Electric drive for conveyor burning-machines

Vyacheslav Lobov

PhD, Associate professor
Computer Science, Automation and Control Systems department
State Higher Educational Institution
"Kryvyi Rih National University",
Ukraine

Karina Lobova

PhD student of Automation and Control Systems department
State Higher Educational Institution
"Kryvyi Rih National University",
Ukraine

Vladislav Malov

PhD student of Automation and Control Systems department
State Higher Educational Institution
"Kryvyi Rih National University",
Ukraine

Abstract

Article introduces electric drive for conveyor burning-machines, which includes asynchronous electric motor, where in stator and rotor circuits there used resistors and thyristors for purposes of control, forming a power converter circuit with resistor-thyristor modules. Meeting the technical requirements applied to industrial mechanisms of this type, an analytical method of determination of the voltage and current during resistor-thyristor modules of the asynchronous electric motor are in charge was developed. Calculation results showed, that flow of the transition process during modeling depends on type of the modules power circuit and type of control over them. The most efficient way to change the voltage and current of the electric motor is the thyristor opening-angle adjustment, in other words – by changing equivalent resistance values, which are a part of resistor-thyristor modules. Scientific novelty is that the proposed method of calculation gives a chance to de-

termine the magnitude of voltage and current, which is used to determine the magnitude of transition current and operating torque of the electric motor. This method allows choosing the most efficient converter power circuits with resistor-thyristor modules and find the simplest laws to control electric motor of the conveyor burning-machine, that is why it has practical meaning.
Key words: CONVEYOR BURNING-MACHINE, ELECTRIC DRIVE, ASYNCHRONOUS ELECTRIC MOTOR, CONVERTER, RESISTOR-THYRISTOR MODULE, VOLTAGE, CURRENT, THYRISTOR OPENING-ANGLE

Introduction

Manufacturing process requires provision of the different work-modes of conveyor burning-machines. Relatively simple parametrical methods of control of the asynchronous electric drive with phase control (AEPC), which uses thyristor voltage regulators (TVR) or frequency converters or converters based on resistor-thyristor modules (RTM), included in the stator and rotor circuits of the asynchronous electric motor (AM) are the most widespread in practice. They successfully can be used during exploitation of the electric drive of burning-machine [1-12].

Formulation of the problem

The choice of the control power circuit of the AM determines possibilities of the AEPC of electric drive of burning-machine in case of realization of required work-modes of the technological object, since these types of electric drives is essentially nonlinear systems. Their AM, RTM and other elements of the control power circuit represent the elements with nonlinear static characteristics. For example, magnetization curve of the AM is nonlinear and ambiguous; electric motor's parameters nonlinearly depend on currents, rotation velocity, temperature, etc. Similar nonlinearity contains in other control circuit elements. Nonlinear elements that have different and difficult characteristics cause considerable difficulties in the mathematical description and research of the asynchronous electric drives for burning-machines [1, 4-7].

The discrete nature of change of the resistors RTM while parametrical control, leads to different equivalent circuits of the AM, which causes some difficulties in calculating the values of voltage and current that flowing through machine windings and elements of the switches. These difficulties are intensified during research of the starting, braking, energy, quasi-frequency and other work-modes of the electric drive, when their implementation there required to adjust the angle α and porosity γ. Change of the α leads to different duration of current flow through windings of the stator and AM rotor. At its certain value current pulse in one phase of the electric motor stopps before the thyristor opens in the other phase, so there may be time intervals where the current in the load has an insignificant value. Besides, work of valves in the stator commutator (SC) differs from work of the valves in rotor commutator (RC), because amplitude and frequency of EMF of the rotor changes at start-up and braking. At the same time amplitude and frequency of the power source stays almost constant, rotation EMF of rotor of the AM depends on values of sliding and static torque on the shaft of the electric machine [2-5].

Performance of the engineering calculations often causes selection of the parameters of elements of the power circuit, therefore one must determine the values of voltage on these components and the windings of AM, and the values of currents flowing in them. Values of the voltage and current may been calculated in analytical way, taking into account the above factors, which may lead to a system of nonlinear differential equations that are non-convenient in case of performing calculations. Their determination is also possible when using mathematical modeling methods and computer or graphical methods [1, 10-12].

Material and research results

Using proposed in [2] generalized scheme of parametric control of the AM with RTM, we are going to determine voltage and current, which flow through windings of the AM and RTM analytically. To receive analytic expressions the following assumptions are accepted:

1) real AM is replaced by its idealized version, where magnetic circuit is not saturated, there is no high harmonic magnetizing force, inductive resistance of the scattering does not depend on the rotor position, air gap is uniform, hysteresis and losses in the steel are not considered;

2) controlled valves of the switches possess ideal current - voltage characteristics;

3) current ripples with slip frequency and velocity fluctuations are absent;

4) current switching from one valve to another is accepted instant.

