Control system of induction motor drive of a hoisting unit with a controlled current converter in the rotor circuit

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Abstract. The use of a double-feed machine circuit is a promising way to modernize induction motor drives of mine hoisting installations. The main problem of using doubly-fed electric machine in the electric drives with a large range of speed control is the release implementation and machine operation of after it at low speed. Existing implementations of electric drives based on a doubly-fed machine (DFM) assume the use of additional resistors in the rotor circuit (rotor station) for releasing the brakes, which complicates the control circuit and significantly reduces the reliability of the drive. In this case, the electric drive circuit with additional active resistances in the rotor circuit has optimal starting characteristics, since a change in the active resistance of the rotor does not cause a change in the critical moment, and, therefore, in the overload capacity, which makes it possible to implement the release mode. It is possible to preserve the advantages of regulating the DFM speed by changing the active resistance of the rotor by using an imitation of its change. The article is devoted to the study of the possibility of implementing such mode using a controlled current converter in the rotor circuit.

1. Introduction
An induction electric drive with a rotary station, despite its shortcomings, is still widely used for existing mine hoisting installations. The use of these drive systems is due to their relative simplicity and good overload capacity. DC electric drive systems built according to the generator-motor (G-M) and valve converter-motor (VC-M) schemes have better control, static and dynamic characteristics, however, they are unreliable and require the use of powerful controlled rectifier units (VC-M) or additional electrical machines with an overall power not lower than the power of the drive motor (G-D). Existing electric drives based on induction electric motors with a wound rotor have low energy efficiency due to the useless dissipation of machine sliding energy on the resistances of the rotor station. In addition, parametric control of the machine speed by means of stepwise switching of the resistances of the rotor station leads to excessive dynamic loads in the ropes, jerks and impacts, and also does not allow smooth control of the machine speed.

To ensure acceptable energy and control characteristics of wound rotor motors, it is optimal to use them in the dual power mode. In this case, a double-feed machine is called a WRIM with a source of additional voltage in the rotor circuit, in which there is the possibility of independent control of the frequency, amplitude and phase of the voltage.

The main problem of using a doubly-fed machine in electric drives with a large range of speed control is the implementation of release and operation of the machine after it at low speed. Existing implementations of electric drives based on a doubly-fed machine assume the use of additional resistors in the rotor circuit (rotor station) for releasing the brakes, which complicates the control
circuit and significantly reduces the reliability of the drive. In this case, the electric drive circuit with additional active resistances in the rotor circuit has optimal starting characteristics, since a change in the active resistance of the rotor does not cause a change in the critical moment, and, therefore, in the overload capacity, which makes it possible to implement the release mode. It is possible to preserve the advantages of regulating the DFM speed by changing the active resistance of the rotor, changing the active component of the rotor current.

2. Controlled current converter in the rotor circuit

In a moving self-orienting coordinate system [1-3], the mathematical model of the DFM will take the form:

\[
\begin{align*}
    i_{\text{sg}} &= \left( u_{\text{sg}} + pL_\mu i_{\text{rg}} + \omega_\mu L_\mu i_{\text{ri}} \right) \cdot \frac{1}{R_S} \frac{1}{T_S p + 1}, \\
    i_{\text{ri}} &= \left( \omega_\mu sL_R i_{\text{rg}} - \omega_\mu sL_\mu i_{\text{sg}} \right) \frac{1}{R_R + R} \frac{1}{T_R p + 1}, \\
    M &= \frac{3}{2} z_p L_\mu i_{\text{sg}} i_{\text{ri}},
\end{align*}
\]

where \( i_s, i_r \) – stator and rotor currents, \( u_s \) – stator voltage, \( R_S R_R \) – stator and rotor intrinsic resistance, respectively, \( R \) – additional resistance, \( L_R, L_\mu \) – rotor and air gap inductances, respectively, \( T_S, T_R \) – electromagnetic constants time of the stator and rotor, respectively, \( z_p \) is the number of pairs of machine poles, the indices \( \text{g} \) and \( \text{i} \) denote the projections of the corresponding values on the axis of the coordinate system associated with the image vector of the stator current.

