^2}.
\]

(6)

The analysis of expression (5) shows that with an increase in the active resistance of the DFM rotor circuit, the critical moment remains unchanged, and the speed at the unchanged moment decreases, that is, the stiffness of mechanical characteristics in this mode is inversely proportional to the total active resistance of the rotor chain. The family of DFM mechanical characteristics in this mode is shown in figure 3.

The bold lines indicate the areas of performance that ensure the machine operation at zero speed, in the braking off mode and in the speed range \( 0 \leq \omega \leq 0.1\omega_0 \). If we simulate the change in the active resistance smoothly (which is equivalent to the increment in the rotor active resistance), then it is possible to achieve the constancy of the moment developed by the machine.

The working zone of the DFM mechanical characteristics in this mode is limited by the speed determined from the parameters of the machine rotor chain and the value of the additional resistance in the rotor circuit. In practice, it is expedient to choose this speed as \( 0.05 \div 0.1\omega_0 \) so that after the braking off the machine could exit the mode of acceleration or low speed \( (0 \leq \omega \leq 0.1\omega_0) \) and change to a synchronous mode. Thus, it is recommended to use the controlled current converter in the rotor circuit for regulating the speed in the range \( 0 \leq \omega \leq 0.1\omega_0 \), while
DFM in its characteristics is similar to the AM PR characteristics with the active resistance in the rotor circuit.

6. Conclusion

Thus, we can draw the following conclusions:

- The main criterion for determining the working areas of the mechanical characteristics of the MHS electric drive is constant negative stiffness and overload capacity;
- The asynchronous mode, the synchronous mode and the active resistance change mode should be combined to achieve a large speed range in the MHS drive.
- For the machine operation in the range, it is advisable to use a controlled current converter in the rotor circuit with an imitation of the change in the active resistance of the rotor circuit, since it provides good overload capacity at a low speed and the possibility of smooth acceleration.
- Synchronous operation mode is recommended to use for acceleration, deceleration and operation at a low speed in the speed range \(0.02 \leq \omega \leq 0.5\omega_0\).
- It is recommended to use asynchronous mode for MHS operation at the maximum hoisting speed, as well as during acceleration and braking of the machine in the speed range \(0.5\omega_0 < \omega \leq \omega_0\).
- The specified combination of modes allows the speed control of the machine in the range of at least 30:1 to be achieved while maintaining the acceptable overload capacity of DFM in the entire speed control range.

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