Operation algorithm of the hoist electric drive based on a doubly-fed machine with combined control

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Abstract. Currently, a large number of existing mine hoisting installations use the electric drive based on an induction motor with a rotary station. Despite the fact that such drives have a large overload capacity and linear (within the working area) mechanical characteristics, they have drawbacks, first of all – significant energy losses. A promising way for modernization of such drives, as well as design of new ones based on a wound-rotor induction motor, is to use a doubly-fed machine. In the article the operation algorithm of the hoist electric drive on the basis of a doubly-fed machine is given. The algorithm realizes a combined method of controlling the machine in the speed function, combining asynchronous and synchronous modes of operation with the mode of changing the active rotor resistance. The control of the hoist electric drive in accordance with the proposed algorithm allows the required range of machine speed control to be reached while maintaining the overload capacity on the entire control range.

1. Introduction
The working cycle of a mine hoisting system (MHS) contains several characteristic modes conditioned by the speed diagram and the diagram of the unit driving forces [1]. These modes include:

- The torque control on the locked motor. This mode is necessary for the realization of the machine retraction, that is to exclude the reverse stroke of the machine drum when the mechanical brake is removed and the movement starts. In this mode, the motor must develop the required torque with the stalled rotor;
- Movement at a low speed. In this mode, the vehicle exits the dumping curves, also the vehicle moves in the inspection mode;
- Speeding-up to the specified speed with a given acceleration;
- Movement at a given speed;
- Slowdown with a specified acceleration.

The presence of these operating modes imposes the following requirements for the MHS electric drive:

1) A large range of speed regulation due to the ratio of maximum and minimum stabilized speeds of vehicles. The required control range should be at least 30:1;

2) Constant stiffness \( \beta = \frac{d\omega}{dM} = \text{const} \) (where \( \omega \) is the angular speed, \( M \) is the moment of the electric drive) and the required overload capacity \( \lambda = \frac{M_{cr}}{M} \) (where \( M_{cr} \) is the critical moment on the specified characteristic) of the drive mechanical characteristics over the entire speed control range.
The majority of existing hoisting installations use an electric drive based on a wound-rotor induction motor (WRIM) and a rotary station. The specified type of a drive satisfies the above requirements, but has the following disadvantages:

1) Useless energy losses due to the rotary station resistances, which can reach 30% of the power consumed by the drive motor;

2) Dynamic overloads in the mechanical part of the drive, which occur when switching stages of the rotary station.

2. The combined control of the double-feed machine in the hoist electric drive

Promising is the application of the scheme of a doubly-fed machine (DFM), which is realized by connecting the frequency converter to a WRIM rotor.

For the DPM, two operating modes are possible [2], [3], [4]:

1) Asynchronous mode. In this mode, the frequency of the additional rotor voltage is set equal to the current frequency of the eigen EMF of the rotor, and the speed is controlled by changing the amplitude and phase of this voltage. The DFM mechanical characteristics in this mode are similar in their shape to the mechanical characteristics of the induction motor. In [5] the condition for maximizing the machine torque over the phase of additional voltage is obtained; if it is observed or the phase shift is fixed at a selected constant value, it is possible to adjust the DFM speed only by changing the amplitude of the rotor voltage. In this mode, because of the drop in the machine overload capacity, its speed control is possible only in the range 0.5ω0 < ω ≤ ω0 (where ω0 – the ideal idling speed of the WRIM), which makes this mode suitable for the MHS operation at the specified maximum speed and for speeding and slowing-down the vehicle in the specified speed range. In this mode, it is possible to recuperate the energy of slip into the network.

2) Synchronous mode. In this mode, the frequency of the auxiliary rotor voltage is set independently of the frequency of the eigen EMF of the rotor in accordance with the expression:

\[ \omega = \omega_0 \frac{f_S - f_R}{f_S} = \omega_0 - \omega_R, \tag{1} \]

where \( f_S, f_R \) – frequencies of stresses on the stator and boost voltage on the rotor, respectively; \( \omega_R = 2sR_f. \)

The speed in this mode is controlled by changing the frequency of boost rotor, the amplitude of the voltage controls the machine overload capability, and the phase shift controls the reactive power consumed. The mechanical characteristics of the machine in this mode are similar to the mechanical characteristics of a induction motor – they have an infinite negative stiffness within the working area. If the overload capacity is exceeded, the DFM goes into synchronous mode on an unstable part of the mechanical characteristic. The speed regulation in this mode is expedient within the speed range 0.1ω0 ≤ ω ≤ 0.5ω0, since in the indicated speed range the DFM in synchronous mode has the maximum overload capacity.

From the analysis it follows that the above-described modes (asynchronous and synchronous) ensure the operation of the machine within the speed range 0.1ω0 ≤ ω ≤ ω0 and are unsuitable in the retraction mode, during speed adjustment when exiting the curves and working in the inspection mode. In this case, the power consumed by the engine is about 10% of the rated power and it is possible to apply the regime with a controlled current converter in the rotor circuit. In this case, the initial equation for the analysis and construction of the algorithmic structure can be the equation of the machine mechanical characteristics:

\[ M = \frac{3U_0^2 k^2 R_{RE}}{\omega_0 s \left( R_S + k^2 \frac{R_{RE}}{s} \right)^2}, \tag{2} \]
where \( U_S \) – the effective value of the stator voltage; \( k \) – coefficient of machine transformation; \( s \) – slip; \( R_S \) – active stator resistance; \( R_{SE} \) – total active resistance of the rotor chain.

