Use of frequency converters in the stator circuit of a doubly-fed induction motor of a hoisting unit

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Abstract. One of the currently accepted options for modernizing an induction electric drive is the use of a frequency motor control. In this case, a frequency converter is connected to the motor stator with the ability to control the voltage parameters at its output. Usually, frequency control is applied to induction squirrel-cage motors, including special machines designed for frequency control. In this case, as a rule, the frequency changes “down” from the nominal frequency of the voltage on the stator of the machine, and the speed control range is determined by the minimum frequency of the voltage applied to the stator. At the same time, for motors used in the electric drive of hoisting installations, the speed control range is limited to 2:1 due to the deterioration of the properties of the magnetic system of the machine. Speed regulation below half the rated speed can be carried out using a controlled rotor current converter.

1. Introduction
The induction electric drive of hoisting units is widely used in mines of the Russian Federation. The scheme with a rotor station used as of 2020 on many lifting installations with an induction motor is outdated and ineffective, since the use of this scheme leads to unproductive energy losses due to the fact that up to 30% of the energy supplied to the motor is dissipated on rotor resistances in the form of heat.

In addition, the switching of the station steps causes jerks and shocks in the mechanical part of the drive [1]. Thus, there is a need to modernize the existing electric drives of hoisting units with a wound rotor induction motor (WRIM) and a rotary station.

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2. Disadvantages of frequency control
The main factors affecting the behavior of the magnetic system of the machine with a decrease in the frequency of the supply voltage are:

a) Change in the reactance of the magnetizing circuit and, as a consequence, decrease in the energy given to the magnetic field of the machine (expressed in the decrease in the magnetizing current).
b) Change in the absolute value and structure of losses in the steel of the machine.

c) Changes in the magnetization curve of the machine and saturation effects.

d) Change in the inductance of the magnetization circuit of the machine due to changes in the magnetic permeability of the winding cores [2].

To maintain a constant main magnetic flux of the machine with frequency control, the condition must be met

\[ \frac{U_s}{f} = \text{const}, \quad (1) \]

where \( U_s, f \) – rms value and frequency of stator voltage, respectively.

Expression (1), also called Kostenko’s law, or its modifications with different shapes of the static moment curve, allow keeping the main magnetic flux of the machine unchanged. However, Kostenko’s law is valid only in cases where the active resistance of the stator is significantly less than the reactance of the magnetizing machine [2]. The influence of the relative growth of the active resistance of the stator with a decrease in the frequency of the supply voltage is eliminated by \( IR \) or \( IZ \) compensation.

The stator current at \( U_s=\text{const} \) is inversely proportional to frequency. According to the research carried out in [2], the stator current increases sharply, starting from frequency of 25 Hz (figure 1).

**Figure 1.** Dependences of the stator current \( I_s \), EMF of magnetization \( E_m \) and the voltage drop across the active resistance of the stator \( U_{rs} \) AM on the frequency of the supply voltage at \( U_s=\text{const} \).

Thus, when using frequency control for high-power WRIM applied in the drive of hoisting units, the frequency range is, however, limited to about 25 Hz [2], which corresponds to a 2:1 speed control range down from the rated motor speed. When the frequency of the stator voltage changes below this value, the efficiency of the machine and its overload capacity sharply decrease, and the critical slip increases, which makes control according to law (1) (scalar control) unsuitable for such machines. At the same time, the introduction of vector control systems for high-power motors meets significant difficulties.

3. **Application of a controlled current converter**

For the IM PR that are currently used in lifting installations, it is possible to supply an additional voltage to the rotor from an external source. Such a circuit for switching on an WRIM is called a doubly-fed machine (DFM), and its application is one of the promising ways to modernize the drive [1, 3-6]. However, in a drive with DFM, it is difficult to implement the mode of release of the hoisting machine and the movement of the vessel at low speed. To solve this problem, it was proposed in [7] to include a controlled current converter (CCC) in the rotor circuit.
DCC allows control of the active component of the machine current to be implemented in such a way that the change in the rectified rotor current is similar to the change in the active resistance of the rotor in its properties. The block diagram of the DFM with CCC in the rotor is shown in figure 2:

![Diagram](image)

**Figure 2.** Structural electric drive based on DFM with CCC drive in the rotor.

When choosing the optimal values of the modulation frequency and inductance of the smoothing reactor (CCC in its properties is completely similar to a rotor station with a continuous change in the active resistance of the rotor), therefore the circuit shown in figure 2 can be presented in the form shown in figure 3, where $k$ is the change coefficient of rotor current.