Accepted offers allow to exclude secondary phenomenon, get enough accurate and quite acceptable analytical expressions for engineering calculations, determining voltage and current values on the elements of the circuit and windings of the AM.

For generalized scheme of parametric control of the AM [2] voltage at the stator clamps is:

$$U_{ss}=U_l K_{1m} e^{-j(\varphi_1-\theta_e)}$$

where U_l – linear voltage of the power source.

Stator current in A – phase (line 1) is determined by stator voltage:

$$I_A=\frac{U_l K_{1m}}{Z_e} e^{-j(\varphi_1-\theta_e)} \quad (1)$$

Equivalent resistance, for example for $S_{12}Z_0\, r_{32}$ scheme depends on resistance of the stator circuits: $Z_1=(r_A+r_{2A})+jX_A$, rotor circuits: $Z_{2S}=(r_a+r_{2a})+jX_A$, magnetization branches: $Z_M=R_M+jX_M$ and is defined as follows:

$$Z_e=Z_1+\frac{Z_M Z_{2S}}{Z_M+Z_{2S}} \quad (2)$$

From equation (2), neglecting R_M there follows:

$$Z_e=\left[(r_a+r_{2a})+\left(\frac{r'_a+r'_{2a}}{S}\right)\frac{tg^2\theta_2}{\tau_2^2+(1+\tau_2)tg^2\theta_2}\right]+j\left[X_A+X'_a\frac{\tau_2+tg^2\theta_2}{\tau_2^2+tg^2\theta_2(1+\tau_2)^2}\right] \quad (3)$$

The real part R_e of equivalent resistance of the $S_{12}Z_0\, r_{32}$ scheme opposed to imaginary part X_e and as it seen from equation (3), depends on thyristors opening angle α and AM slip.

The minimum value of the real part of equivalent resistance is achieved with slide value close to one, maximum value – with nominal slide of the electric motor S_H [2]. Imaginary part of the equivalent resistance is non-considerably depends on α. The phase angle of the rotor circuit impedance is equal:

$$tg\theta_2=\frac{X'_a}{r'_a+r'_{2a}} \quad (4)$$

Phase angle of the rotor circuit equivalent resistance, which follows from expression (4), depends on RTM thyristors opening angle α on the one hand and the slide of the AM on another. Besides that, this angle affected by equivalent value of the RTM resistance of the stator and rotor, decrease of which causes increase of the phase angle. The phase angle of the equivalent resistance Z_e for $S_{12}\, Z_0\, r_{32}$ scheme is determined by the scattering coefficients of the stator τ_1 and rotor $-\tau_2$:

$$tg\theta_e=\frac{X_A\left[\tau_2^2(1+\tau_2)^2 tg^2\theta_2\right]+X'_a\left[\tau_2^2+(1+t_2)tg^2\theta_2\right]}{(r_A+r_{2A})\left[\tau_2^2(1+\tau_2)^2 tg^2\theta_2\right]+\left[(r'_a+r'_{2a})+tg^2\theta_2\right]/S} \quad (5)$$

Taking into account (5) and, neglecting R_M, expression (1) is:

$$I_A=\frac{U_л K_{1m}e^{-j(\varphi_1-\theta_e)}\left[tg^2\theta_2(1+\tau_2)^2+\tau_2^2\right]}{(r_A+r_{2A})\left[\tau_2^2+tg^2\theta_2(1+\tau_2)^2+(r'_a+r'_{2a})tg^2\theta_2\right]+j\left\{x_A\left[\tau_2^2+tg^2\theta_2(1+\tau_2)^2\right]+x'_a\left[\tau_2^2+tg^2\theta_2(1+\tau_2)^2\right]\right\}} \quad (6)$$

EMF of the stator and presented EMF of the rotor of AM are equal, both depend on current of the stator, complex resistance of the magnetization branches and given to the stator resistance of the rotor. Taking into account (1), we will obtain a reduced EMF of the rotor:

$$e'_r=U_л K_{1m}e^{-j(\varphi_1-\theta_e)}\frac{z_M z_{2s}}{z_M z_1+(z_M+z_1)z_{2s}}=$$

$$=U_л K_{1m}e^{-j(\varphi_1-\theta_e)}\frac{\frac{r'_a+r'_{2a}}{s}\{[(r_A+r'_{2a})+\left(\frac{r'_a+r'_{2a}}{s}\right)+(x_A+x'_a)+\tau_1(r'_a+r'_{2a})+}{\left[(1+\tau_2)(r_A+r'_{2a})+(1+\tau_1)\left(\frac{r'_a+r'_{2a}}{s}\right)\right]^2+}$$

