Algorithmization of control processes of a hoisting unit induction motor with adjustable resistances in the rotor

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Abstract. The induction electric drive with a rotary station, despite its shortcomings, is still widely used for existing lifting installations. One of the ways to modernize these electric drives is the transition to a digital control system. The article presents a mathematical model of an induction motor when regulating resistances in the rotor circuit. A mathematical model of a logical control system is proposed and an algorithmic structure of a digital logical control system is drawn up, which allows problems of implementing these control systems to be solved.

1. Introduction
Currently, most electric drives of hoisting machines equipped with a wound rotor induction motor (WRIM) have been in operation for more than 30 years. [1] WRIM control systems with resistance regulation in the rotor circuit are implemented on relay-contactor circuits (RCC), which need constant repair due to the great physical and moral wear and tear of the equipment. The use of RCC does not allow the mine hoisting installation to be fully integrated into the mine dispatching system. The use of modern microprocessor tools makes it possible to create a reliable automated control system for the lifting process and quickly rebuild its structure in accordance with the requirements of the production process. [2] In addition, the automation of mine hoists makes it possible to limit, and for skip hoisting machines to completely exclude, the influence of the human factor on the efficiency of work, therefore, both the development of digital control systems for the WRIM of the hoisting unit and the design methods of such devices are currently relevant.

The purpose of this work is to implement a digital logic control system with a mathematical model of WRIM when controlling the IM torque by changing the active resistances in the rotor circuit.

To implement a digital logic control system (DLCS) on microprocessor devices, it is necessary to solve the following tasks:
1. Mathematical description of a wound rotor induction motor when changing the active resistance in the rotor circuit;
2. Mathematical model of the logical control system of the induction motor of the hoisting unit with adjustable resistances in the rotor circuit;
3. Development of the algorithmic structure of the logical control system of the induction motor of the hoisting unit with adjustable resistances in the rotor circuit.

2. Algorithmization of induction motor control processes
WRIM control, when regulating the resistance in the rotor according to certain laws, is provided by the contactor control circuit. Figure 1 shows a schematic power diagram of a WRIM hoisting unit [3]. The regulation of the motor speed and torque is carried out as a function of time with correction for the rotor
current, bypassing the rheostat stages by the contactors of the rotor station (acceleration contactors AC), which leads to a change in the active resistance in the rotor circuit. The machine is started by rearranging the handle of the master controller of drive control CAR drive controller to the position “Forward” (F) or “Backward” (B), the power circuits of the contactor coil F or N are switched. Having closed, the contactors F or B, with normally open contacts, will connect the power circuits of the coil of arc blocking relay of ABR and engine acceleration schemes.

When the position of the KAR controller is from 1 to 5, the ABR with a time delay opens its contact in the coil circuit of the acceleration relay AR1, which, after de-energizing, with a time delay, closes its contact in the AC1 circuit. Contactor AC1 with power contacts will bypass a part of the resistance (first stage) in the rotor circuit and with additional contacts will switch the power supply of the AR2 relay through the closing contact of the current setting relay CSR. If, the first and subsequent stages of rotor resistance are closed, the value of the current in the rotor is higher than the threshold current, then the CSR relay will maintain its contact in the AR circuits until the rotor current decreases. As soon as the CSR contact is open, the power supply of the AR2 relay will stop, the AC2 contactor will close. The connection of the coils of the AC contactors is ensured by closing the normally closed contacts of the AR relay. Switching off the switchgear occurs strictly sequentially, excluding the possibility of their simultaneous shutdown in normal operation.

![Figure 1. Schematic power diagram of a drive with a mine hoist WRIM.](image)

To study an induction motor when changing the active resistance of the rotor and drawing up a structural diagram of the control object, we write, based on the T-shaped equivalent circuit, [4] (shown in figure 2) Kirchhoff’s laws for machine windings and an expression for its electromagnetic moment in vector form.
Figure 2. T-shaped equivalent circuit of WRIM with stepwise change in the rotor active resistance.

Where $\bar{U}_s$ is the complex value of the stator voltage; 
$R_s, x_s$ – active and reactive stator resistance; 
$R_r, x_r$ – reduced active and reactance resistance of the rotor; 
$R_{\mu}, x_{\mu}$ – active and reactive resistance of the magnetizing circuit; 
$R_{d1}, R_{dn}$ – the first and n-th additional resistance of the rotor; 
$KM_{dl}, KM_{dn}$ – the first and nth by-passing key; 
$\bar{I}_s, \bar{I}_r, \bar{I}_\mu$ – complex value of stator current, reduced rotor current, magnetizing circuit current.

The system of equations describing the equivalent circuit [4] will have the form:

$$
\begin{align*}
U_s &= \bar{I}_s R_s + j \bar{I}_s x_s, \\
0 &= \bar{I}_r (R_r + R_{dn}) + j \bar{I}_r x_r, \\
M &= \frac{3}{2} \pi n \frac{L_{\mu}}{L_s L_r - L_{\mu}^2} [\bar{\psi}_s \times \bar{\psi}_r],
\end{align*}
$$

where $L_{\mu}$ is the inductance of magnetization; 
$L_s$ – stator inductance; 
$L_r$ – the rotor inductance.

