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INVESTIGATION OF AN ELECTRIC DRIVE WITH REPEATED SHORT-DOWN MODES OF OPERATION WITH FREQUENCY BY DEPENDENT INDUCTION RESISTORS

Abstract: *Nowadays, asynchronous motors (AM) occupy not less than 80% of all types of electric motors involved in industry and everyday life. As is known, among such type of electric motors there are AM with short-circuit rotor (ShCR) and a phase rotor (PhR). Advantages of AM with PhR are in having better starting properties than AM from ShCR. The disadvantage of AM with PhR is the large mass-dimensional characteristics associated with the limitation of starting currents.*

Keywords: *asynchronous motors, electric motors, short-circuit rotor, phase rotor*

Introduction

In order to reduce the starting current in the AM with PhR, a widespread application has been made to switch on the active resistance in the circle of the winding of the PhR resistor with a smooth or step contact switch. Typically, in such electric drive systems (EDS), resistors are connected to phase windings through brushes and contact rings located on the shaft AM. When working in a nominal mode of AM, the resistor is switched off, and the rotor winding phase is shortened [1-4].

During the exploitation of such systems, it appeared that the contact equipment has low reliability, and large mass-dimensional characteristics reduce the efficiency and complicate their operation in difficult starting conditions. One of the ways to solve this problem is to turn the inductor resistor into the rotor circle (IR) [3, 4]. Figure 1 shows the start of AM with PhR of the type SMR250M4 of the electric drive of the drawing state with the trigger resistors (fig. 1a) and IR (fig. 1b).

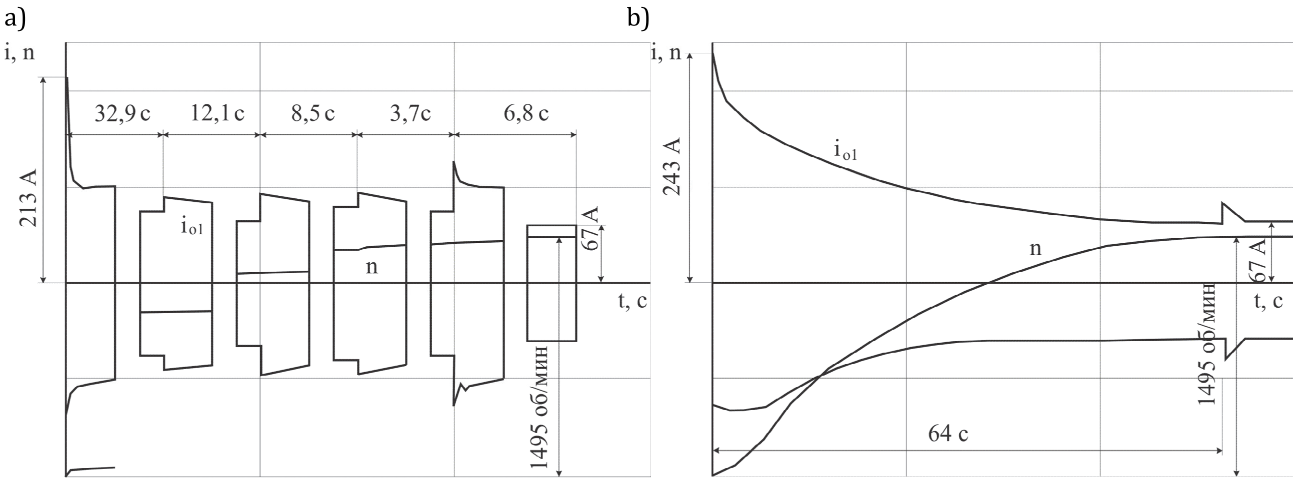


FIGURE 1. *Startup Oscilloscope AM SMR250M4 starting resistor (a); Startup Oscilloscope AM SMR250M4 with i IR (b)*

On figure 1, it is clear that the maximum current value is 213 A and the engine is started by switching the resistors. When starting AM with IR, the maximum current value is 243 A, which exceeds 14%. The start of the AM with IR allows smooth start-up, reducing the number of starting equipment and increasing the resistor. The main disadvantage of IR is the need to use a large amount of copper for an IR coil and to design IR taking into account electromagnetic parameters of AM.