Thus, the combination of the above-described modes of DFM operation makes it possible to realize all sections of the MHS speed diagram:

1) The control of the machine torque within the speed range \( 0 \leq \omega \leq 0.1\omega_0 \) is realized by controlling the active component of the rotor current;
2) The work of the MHS and its acceleration/deceleration in the speed range \( 0.1\omega_0 \leq \omega \leq 0.5\omega_0 \) are expedient in synchronous mode;
3) The MHS operation its acceleration/deceleration within the speed range \( 0.5\omega_0 < \omega \leq \omega_0 \) are expedient in the asynchronous mode.

Thus, the electric drive of the double-feed MHS and controlled current converter in the rotor circuit satisfies the requirements for the drive of hoisting machines provided that combined control is performed combining these three operating modes of the machine.

The block diagram of the electric drive using the combination of all three operating modes will take the form shown in figure 1.

![Figure 1. Structural diagram of a double-feed machine.](image-url)
\( U_{Sg} \) – stator voltage;
\( f_{\omega_g}(u_{Sg}) \) – functional relation between the amplitude and frequency of the voltage at the stator;
\( E_S \) – stator EMF;
\( U_{torR} \) – voltage of the setting the boost voltage frequency on the rotor (speed in synchronous mode);
\( U_{R} \) – voltage of the setting the value of additional active resistance in the rotor circuit;
\( C_{em} \) – electromagnetic stiffness;
\( M_{cr} \) – critical moment on the natural mechanical characteristic of the WRIM;
\( S_{cr} \) – critical slip on the natural mechanical characteristic of the WRIM;
\( K_m \) – motor transmission ratio;
\( M \) – electromagnetic moment;
\( M_s \) – moment of loading (static moment);
\( J \) – total moment of inertia of the MHS mechanical part reduced to the rotor of the hoisting motor;
\( \omega \) – angular velocity of rotor rotation;
\( K1, K2, K3 \) – switches (logic functions) specifying the mode of DFM operation;
\( CSB \) – converter synchronization block (see figure 2).

The following system of logical expressions corresponds to the description provided above (we assume conditionally that the position of the switches K2 and K3 in position 1 corresponds to logical “0”, and in the position 2 – to logical “1”, the closed position K1 corresponds to “1” and the open “0”):

\[
\begin{align*}
(K1=0) \land (K2=0) \land (K3=1) & \text{ – mode of the controlled current converter;} \\
(K1=1) \land (K2=1) \land (K3=0) & \text{ – synchronous mode;} \\
(K1=1) \land (K2=0) \land (K3=0) & \text{ – asynchronous mode}
\end{align*}
\]
Thus, when implementing a combined DFM control, the drive has a variable structure. The functional diagram of MHS electric drive based on DFM with a combined control, corresponding to the structural diagram in figure 1, is given in figure 2.

**Figure 2.** Functional diagram of MHS electric drive based on DFM with a combined control.

In figure 2, the following designations are used: M – wound rotor induction motor; T – power transformer; RFCCB – rotor frequency converter control block; NFCCB – network frequency converter control block; CSB – converters synchronization block; LCB – load control block; ICS – information and control system; K1, K2, K3 – switches, corresponding to the switches in figure 1.

The scheme shown in figure 2 works as follows:

1) With the stalled rotor, the switch K1 is open, K2 is in position 1, and no boost voltage is applied to the rotor. Switch K3 is in position 2, an uncontrolled rectifier is included in the rotor circuit, in the circuit of which a controlled current transducer (CCT) is included. Regulation of the motor torque occurs by changing the rectified rotor current in the CCT. Such regulation is equivalent to a change in the active resistance of the rotor chain.

2) After removing the mechanical brake and the start of movement, the current in the circuit of the CCT decreases and the machine begins to accelerate. When achieving the speed $0.1 \omega_0$, the regulation with the help of CCT becomes impractical, therefore it is necessary to switch the DFM to synchronous mode. For this, the frequency inverter FI is switched to the rectifying mode, the rotary FI – into inverted mode, the frequency of the voltage at the output of the rotary FI is set equal to the current frequency of the rotor EMF, the voltage amplitude is set according to the required overload capacity. Upon reaching the specified threshold speed, K3 switches to position 1, K1 closes, connecting the rotary FI to the rotor circuit, K2 switches to position 2.
3) The voltage frequency at the output of rotor FI gradually decreases while maintaining the given amplitude, the machine accelerates in synchronous mode. If it is necessary to accelerate to a full speed, the acceleration in synchronous mode is performed up to the speed $0.5\omega_n$. Upon reaching it, K2 switches to position 1, K1 is closed, K3 is in position 1. The voltage frequency of the rotor starts to be dependent on the current frequency of the eigen rotor EMF. The amplitude of the rotor voltage begins to gradually decrease until the machine reaches the specified speed. When reaching the specified speed, the machine operates in asynchronous mode.

