Operation modes of frequency converter in the rotor circuit of induction motor drive of a mine hoist

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Abstract. The electric drive of a hoist must ensure the formation of the required tachogram and the diagram of driving forces. The tachogram depends on the type of lifting vehicles. For hoist electric drives based on a wound-rotor induction motor, it is possible to use a frequency converter in the rotor circuit to control the motor speed and torque. When designing a converter, the problem arises of determining the operating modes of its bridges and the current direction between them. The article analyzes the operating modes of the hoisting motor in accordance with various sections of the tachogram of the unit and the connection between the mechanical and electrical coordinates of the drive. The analysis carried out in the work makes it possible to obtain and implement methods for determining the parameters of the frequency converter in the rotor circuit and developing an algorithm for controlling the converter bridges to ensure the required tachogram and driving force diagram.

1 Introduction

The mine hoist electric drive must ensure the formation of the required tachogram of the shaft vehicles movement, as well as the required diagram of the driving forces (torques). The type of tachogram depends on the type of shaft vehicles. When constructing tachograms, the initial data, in particular, the values of speeds and accelerations in the sections of the tachogram, are regulated by the safety requirements of hoisting and technological restrictions. For electric drives of hoisting installations based on a wound-rotor induction motor (WRIM), it is possible to use a frequency converter in the rotor circuit to control the speed and torque of the motor.

When designing a converter, the problem arises in determining the operating modes of its bridges and the direction of the current between them. Since the force on the WRIM shaft determines the rotor current, it is advisable to analyze the operating modes of the bridges of the proposed converter shown in Fig. 1, to analyze the operating modes of the hoist in accordance with [1, 2] and compare them with the known operating modes of the drive motor [3].

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The analysis of the operating modes of the converter bridges can be carried out using the example of A rotor phase. In this case, an equivalent circuit and Kirchhoff's equations for the i_{ap}-*B1*-*B2c*-i_{ac}-i_{bc}-*B3c*-i_{bp} circuit are composed (Fig. 1).

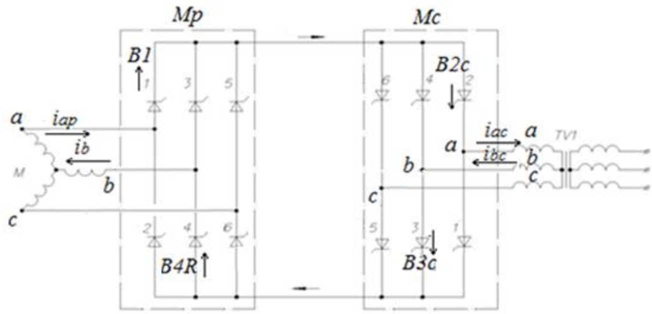

Fig. 1. Circuit of the proposed converter.

2 Mechanical and electromechanical characteristics of engine

The diagram shows that the direct current between the bridges has the same direction; hence the task of determining the indicated direction depending on the operating mode of the drive. The indicated direction is maintained regardless of the direction of power transmission in the rotor chain. In this regard, it is necessary to conduct research on the implementation of the technological process. For the hoist, the work is possible in all quadrants of the mechanical characteristic, i.e. the basic equation of motion of the drive in this case has the form:

$$\pm M_d \mp M_s = J_\Sigma \frac{d\omega}{dt} \tag{1}$$

where M_d – the torque developed by the engine; M_s – static torque (load torque) on the motor shaft; J_Σ – total torque of inertia of all moving parts of the unit reduced to the machine drum.

In this case, for WRIM, mechanical characteristics are realized, determined [6] in accordance with the expression:

$$M = \frac{3U_1^2 R_2'}{\omega_0 s\left[\left(R_1+\frac{R'_2}{s}\right)^2+(X_{1\sigma}+X_{2\sigma})^2\right]} = \frac{3U_1^2 R_2'}{(\omega_0-\omega)\left[\left(R_1+\frac{\omega_1 R'_2}{(\omega_1-\omega)}\right)^2+(X_{1\sigma}+X_{2\sigma})^2\right]} \tag{2}$$

where M – electromagnetic torque of the motor, U_1 – stator voltage, R_1, R'_2 – the active resistance of the stator circuit and the reduced active resistance of the rotor circuit, respectively, $X_{1\sigma}$, $X_{2\sigma}$ – leakage inductive resistances of the stator and rotor circuits, respectively, s – slip, ω_1 – synchronous speed, ω – rotor speed.