This system of equations describes the mode of operation of an induction motor without an energy source in the rotor circuit of the motor (the voltage supplied to the rotor is equal to zero $U_R=0$). Having compiled a two-phase model of the machine in the orthogonal coordinate system described in [5], using the approach to compensating the EMF of the windings [6], system (1) can be represented in the form [7]:
\[
\begin{align*}
\epsilon_{SgRi} &= -k_e\omega + U_s \frac{\cos \phi}{k_r}, \\
i_{Ri} &= \epsilon_{SgRi} \cdot \frac{1}{R_{g} + \frac{1}{R_{g} + \frac{1}{T_R p + 1}}}, \\
M &= \frac{3\mu \epsilon}{} \\
\omega &= M - M_c \\
\end{align*}
\]

where \(e_{SgRi}\) – balancing EMF; index S – stator winding; index R – rotor winding; index g – winding on the g-axis of the two-phase model; index i – winding on the i-axis of the two-phase model; \(u_{Sg} = u_s \cos \varphi_s\), where \(\varphi_s = \arctan \frac{X_s}{R_s}\) is the phase shift between the stator current and voltage; \(k_e\) – coefficient of internal feedback on the rotor EMF; \(\omega\) – angular speed of rotation of the rotor; \(k_r\) – rotor coupling coefficients.

The expression for determining the rotor current is presented in the form:

\[
I_{Ri} = \Delta u_{Ri} \cdot \frac{1}{T_R p + 1} = \epsilon_{SgRi} \frac{1}{T_R p + 1} = \epsilon_{SgRi} \frac{1}{R_{g} + \frac{1}{R_{g} + \frac{1}{T_R p + 1}}}
\]

Let us make the replacement \(K = R_e / R_d\), where \(K\) is the ratio of the nominal rotor resistance to the additional one, then we get:

\[
I_{Ri} = \epsilon_{SgRi} \frac{1}{T_R p + 1} = \epsilon_{SgRi} \frac{1}{R_e + \frac{1}{1 + K R_g}}
\]

Substituting expression (4) into the system of equations (2), we obtain the system of equations describing an induction motor with adjustable rotor resistances:

\[
\begin{align*}
\epsilon_{SgRi} &= -k_e\omega + U_s \frac{\cos \phi}{k_r}, \\
i_{Ri} &= \epsilon_{SgRi} \cdot \frac{1}{R_{g} + \frac{1}{T_R p + 1}} = \epsilon_{SgRi} \frac{1}{R_{g} + \frac{1}{T_R p + 1}} = \epsilon_{SgRi} \frac{1}{T_R p + 1} = \epsilon_{SgRi} \frac{1}{R_{g} + \frac{1}{K + 1}}, \\
M &= \frac{3\mu \epsilon}{2R_s} I_{Ri} \frac{U_{Sg}}{T_R p + 1}, \\
\omega &= M - M_c \\
\end{align*}
\]

The change in the value of the additional resistance occurs due to the change in the coefficient \(K\), coming from the logical control system. The system of equations (5) corresponds to the block diagram shown in figure 3.
3. The obtained mathematical model of WRIM allows investigating changes in currents, torque, engine speed when changing the active resistance in the rotor circuit. The development of a logical control system is developed based on the obtained mathematical model for the control object.

4. When designing a logical control system, the important stages are the formal presentation of the control algorithm and the compilation of an algorithmic structural diagram of the logical control, which must satisfy the requirements of uniqueness, completeness and non-contradiction. [8] Often, the results of these stages are not complete and do not have a display in the design documentation, in this regard, there is no unified algorithm for the management process of the hoisting machine WRIM.

To create an algorithmic structure for WRIM control, it is necessary to present the relay-contactor circuit (figure 1) in the form of simple logical operations that are easily implemented in the program code. The principle of operation of logical control systems consists in issuing discrete control signals with two states “0” and “1”, which serve to form the algorithm for the operation of the hoisting unit EF.

The operation AND is carried out by a group of series-connected contacts of the control relays in the output relay winding circuit, and the operation OR is performed by a group of parallel-connected contacts. The delay of the actuation time of the contacts of the electromagnetic relays, if necessary, is implemented by timers.

In general, the model of a logical control system can be represented as a set of boolean formulas:

\[
\begin{align*}
Z_1 &= f(X_1 \ldots X_m, Y_1 \ldots Y_l, \tau_1 \ldots \tau_k) \\
Z_n &= f(X_1 \ldots X_m, Y_1 \ldots Y_l, \tau_1 \ldots \tau_k)
\end{align*}
\]

where \( Y_1 \ldots Y_l \) is a set of discrete signals generated within the system; \( X_1 \ldots X_m \) – set of discrete input signals; \( Z_1 \ldots Z_n \) – a set of discrete input signals; \( \tau_1 \ldots \tau_k \) – time delays present in the system [9].