4) When the deacceleration starts, the voltage amplitude on the rotor starts to increase, the machine starts to slow down. The phase shift is set according to the condition [6], the frequency of the boost voltage on the rotor is equal to the frequency of the eigen rotor EMF.

5) After the machine reaches the speed $0.5\omega_n$, it is switched to synchronous mode, the amplitude of the boost voltage is constant, the frequency of the boost voltage is set independently of the frequency of the eigen rotor EMF. When the frequency of the boost voltage decreases, the machine slows down. Deacceleration in synchronous mode is possible until the machine is completely stopped and the mechanical brake is used.

If there is a necessity for a speed reversal, it should be carried out by changing the alternation of the stator phases with the locked rotor by means of a reverser (it is not shown in figure 2).

3. The algorithm of combined drive control
The above description of the algorithm can be formalized:

1) Torque control at zero speed:

\[
\text{If } \omega = 0: \begin{align*}
K1 &= 0, \\
K2 &= 0, \\
K3 &= 1, \\
R_{add} &= \text{var}.
\end{align*}
\]  

(5)

2) Movement at a low speed:

\[
\text{If } 0 < \omega \leq 0.1\omega_b: \begin{align*}
K1 &= 0, \\
K2 &= 0, \\
K3 &= 1 \\
R_{add} &= \text{const}.
\end{align*}
\]

\[
\text{If } 0.1\omega_b < \omega \leq 0.5\omega_b: \begin{align*}
K1 &= 1, \\
K2 &= 1, \\
K3 &= 0, \\
U_n &= \text{const}, \\
f_n &= \text{const}.
\end{align*}
\]

(6)

3) Machine acceleration:

\[
\text{If } 0 < \omega \leq 0.1\omega_b: \begin{align*}
K1 &= 0, \\
K2 &= 0, \\
K3 &= 1, \\
R_{add} &\downarrow.
\end{align*}
\]
\[
\begin{cases}
K1 = 1, \\
K2 = 1, \\
If \quad 0,1\omega_0 < \omega \leq 0,5\omega_0 : \\
K3 = 0, \\
U_R = \text{const}, \\
f_R \downarrow.
\end{cases}
\]

\[
\begin{cases}
K1 = 1, \\
K2 = 0, \\
If \quad 0,5\omega_0 < \omega \leq \omega_0 : \\
K3 = 0, \\
U_R \downarrow, \\
f_R = \frac{\omega_0 - \omega}{\omega_0} f_s.
\end{cases}
\]

4) Machine operation at the specified maximum speed \( \omega_m \):

\[
\begin{cases}
K1 = 1, \\
K2 = 0, \\
If \quad \omega = \omega_m : \\
K3 = 0, \\
U_R = 0, \\
f_R = \frac{\omega_0 - \omega}{\omega_0} f_s.
\end{cases}
\]

5) Machine deacceleration:

\[
\begin{cases}
K1 = 1, \\
K2 = 0, \\
If \quad 0,5\omega_0 < \omega \leq \omega_0 : \\
K3 = 0, \\
U_R \downarrow, \\
f_R = \frac{\omega_0 - \omega}{\omega_0} f_s.
\end{cases}
\]

\[
\begin{cases}
K1 = 1, \\
K2 = 1, \\
If \quad 0 \leq \omega \leq 0,5\omega_0 : \\
K3 = 0, \\
U_R = \text{const}, \\
f_R \downarrow.
\end{cases}
\]
The operation of the circuit, shown in figure 2 according to the algorithm (5-9), makes it possible to implement a combined electric drive of the hoisting unit with a dual-feed machine that provides speed control in the range not less than 30:1 (according to the authors’ estimate the range, depending on the type of speed diagram of particular unit, can reach 40-50:1).

4. Conclusion
All required modes can be realized on the basis of a combination of methods of electric drive control, which consists in the combination of control over frequency and the amplitude of boost voltage on the DFM rotor and the application of a controlled current converter in the rotor circuit.

The advantages of this method for controlling the electric drive are obvious, since the combined method makes it possible to take advantage of all known control methods, and, therefore, significantly improve the efficiency of control.

References
[1] Ostrovlyanchik V Yu 2004 Automatic Electric Drive of Direct Current of Mining and Metallurgical Production (Novokuznetsk) p 382
[2] Onischenko G B and Lokteva I L 1979 Asynchronous Valve Cascades and Dual-feed Motors (Moscow: Energia) p 200
[3] Fiargo B I and Pavlyuchik L B 2006 Regulated Electric Drives of Alternating Current (Minsk: Technoprospectiva) p 363
[4] Klyuchev V I 2001 Theory of Electric Drive (Moscow: Energoatomizdat) p 704
[5] Chilikin M G et al 1974 Fundamentals of an Automated Electric Drive (Moscow: Energia) p 568
[6] Ostrovlyanchik V Yu et al 2017 IOP Conference Series: Earth and Environmental Science 84 012030