Taking into account the compensation of the windings EMF [4, 5], expression (1) can be transformed to the form:

\[
M = \frac{3}{2} U_S g \frac{z_p L_\mu}{R_S} \cdot \frac{1}{R_R + R} \frac{1}{T_R p + 1} \left( U_S - \omega k_E \right),
\]

where \( k_E \) is the coefficient of internal feedback for the rotor EMF.

From equation (2), the speed of the machine is determined as:

\[
\omega = \left\{ \frac{3}{2} \frac{z_p L_\mu}{R_S} U_S g \frac{1}{R_R + R} \frac{1}{T_R p + 1} \left( U_S - \omega k_E \right) - M_S \right\} \frac{1}{J p},
\]

where \( M_S \) – load moment (static moment); \( J \) is the total moment of inertia of the drive reduced to the motor shaft.

Equation (3) corresponds to the block diagram shown in figure 1.
Figure 1. Block diagram of the machine when changing the active resistance of the rotor.

The circuit shown in figure 1 can be converted taking into account the following relationship:

$$\frac{1}{R_r + R} = \frac{1}{1 + \frac{R}{R_r}} \cdot \frac{1}{1 + k},$$

(4)

where $k$ is the multiplicity of the additional resistance, which determines the value of the rotor resistance of the corresponding stage. For hoisting installations based on IM WR with a rotary station, the coefficient $k$ is usually 4 ... 8.

Taking into account (4), the diagram shown in figure 1 will take the form shown in figure 2a or 2b.

Figure 2. Algorithmic structure of IM WR when changing the additional resistance in the rotor circuit (structures 2a and 2b are equivalent).

As mentioned above, change in the rotor resistance by switching the stages of the rotor station causes surges in the rotor current when switching stages, which leads to jerks in the mechanical part of the drive and shortens the service life of gears and ropes. In addition, when regulating the speed of the machine using a rotary station, the energy loss in its resistances can be up to 30% of that consumed by the engine.
Regulation of the machine speed by changing the active resistance of the rotor is equivalent to changing the active component of the rotor current. This can be implemented using the proposed by the authors drive circuit with a controlled current converter in the rotor circuit, shown in figure 2 and described in detail in [6]. The proposed circuit has a rectifier, in the rectified current circuit of which a current converter is included, realizing the regulation of the rectified rotor current $I_d$ with the condition $\frac{\Delta I_d}{\Delta t} \to 0$. At a continuous change in the rectified rotor current, there is a continuous change in the active component of the rotor current, and, consequently, the torque of the machine.

The main way to implement such control is to regulate the rectified rotor current when the rectifier is connected to the rotor circuit (figure 2). Regulation of the active component of the rotor current can be carried out by including a power switch in the rectified current circuit of the rotor. It is advisable to use an IGBT with pulse-width modulation as a switch, since in this case the range of regulation of the current flowing through the transistor is maximally expanded, and the switching power is minimal.

![Diagram](image)

**Figure 3.** The proposed power circuit of the DFM with the DCT in the rotor circuit (WRIM - wound rotor induction motor, CCC – controlled current converter, – voltage control unit).

The above scheme works as follows. By controlling the duration of the pulses at the VT14 gate using a PWM signal from the VCU, it is possible to change the active component of the rotor current in accordance with the considerations stated above. Resistances $R_{sh}$ and $R_o$ serve to implement current limitation, the LR reactor serves to filter and smooth out current pulses in the IGBT circuit, and the diode connected in parallel with the transistor protects the IGBT from switching overvoltages, which in this circuit are quite large due to the value of the intrinsic inductance of the rotor winding and the inductance of the smoothing reactor.