Formulating the purpose of the study

The objective of the study is the development of the mathematical model of IR for optimization the electromagnetic parameters when powered from high frequency voltage. The objective of the study is to reduce the amount of copper in the IR and to develop a natural field with the ability to control the electromagnetic parameters of IR.

Main part

The main designs of the IR are shown on the figure 2. The simplest IR design is a coil wound on a steel cylinder, a rod or other form of cores that is covered by a ferromagnetic screen. Further improvements to the IR design can be achieved by increasing the current frequency in the coil. This will reduce the cost of copper and unify IR. In this case, the IR can be developed not for each individual engine, but for the creation of a universal IR, the electromagnetic parameters of which are chosen by changing the frequency of the current in the coil. To solve this problem, a mathematical IR model was developed, which is based on the Maxwell equations in the three-dimensional setting taking into account the IR coil.

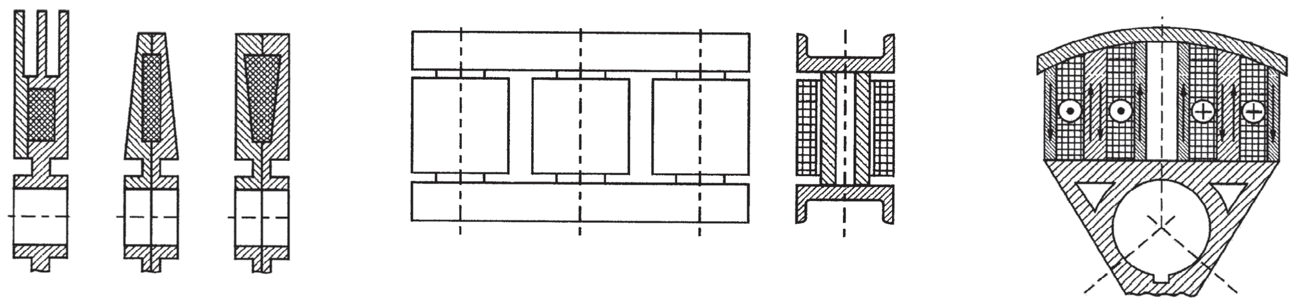


***FIGURE 2.** Existing variants of execution of IR in the form of: a) IR in the form of empty massive ferromagnetic disks; b) IR of rod type; c) IR tooth structure*

Formula for three-dimensional field problem with respect to a vector magnetic potential describing an electromagnetic field in an IR in the Cartesian coordinate system has the form:

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial A}{\partial z}\right)+\sigma\frac{\partial A}{\partial t}=J \qquad (1)$$

where:

A – magnetic vector potential;

σ – specific conductivity of the medium;

x, y, z – area coordinates;

J – current density.

The current density in the winding IR is determined by the expression

$$J=\frac{N_{Wr}i}{S_{Wr}} \qquad (2)$$

where:

N_{Wr} – number of turns of the winding phase of the IR;

S_{Wr} – the area occupied by the coil.

The voltage is calculated in this way:

$$u_{02} = r_{02} i_{02} + \frac{N_{Wr} l}{S_{Wr}} \int_{S_{Wr}} \frac{\partial A}{\partial t} dS_{Wr} \tag{3}$$

where:

r_{02} – active resistance in the coil;

i_{02} – current in the coil;

N_{Wr} – number of turns of IR coil;

l – length of turn.