![Diagram](image)

**Figure 3.** Structural electric drive based on DFM with CCC drive in the rotor.

In the general case, the construction of a mathematical model of WRIM is a rather difficult task, and the resulting models are very complex and contain a large number of links [8]. However, when implementing the frequency control of the WRIM and considering the working section of the mechanical characteristics of the machine (i.e., in the region $s<s_{kr}$), the equation of the dynamic mechanical characteristics of the machine will take the form [8, 9]:

$$ (T_s p + 1)M = k_B u_{im}, $$

where $T_s = \frac{L_s + L_g}{R_s + R_g}$ is the electromagnetic time constant of the machine, $k_B = C_{em}$ is the electromagnetic stiffness coefficient.
4. Description of the proposed electric drive circuit

As mentioned above, the \( f_S \) control range is limited due to the deterioration of the properties of the magnetic system of the machine when the frequency of the stator voltage decreases \([2]\). It is undesirable to decrease the frequency \( f_S \) below 25 Hz, which limits the speed control range in the described mode as 2:1. To regulate the speed of IM PR below the speed of \( 0.5\omega_0 \), the authors proposed a controlled current converter (CCC), described in detail in \([7]\) and in the second article of the authors in this conference proceeding.

By combining the operation of the machine in the speed range \( 0 - 0.5\omega_0 \) from the CCC and in the speed range \( 0.5\omega_0 - \omega_0 \) from the frequency converter, it is possible to control the WRIM in the speed range from 0 to nominal with a continuous change in the rotor current (torque) and speed over the entire range regulation. Such control implies, in fact, two-zone control of the machine, since when the CCC is connected to the rotor circuit, the active component of the rotor current (torque) is regulated, and with frequency control, the speed of the machine is controlled. In this case, since the frequency control of the motor involves a change in both the amplitude and the frequency of the voltage, the circuit requires a device that matches them. The proposed functional diagram of the described drive is shown in figure 4:

![Functional diagram of an electric drive based on an WRIM with a frequency converter and CCC.](image)

In figure 4, the following designations are adopted: PM – torque regulator; SR – speed regulator; SSB – speed setting block; TS – torque sensor; MU – matching unit; FC – frequency converter.

The drive circuit shown in figure 4 works as follows. When starting the engine, retraction and in the speed range \( 0 - 0.5\omega_0 \) the nominal values of the amplitude and frequency of the stator voltage are set at the output of the frequency converter, and the CCC changes the active component of the rotor current by changing the coefficient \( k \). After reaching the set speed, the duty cycle of the CCC is set to 1 (the power switch is fully open), and a signal for generating the amplitude and frequency is sent to the frequency converter in such a way as to continue the acceleration of the machine and reach the rated speed.

In this case, the speed reference is carried out from an integrating device (intensity generator), which makes it possible to form any required drive motion diagram. Non-linear limiting blocks allow the required relationship between the amplitude and frequency of the stator voltage and torque to be formed. The torque sensor calculates the torque in accordance with the specified parameters of the stator voltage, speed and active component of the rotor current.

5. Conclusions

Thus, based on the study, we can come to the following conclusions:
1) For WRIM it is possible to control the speed by changing the frequency of the voltage on the stator in the range 1:2, which corresponds to a change in frequency from 25 to 50 Hz. In this case, the critical moment of the engine and the rigidity of the working section of its artificial characteristics are equal to those in the natural mechanical characteristic, and the reactive currents do not significantly affect the properties of the machine.

2) To regulate the speed of the WRIM below the speed of $0.5\omega_0$, a controlled current converter in the rotor circuit should be used, which allows the torque and speed of the machine to be controlled by changing the active component of the rotor current.

3) The combination of the frequency control of the motor with the control of the WRIM using the CCC in the rotor circuit makes it possible to adjust the speed in the range from 0 to $\omega_0$ and implement the required diagram of the movement of the lifting machine.

References

[1] Ostrovlyanchik V Yu et al 2017 *IOP Conference Series: EES* **84** 012030
[2] Ostrovlyanchik V Yu and Popolzin I Yu 2016 *Vestnik KuzSTU* **2(114)** 75–84
[3] Ostrovlyanchik V Yu et al 2018 *IOP Conference Series: EES* **206** 142714
[4] Ostrovlyanchik V Yu and Popolzin I Yu 2018 *IOP Conference Series: MSE* **351** 012017
[5] Ostrovlyanchik V Yu and Popolzin I Yu 2019 *IOP Conference Series: EES* **377** 012041
[6] Ostrovlyanchik V Yu and Popolzin I Yu 2019 *Mining Equipment and Electromechanics* **1** 40-46
[7] Klyuchev V I 2001 *Electric Drive Theory* (M.: Energoatomizdat) p 704
[8] Chernyshev A Yu et al 2011 *AC Drive* (Tomsk: TPU) p 213