The electromechanical characteristic of WRIM is determined in accordance with the expression:

$$I'_2 = \frac{U_1}{\sqrt{\left(R_1+\frac{R'_2}{s}\right)^2+(X_{1\sigma}+X_{2\sigma})^2}} = \frac{U_1}{\sqrt{\left(R_1+\frac{\omega_1 R'_2}{(\omega_1-\omega)}\right)^2+(X_{1\sigma}+X_{2\sigma})^2}} \tag{3}$$

where I_2' – is the reduced rotor current.

The characteristics corresponding to expressions (2) and (3) are shown in Fig. 2 [6].

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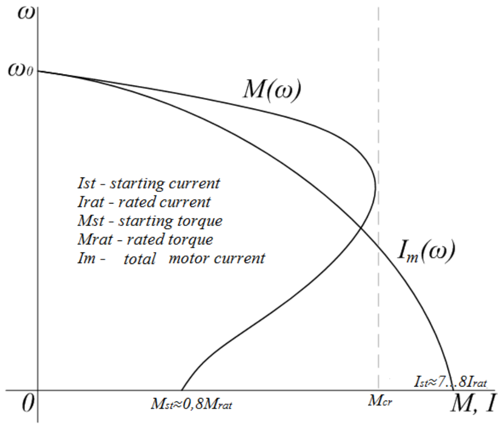

Fig. 2. Mechanical *M(ω)* and electromechanical *I(ω)* characteristics of wound-rotor induction motor.

3 Analysis of the converter operating modes

From the characteristics shown in Fig. 2, it follows that the main task of WRIM control is to maintain the motor torque at a level not exceeding M_{cr}. In this case, the magnitude of the motor current does not exceed 2...2.5 of the nominal value, which corresponds to the overload capacity of the motor, determined by the critical torque. For WRIM, the critical torque is defined as $M_{CR} = 2 \div 2.5M_N$, this torque corresponds to the motor current $I_1 = 2 \div 2.5I_{1N}$.

In the scheme with a rotor station, compliance with this condition is ensured by the introduction of additional resistances into the rotor circuit. In this case, we investigate the possibility of introducing a frequency converter into the rotor of not only obtaining a similar limitation of the current and torque of the WRIM, but also optimizing the control processes and correction of the rigidity of WRIM mechanical characteristics.

To determine the operating modes of the drive motor, it is necessary to construct jointly a tachogram of the hoist and a diagram of driving forces or torques. Fig. 3 shows a typical tachogram *ω* and diagrams of torques when hoisting the loaded *Mg* and empty *Mn* vehicles of the hoist operation for the hoisting cycle.

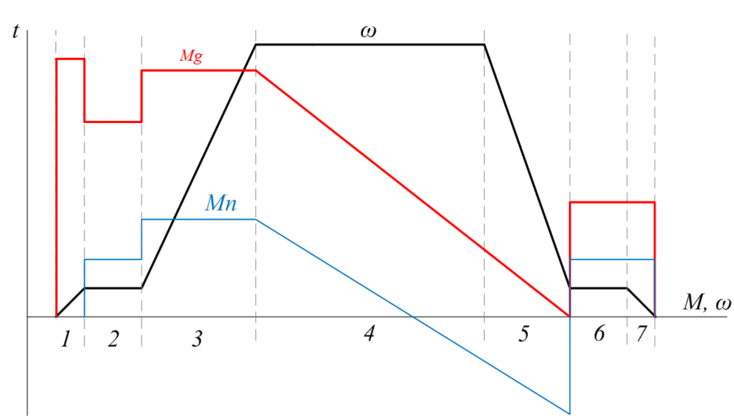

Fig. 3. Typical diagrams of the “Hoisting” technological process.

The modes corresponding to the sections of "Hoisting" cycle shown in Fig. 3 can be carried out using WRIM motor mode and plugging mode.

In this case, the motor either gives energy to the network through the rotor when it is released (section 1), moving in curves (section 2) and acceleration (section 3), or consumes energy from the network through the stator, converting the mechanical energy of movement into electrical energy. In this case, the rotor outlet is short-circuited (section 4). When braking (sections 5-7), the energy is transferred by the rotor to the network.