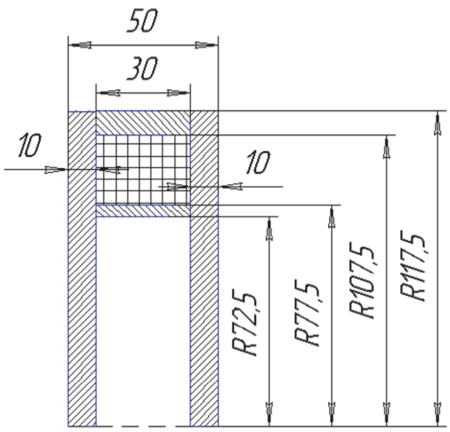
Then the complete three-dimensional mathematical model of IR in the field of formulation will look like [4]:

$$-\nabla\left(\nu \nabla A\right) = \begin{Bmatrix} 0 & - \text{ in airspace} \\ -\sigma \dfrac{\partial A}{\partial t} & - \text{ in IR screen} \\ \dfrac{N_{Wr} i_{02}}{S_{Wr}} & - \text{ in IR coil} \end{Bmatrix} \tag{4}$$

As is known, in the presence of massive ferromagnetic elements in the IR, electromagnetic parameters change nonlinearly, depending on the value of the applied voltage, the frequency of current in the windings of the rotor, the magnetic properties of the core and screen, geometric sizes, etc.

We accept the assumption that in the IR, which is investigated, cooling regimes are not taken into account. The virtual model is executed according to the geometric dimensions of the "classical" design of the IR for the AM type of MTB-412-8, which is depicted on figure 3a. The IR consists of a cylindrical part, in which there is a copper coil, and side plates of square shape. Initial number of turns of the winding is $W = 50$. The massive elements of the design are made of steel grade P.3. The design of the IR under consideration, with massive plates, is completely shielded, and its shape of the radial cross-section has the form of a rectangle.

After triangulating IR with the help of the automatic generator of a finite element network (AGFEN), a three-dimensional discrete IR model was obtained (fig. 3b).



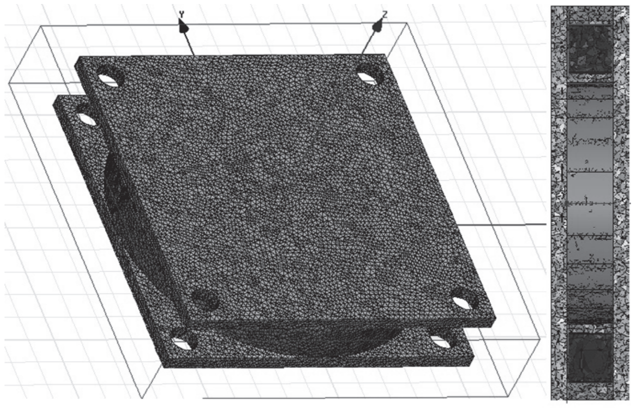


***FIGURE 3**. Geometric dimensions of the classical construction of IR (a); discrete IR model and cross section of IR with AGFEN (automatic generator of a finite element network) (b)*

The calculation of the model is carried out at a voltage of 20 to 200 volts and a frequency of 50, 130, 200, 350 Hz. The calculation was made in increments of 20 W for each of the frequency ranges. Table 1 shows the simulation results. As can be seen from the table data, the resistance of the IR increases with the increase in the frequency of supply voltage. So, there are all the bases for reducing the coils of the IR coil. At a frequency of 130 Hz and the number of turns W = 25, the resistive characteristics of the rheostat remained at the level that occurs at a voltage of 50 Hz and the number of turns: W = 50 (fig. 4).

TABLE 1. *Simulation results*

F = 50 Hz *W* = 50		*F* = 130 Hz *W* = 25		*F* = 200 Hz *W* = 50		*F* = 350 Hz *W* = 50	
U (B)	*Z* (ohm)	*U* (B)	*Z* (ohm)	*U* (B)	*Z* (ohm)	*U* (B)	*Z* (ohm)
19.9	17.1	19.9	15.4	19.9	71.1	20.0	110.9
39.5	4.1	39.7	5.0	39.8	88.4	40.0	128.9
59.2	1.2	59.0	1.3	59.8	99.6	60.0	146.2
77.6	0.8	78.3	0.8	79.8	88.6	79.9	159.8
95.0	0.6	97.3	0.6	99.7	76.7	99.9	166.5
111.7	0.5	114.9	0.5	119.7	39.9	119.8	171.1
128.42	0.41	130.97	0.4	139.3	19.9	139.8	162.55
145	0.33	146.17	0.31	158.83	11.83	159.8	149.34
158.8	0.28	163.65	0.27	177.3	7.95	179.8	125.7
176.15	0.24	178.32	0.24	194.5	6.13	199.8	87.63
193.63	0.22	194.87	0.218	213.3	5.05	219.7	56.3