In the diagram of a controlled current converter (CCC) shown in figure 3, the active component of the rotor current flowing through the resistance $R_o$ is regulated, which in this case performs the function of limiting the current through the transistor. If the duty cycle of the PWM IGBT is denoted as $D$, then the average current flowing through the resistance $R$, in this case, is defined as:
\[ I_R = \frac{1}{T} \int_0^T D i_R(t) dt, \]  

where \( T \) is the switching period of the key.

3. Experimental research

In order the rotor station to be replaced by the CCC, it is necessary that the processes occurring in the rotor circuit during the switching of the CCC key correspond to the processes that arise when the active resistance of the rotor changes. If for the rotary station the range of change in active resistance is limited only by the number of steps of the station, and the current changes continuously, then in the circuit with CCC there are current ripples of two types, which limit the range of current change:

1) Ripple caused by the control circuit used. In this case, the ripple of the rectified current corresponds to the six-phase rectification circuit:

\[ f_p = 6 f_R, \]  

where \( f_R \) – the rotor EMF frequency, depending on the rotor speed in accordance with the following expression [7]:

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

where \( f_s \) – is the stator voltage frequency, \( \omega \) is the angular speed of the rotor rotation, \( \omega_0 \) is the ideal no-load speed.

Since the maximum frequency of the rotor EMF is 50 Hz, the maximum frequency of the rectified current ripple in accordance with (5) is 300 Hz.

2) Ripple caused by commutation of the power switch. These pulsations depend both on the switching parameters of the key and on the parameters of the machine rotor circuit. In this case, the switching frequency must be a multiple of the rectified current ripple frequency so that the ripple does not enter into resonance.

Thus, the range of current variation through the CCC link is limited by the level of ripple of both types. Since pulse width modulation is used for switching in the IGBT, current surges occur in the transistor at the moments of locking and unlocking the gate. In order the current inrushes during switching do not affect the processes of electromagnetic energy conversion in the machine, it is necessary to use a filter, which in the simplest case is a reactor connected to the rectified current circuit of the CCC. The level of current ripple in the rotor circuit depends on the inductance of the reactor.

When using PWM, the output voltage of the converter is determined according to the following expression:

\[ U_{out} = U_{in} \cdot \frac{t}{T} = \frac{U_{in}}{\gamma} = D U_{in}, \]  

where \( U_{in}, U_{out} \) – the input and output voltages, respectively, \( t \) is the pulse duration, \( T \) is the period duration, \( k_{shim} \) is the PWM enhancement factor, \( \gamma \) is the modulation duty cycle, \( D \) is the duty cycle.

When using PWM, the output signal of the converter is formed as a set of rectangular pulses. The following system of equations can be used to describe a single pulse not out of phase:

\[
U_{PWM}(t) = \begin{cases} 
0, & t < t_1 \\
DU_{in}(t), & t_1 \leq t \leq t_2 \\
0, & t_2 < t < t_3.
\end{cases}
\]
where \( t_1, t_2 \) – the start and end times of the impulse, \( t_3 \) – the end time of the firing period, while:

\[
t_1 + t_2 = T_s,
\]
\[
f_s = \frac{1}{T_s},
\]
\[
D = \frac{t_2 - t_1}{T_s},
\]
\[
\gamma = \frac{1}{D}.
\]

In the circuit shown in figure 3, there is a smoothing choke (filter) \( L_R \), the presence of which affects the parameters of the rotor circuit. Taking into account the inductance \( L_d, \) the active resistance of the smoothing choke and the additional resistance \( R_{ad}, \) the transfer function of the DFM rotor circuit will take the form:

\[
W_R(p) = \frac{1/(R_R + R_{ad} + R_d)}{(T_R + L_d/R_d)p + 1}.
\] (9)

As follows from (5-9), the controlled parameters of the CCC in the rotor circuit are the duty cycle \( D, \) the switching period \( T_c, \) as well as the inductance and active resistance of the reactor \( L_d, R_d. \)

To study the effect of changing the PWM parameters on the CCC current shape and the range of its variation, we will use the rotor current circuit model shown in figure 4.