To work with the values of continuous signals, such as: current, speed, voltage, their values must be brought through the threshold variables to certain logical internal variables that they affect.

\[
\begin{align*}
Y_{i,1} &= \begin{cases} 
1, & \text{if } I(t) \geq I'_{i,1} \\
0, & \text{if } I(t) < I'_{i,1} 
\end{cases} \\
Y_{i,2} &= \begin{cases} 
1, & \text{if } I(t) \geq I'_{i} \\
0, & \text{if } I(t) < I'_{i}
\end{cases}
\end{align*}
\]
where $I_1...I_r$ – a set of continuous input signals, which must be monitored by the system; $I'_1...I'_r$ – a set of boundary values of parameters that determine the achievement of a certain value by a continuous signal.

To start operation and turn on the contactors of the reverse device “Forward” or “Backward”, it is necessary to have readiness (signal $x_{10}$), a signal from the CRT “released” (signal $x_{20}$), a signal from the KAR “Forward” or “Backward” (signals $x_{30}$ and $x_{31}$ respectively), the system of equations will look like this:

$$
\begin{align*}
  z_{10} &= x_{10} x_{20} x_{30}, \\
  z_{11} &= x_{10} x_{20} x_{31}, \\
  y_{10} &= z_{10} + z_{11}.
\end{align*}
$$

(8)

where $z_{10}$ and $z_{11}$ – signals of closing the reverse contactors “Forward” and “Backward”; $y_{10}$ is a merging signal indicating that one of the reverse contactors is on, allowing the acceleration circuit to operate.

Let us compose a logical system of equations for controlling the acceleration contactors of AC. Let us introduce a system of equations for tracking the value of the rotor current, which implements the function of an acceleration current relay (ACR):

$$
\begin{align*}
  y_{20} &= 1, \text{if } I_r(t) > I_{th}, \\
  y_{20} &= 0, \text{if } I_r(t) < I_{th}.
\end{align*}
$$

(9)

where $y_{20}$ is an internal signal allowing the inclusion of the AC; $I_r$ – the current value of the rotor current; $I_{th}$ – rotor current threshold for activating acceleration contactors

The expression for the first stage bypass will look like this:

$$
\begin{align*}
  z_{20} &= y_{10} y_{20} x_{40}, \text{if } T = t,
\end{align*}
$$

(10)

where $x_{40}$...$x_{44}$ – input signals coming from the master controller; $T$ – time delay for activation of acceleration contactors.

Subsequent switch-ons of acceleration contactors are carried out identically, but with the addition of the closing condition of the previous stage. The system of equations for closing the acceleration contactors of the AC will have the form:

$$
\begin{align*}
  z_{21} &= y_{10} y_{20} x_{41} z_{20}, \text{if } T = t, \\
  z_{22} &= y_{10} y_{20} x_{42} z_{21}, \text{if } T = t, \\
  z_{23} &= y_{10} y_{20} x_{43} z_{22}, \text{if } T = t, \\
  z_{24} &= y_{10} y_{20} x_{44} z_{23}, \text{if } T = t,
\end{align*}
$$

(11)

A multiplexer is used to generate a change in the value of the active resistance in the rotor circuit during mathematical modeling. The multiplexer is a link that connects the DLCS with the OA, providing interconnection between the DLCS and the power part of the rotor controlled circuit. A certain state of logical signals corresponds to the values of $K$, ranging from 0 to 1.

Expressions (8-11) define the logical control system of hoisting units with WRIM. According to the compiled expressions, the final states of the system can be selected, and the main events for the transition from the states to be set.

The algorithmic structure of the logical control of hoisting unit together with the control object (WRIM) is shown in figure 4.
Figure 4. Algorithmic structure of the digital system of hoisting unit logical control together with WRIM when regulating resistances in the rotor circuit.

This DLCS provides speed control as a function of time with correction for the rotor current. The speed control of the hoisting unit is provided by changing the rotor current of the induction motor, in proportion to the change in torque, by changing the active resistance in the rotor circuit. The simplest logical elements, timers and memory elements (triggers) are used in the DLCS.

The use of timers for each stage allows a smoother motor acceleration at various loads to be set up, as it allows each contactor to be switched on with an individual time delay. The use of memory elements allows the operation of the system not to be disrupted when external influences change (excess of the rotor current of the threshold value, does not disconnect already closed acceleration contactors). This algorithmic structure is designed to implement the corresponding algorithm and software implementation of the DLCS hoisting units.

3. Conclusion

As a result, several conclusions can be drawn:

1. The mathematical model of WRIM when changing the active resistance in the rotor circuit is developed;
2. The mathematical model and algorithmic structure of the logical control system of an induction motor of a hoisting unit with adjustable resistances in the rotor circuit is developed;
3. Mathematical models make it possible not only to implement the DLCS, but also to obtain design methods and setting up digital electric drives;
4. The implementation of the DLCS makes it possible to increase the reliability and productivity of a hoisting unit, to adjust the control system without any changes in the hardware.

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