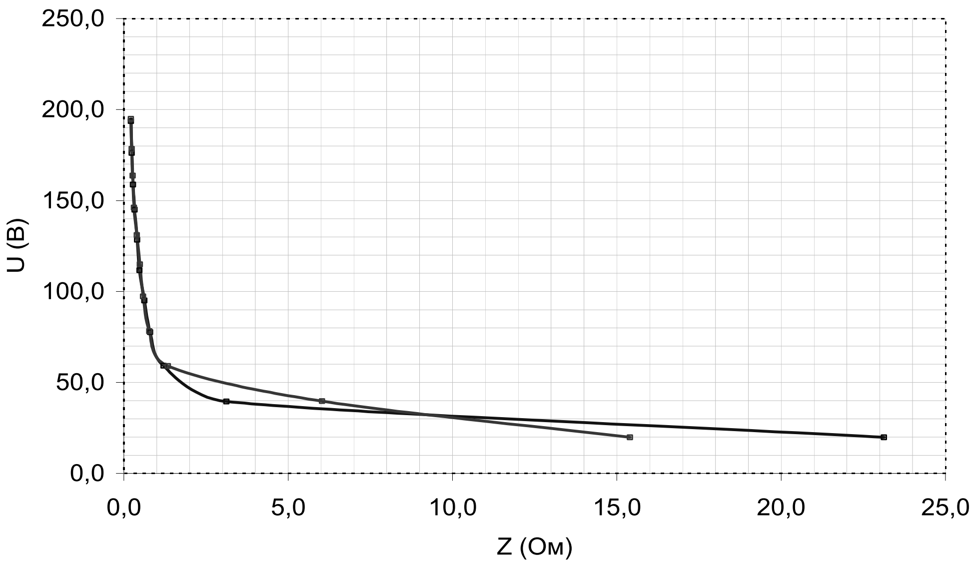


FIGURE 4. *The dependence of the resistance of the IR on the supply voltage with a frequency of 50 Hz and 130 Hz with the number of turns of the coil 50 and 25, respectively*

As a result of the simulation and calculations, it can be concluded that the increase in the frequency of supply voltage in the IR leads to a reduction in the number of turns in the coil and a decrease in its weight from 2 kg to 1.2 kg, so, almost twice. As it can be seen from the results of simulation, namely resistive indicators, further increase of frequency allows to reduce the number of turns of the coil several times. Thus, according to the mathematical models of IR, realized in the nonlinear software environment, improvement of the design of IR in the direction of reduction of mass-size indicators is technically feasible and economically feasible. The natural field system in this case will include AM, frequency converter (FC) and IR. The frequency converter consists of a rectifier, a DC link and an autonomous inverter.

For a joint study of AM with IR, a mathematical model has been developed, including a AM transducer and IR (fig. 5).

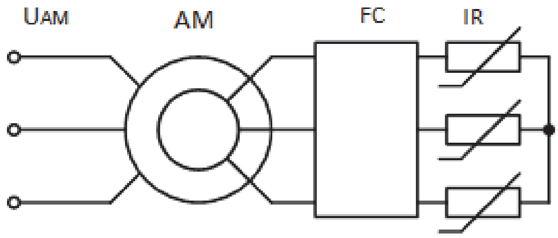


***FIGURE 5**. Flow chart of the natural field with IR and frequency converter*

Processes in charged stator and rotor cells are not considered in this AM model, and differential equations of the equilibrium voltage are written for circuits AB and BC [4]:

$$\left.\begin{array}{c} [u]=[r][i]+\left([L(\gamma,i)]+[D(\gamma,i)]\right)\dfrac{d[i]}{dt}+[G(\gamma,i)]\dfrac{d\gamma}{dt}p[i] \\ \dfrac{d\omega_2}{dt}=\dfrac{M-M_C}{J} \\ \dfrac{d\gamma}{dt}=\omega_2 \\ -\nabla(\nu\nabla A)=\left\{\begin{array}{l} -\sigma\dfrac{\partial A}{\partial t}-\text{in IR screen} \\ \dfrac{N_{Wr}i_{02}}{S_{Wr}}-\text{in IR coil} \end{array}\right\} \end{array}\right\} \tag{5}$$

where:

i – instantaneous values of currents in phases;

u – the instantaneous values of linear voltages;

r – phase active supports;

γ – rotation angle relative to stator;

p – the number of pairs of poles;

ω_2 – angular rotor speed;

J – inertia moment;

M_C – static load moment.

Matrix $[G(\gamma,i)]$ is determined by matrix differentiation $[L(\gamma,i)]$ by the rotor angle of rotation, a $[D(\gamma,i)]$ by current: $[G(\gamma,i)]=\dfrac{\partial[L(\gamma,i)]}{\partial\gamma}$; $[D(\gamma,i)]=\dfrac{\partial[L(\gamma,i)]}{\partial i}$.

The matrixes in the expanded form are presented below:

$$[i]=\begin{bmatrix} i_A \\ i_B \\ i_a \\ i_b \end{bmatrix}$$

$$[u]=\begin{bmatrix} u_{AB} \\ u_{BC} \\ u_{ab} \\ u_{bc} \end{bmatrix}$$

$$[r]=\begin{bmatrix} r_A & -r_B & 0 & 0 \\ r_C & (r_B+r_C) & 0 & 0 \\ 0 & 0 & r_a+r_{IP} & -r_b+r_{IP} \\ 0 & 0 & r_c+r_{IP} & -(r_b+r_c+2r_{IP}) \end{bmatrix}$$

$$[L(\gamma,i)]=\begin{bmatrix} L_s(i) & -L_s(i) & L_\mu(i)C_1 & L_\mu(i)C_2 \\ L_s(i) & 2L_s(i) & L_\mu(i)C_2 & 2L_\mu(i)C_3 \\ L_\mu(i)C_2 & -L_\mu(i)C_1 & L_r(i) & -L_r(i) \\ L_\mu(i)C_1 & 2L_\mu(i)C_3 & L_r(i) & 2L_r(i) \end{bmatrix}$$

$$[G(\gamma,i)]=\begin{bmatrix} 0 & 0 & L_\mu(i)C_4 & -L_\mu(i)C_5 \\ 0 & 0 & L_\mu(i)C_5 & 2L_\mu(i)C_6 \\ L_\mu(i)C_5 & -L_\mu(i)C_4 & 0 & 0 \\ L_\mu(i)C_4 & 2L_\mu(i)C_6 & 0 & 0 \end{bmatrix}$$

where

$L_s(i)=L_{\sigma s}+L_\mu(i)$ – complete stator winding inductance;

$L_r(i)=L_{\sigma r}+L_\mu(i)$ – full inductance of the rotor winding;

$L_{\sigma s}, L_{\sigma r}$ – the scattering inductance of the stator and the rotor winding;

$L_\mu(i)$ – inductance of interinduction.