![Figure 4. Schematic of the rotor current circuit model.](image)

In the experiment, we used the setting of \( U_{in} \) as a single step action, i.e. The PWM produced a voltage with an amplitude of 1 V. The rotor current and its average value, determined by (4), were fixed.

To determine the possible range of current variation using the CCC, the operation of circuit 4 was simulated without PWM and with a change in the rotor resistance and with a PWM without changing the rotor resistance, a constant switching frequency and a change in the duty cycle. The simulation results are shown in figure 5.

The graphs presented in figure 5 show that in the circuit with a rotor station, the current changes smoothly, and the range of its change is limited only by the value of the additional resistance. In a circuit with a CCC, the ripples in the average current curve are greater in the number, the lower the duty cycle of the PWM.

So, at \( D=0.1, \) the amplitude of the pulsations is about 50%; at \( D=0.2 \) – about 45%; at \( D=0.7 \) – about 11%; at \( D=0.8 \) – about 5%; at \( D=0.88 \) – about 3%; with \( D=0.95 \) – less than 1%. It can be seen that the range of \( D \) variation is limited by the permissible ripple amplitude (no more than 5%) and can be estimated as \( 1 \ldots \approx 0.8, \) which corresponds to the current variation range of about 0.8-0.85 ... 1.0\( I_{in}. \)
Figure 5. (a) transient current processes at different values of the rotor resistance in a circuit with a rotor station; (b) transient current processes at different values of the duty cycle in a circuit with a CCC with a switching frequency of 50 Hz.

A decrease in ripple can be achieved by changing the commutation frequency of the PWM and increasing the inductance of the smoothing reactor in the rectified current circuit of the rotor. As shown above, the commutation frequency must be a multiple of the ripple frequency of the rectified rotor current. Experimental studies were carried out at a switching frequency of 50, 300 and 1000 Hz. The experimental results are shown in figure 6 (with a duty factor of 0.8).

Figure 6. Transient processes of the average rotor current at different commutation frequencies and a fixed duty cycle 0.8.

It can be seen that an increase in the commutation frequency reduces the ripple of the average current in the rotor circuit, and, in addition, somewhat speeds up the transient process of its growth. Thus, the optimal switching frequency is 1 kHz.

We also studied the effect of increasing the reactor inductance in the rectified current circuit on ripple. The results of the study for several values of the inductance of the reactor are presented in figure 7. The studies were carried out for a commutation frequency of 50 Hz, as it gives the highest ripple value.

As it can be seen from the graphs shown in figure 7, an increase in the inductance of the smoothing reactor decreases the ripple, but delays the current transient. In general, \( L_d = 4L_R \) can be recognized as the optimal inductance value that provides a sufficiently effective smoothing of the current curve and does not cause an excessively long rise in it.

Figure 8 shows the graphs of transient current processes in the DCT with a certain optimal commutation frequency of 1000 Hz and inductance \( L_d = 4L_R \). From the comparison of the graphs shown in figure 8 with the graphs shown in figure 5a, it can be seen that with the selected parameters of the CCC, the converter in its properties is completely similar to the change in the active resistance of the rotor using a rotor station.
4. Conclusions

Thus, based on the performed study, we can come to the following conclusions:

1) The use of CCC in the rotor circuit is an alternative to the use of a rotor station.
2) The range of current variation when using the CCC is limited to $0.8-0.85 \ldots 1.0I_{Rn}$ due to the significant amplitude of current ripple at low values of the duty cycle.
3) With an optimal selection of the switching frequency of the valve and the inductance of the smoothing reactor, the CCC in its properties is completely similar to the change in the active resistance of the rotor in the rotor station, however, it allows a smooth change in the rotor current without jerking.
4) The algorithmic structure shown in figures 2a and 2b can be considered in the implementation of the speed control system in the case of the use of CCC in the rotor circuit. In this case, the value of $k$ changes continuously according to the given law of motor torque control.
4) The mathematical model of the CCC in the rotor circuit is obtained and the method for selecting the parameters of the PWM for the electric drive of the lifting unit is developed obtained:

References

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