Expressions (1) for the motor mode will take the form:

$$\begin{cases} M_D - M_S = J_\Sigma \frac{d\omega}{dt}, \\ \frac{d\omega}{dt} \geq 0. \end{cases} \quad (4)$$

For the opposition mode, expressions (1) will be written as:

$$\begin{cases} -M_D + M_S = J_\Sigma \frac{d\omega}{dt}, \\ \frac{d\omega}{dt} < 0. \end{cases} \quad (5)$$

From [4] it follows that the effective values of the stator and rotor EMF are respectively equal: $E_1 = \omega_1 k_{w1} \Phi_a$, $E_2 = 4.44 f s \omega_1 k_{w2} \Phi_a$, where E_1, E_2 – stator and rotor EMF, respectively, f – voltage frequency on the stator; Φ_a – total magnetic flux in the air gap; k_w – winding ratio of the corresponding winding; Ψ_1, Ψ_2 – stator and rotor flux linkages, respectively; ω_1, ω_2 – angular frequencies of the stator and rotor EMF; s – slip. Taking this into account, we have:

$$E_2 = \frac{E_1}{k_T} s \quad (6)$$

Considering that $\frac{E_1}{k_T} = E_{2s}$ and $s = \frac{\omega_1 - \omega_2}{\omega_1}$, we get:

$$E_2 = E_{2s}\left(1 - \frac{\omega_2}{\omega_1}\right) = E_{2s} - k_E \omega_2 = E_{2s} - E_\omega \quad (7)$$

where $k_E = \frac{E_1}{k_T \omega_1}$ – coefficient of internal feedback of the machine in terms of EMF, E_{2s} – EMF of a stationary rotor, E_ω – back-EMF of the rotor.

When a frequency converter with an output voltage U_{fc} is included in its rotor, the total EMF of the rotor is determined as:

$$E_{2\Sigma} = E_{2s} - E_\omega \pm U_{fc} \quad (8)$$

Taking into account (6-8), the expression for the rotor current I_2 will take the form: $E_{2s} - E_\omega \pm U_{fc} = I_2 R (T_2 p + 1)$, or:

$$I_2 = \frac{E_{2s} - E_\omega \pm U_{fc}}{R(T_2 p + 1)} \quad (9)$$

where R_1, R_2 – active resistance of the stator and rotor, respectively, T_2 – electromagnetic time constant of the rotor circuit [5].

The moment of the car is determined by the following ratio:

$$M = I_2 \frac{3 z_P L_\mu E_{2s}}{2 \omega R_1} \quad (10)$$

Expressions (6-10) correspond to the structural diagram of the machine shown in Fig 4.

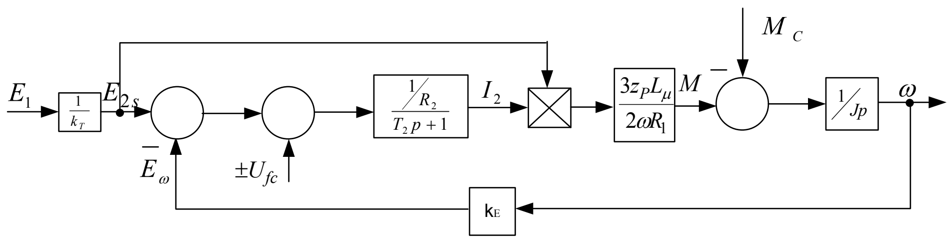

Fig. 4. Block diagram of ADFR with a frequency converter in the rotor.

The above expression for the machine torque (6) and the block diagram shown in Fig. 4 allow the values of the engine torque for all modes of its operation to be determined [6], which in turn allows, based on the equivalent circuit corresponding to Fig. 1, and Kirchhoff's equations for the ciruit i_{ap}-*B1-B2c*-i_{ac}-i_{bc}-*B3c*-i_{bp} to obtain methods for determining the parameters of the main elements in the rotor circuit with a frequency converter.

4 Conclusions

In view of the foregoing considerations the following conclusions can be drawn:

1. Inclusion of a frequency converter into the rotor with an output voltage directed opposite to the rotor EMF provides the possibility of continuous control of the motor torque (current) within the specified limits. This mode can be recommended at $\omega \leq 0.5\omega_1$.
2. Inclusion in the rotor of a frequency converter with an output voltage directed according to the rotor EMF will ensure the optimization of the basic control characteristics. Moreover, in both cases, equality of frequency and EMF phase and voltage is necessary.
3. The required operating modes of the electric drive are provided when the frequency converter is connected to the rotor circuit at $\omega=(0.7..0.8)\omega_1$ due to the smallness of the absolute values of the amplitude and frequency E_2.
4. The relations obtained in the work (the analysis carried out in the work) make it possible to obtain and implement the methods for determining the parameters of the frequency converter in the rotor circuit, as well as to obtain the required control algorithm for the converter bridges.

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