The periodic coefficients in the matrices are determined as

$$C_1=\cos(p\gamma)-\sqrt{3}\sin(p\gamma);\quad C_2=\cos(p\gamma)+\sqrt{3}\sin(p\gamma);\quad C_3=\cos(p\gamma)$$

$$C_4=\sin(p\gamma)+\sqrt{3}\cos(p\gamma);\quad C_5=\sin(p\gamma)-\sqrt{3}\cos(p\gamma);\quad C_6=\sin(p\gamma)$$

The electromagnetic moment is determined by the formula:

$$M=L_\mu(i)p\Big(\big[(2i_a+i_b)i_A+2(i_a+i_b)i_B\big]\sin(p\gamma)+(i_Ai_b-i_Bi_a)\sqrt{3}\cos(p\gamma)\Big)$$

The Ansys student version was used to solve these equations. The model scheme is shown on figure 6. The model consists of a AM represented by circle equations, a frequency converter which includes an uncontrolled rectifier, a DC link, and an inverter. The induction resistor is represented by the active resistance of the coil and the scattering inductance. The electromagnetic parameters of the IR coil screen are calculated by the field method in a three-dimensional formulation at each time step of the calculation of the transition process.

The simulation is done for the crane AT MTB-412-8 ($P_{\text{ном}}$ = 22 kW; $n_{\text{ном}}$ = 720 r/min; cosφ = 0.69; η = 83%; $I_{1\text{ном}}$ = 58 A, J = 3 Kgm^2) when winding a star. The frequency of the supply voltage in the rotor varied from 200 Hz to 2 Hz at a time interval of 0-2 s in increments of 10 Hz. Based on the results of the study, graphs of transient rotor current, electromagnetic moment, velocity, as well as the graph of changes in the IR bearers in the rotor, based on the frequency of the power supply, were constructed (fig. 7).

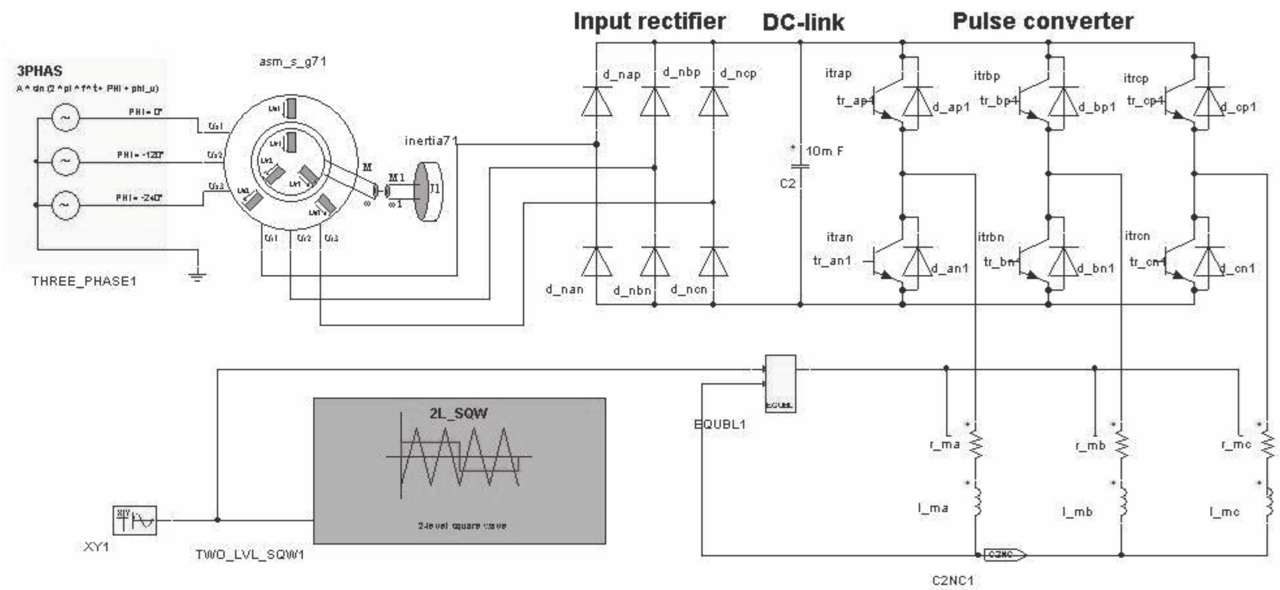


Figure 6. *Simulated model AM with IR*

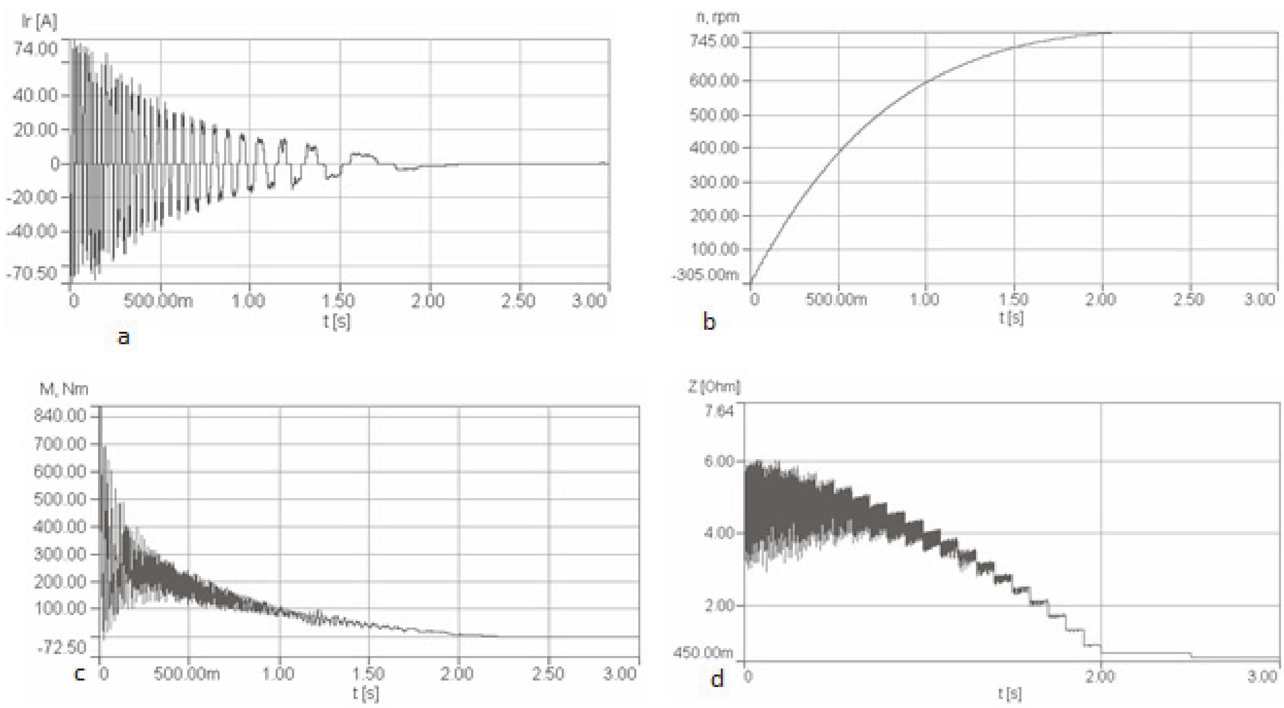


Figure 7*. Starting AM with IR from the network*

From the figure 7 it is seen that the frequency converter changes the frequency of the current (fig. 7a) in the rotor circle, depending on the speed of rotation of the rotor (fig. 7b), the engine moment has an excavator form (fig. 7c), the supports of the rotor vary with given dependence (fig. 7d).

Conclusions and future prospective researches

Investigation of electromagnetic parameters of IR powered by the frequency converter showed that an increase in the frequency of the supply voltage can reduce the number of turns in the IR coil twice, with electromagnetic parameters corresponding to the parameters of the IR in the feed on the rotor windings.

From the results of the mathematical modeling of the natural field, it is established that the change of the frequency of the supply current in the rotor circuit of the AT MTB-412-8 from 2 Hz to 200 Hz leads to the expansion of the resistance range of the IR, which is 0.45-7.6 ohms, and allows to limit the magnitude of the starting currents of blood pressure.

In further researches, it is necessary to ensure the automatic control of the IR depending on the mode of operation.

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