$$\frac{+\tau_2(r_A+r_{2A})\left(\frac{2x'_a-r'_a-r'_{2a}}{x'_a}\right)]+[(r_A+r_{2A})+\left(\frac{r'_a+r'_{2a}}{s}\right)-(x_A+x'_a)+\tau_1(r'_a+r'_{2a}-x'_a)+\tau_2(r'_A+r'_{2a})\frac{x'_a+r'_a+r'_{2a}}{x'_a}}{+\left\{\left[x'_a+(1+_1)x'_a\right]-\left[\frac{(r_A+r_{2A})r'_a\tau_2}{s}\right]\right\}^2} \quad (7)$$

The induced current of the rotor A – phase (line 1) is equal to:

$$I'_a = U_л K_{1m} e^{-j(\varphi_1-\theta_e)} \frac{z_M}{z_M z_1 + (z_M + z_1) z_{2s}} =$$

$$= U_л K_{1m} e^{-j(\varphi_1-\theta_e)} \frac{\left[(1+\tau_2)(r_A + r_{2A}) + (1+\tau_1)\left(\frac{r'_a + r'_{2a}}{s}\right)\right] - j\left[x_A + (1+\tau_1)x'_a - \frac{(r_A + r_{2A})(r'_a + r'_{2a})x'_a\tau_2}{s}\right]}{\left[(1+\tau_2)(r_A + r_{2A}) + (1+\tau_1)\left(\frac{r'_a + r'_{2a}}{s}\right)\right]^2 + \left[x_A + (1+\tau_1)x'_a - \frac{(r_A + r_{2A})(r'_a + r'_{2a})x'_a\tau_2}{s}\right]^2} \quad (8)$$

Values of the equivalent resistance r_{2A} and r_{2a}, which are art of equation (6 – 8), are determined by switching functions [3]. As it follows from the received expressions, currents and EMF of the stator and rotor depends on voltage, RTM parameters and asynchronous machine. Value of the stator current decreases with rising of the equivalent resistance of the RTM. With increase of the rotor complex resistance, given to stator, reduced current of the rotor decreases.

Equation (5 – 8) allows choosing parameters for elements of the circuits, which are part of different switches. They may be used to calculate the mechanical, velocity and other characteristics of asynchronous electric drive. When operating on rotor circuit via switches, which have a power circuit types $Z_K R_{22}$, $Z_K R_{32}$, $Z_0 R_{32}$, $Z_0 R_{33}$ and other circuits, the voltage and currents of the electric motor can be calculated using analytical expressions given in table 1. This expressions taking into account the operating conditions of valves while regulating opening angle of thyristors, changing the parameters of the RTM and AM.

Phase current of the AM, which is calculated using expressions (8) and table 1, has a good convergence and difference between them is about 5%. Fig. 1 shows the calculated and experimental waveform of the rotor currents I_a and voltage on resistor-thyristor modules U_{RTM} for $S_{13}Z_K R_{32}$ schemas. The phase current of the AD reaches its maximum value with angle α = 50° (fig. 1, d, h). This is because inverter thyristors most of time operate on the linear voltage of the rotor, and current hardly flows through

Table 1. Voltages and currents of the AM, calculated using analytical expressions for boundary mode 2/3π ≤α≥ π

Plot limits	Phase angle	Rotor phase current
$2/3\pi\varphi_3 \le x \le \alpha$	$\varphi_1 = arg\frac{\omega L}{R_r + r'_a}$	$\frac{E_m(\omega)\sin(x-\varphi_1)}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}}$
$\alpha_r - 2/3\pi \le x \le \pi/3+\varphi_3$	$\varphi_2 = arg\frac{\omega L}{R_r + r'_a}$	$\frac{\sqrt{3}E_m(\omega)\sin\left(x - \frac{\pi}{6} - \varphi_2\right)}{\sqrt{(R_r + 4r'_a)^2 + (\omega L)^2}} + \frac{E_m(\omega)\sin(\alpha_r - 2/3\pi - \varphi_1)}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}} e^{-\frac{(R_r+4r'_a)}{L}t}$
$\pi/3+\varphi_3 \le x \le \alpha_r - \pi/3$	φ_1	$\frac{E_m(\omega)\sin(x-\varphi_1)}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}} + \frac{\sqrt{3}E_m(\omega)\sin\pi/3}{\sqrt{(R_r + 4r'_a)^2 + (\omega L)^2}} e^{-\frac{(R_r+4r'_a)}{L}t}$
$\alpha_r - \pi/3 \le x \le 2/3\pi+\varphi_2$	φ_2	$\frac{\sqrt{3}E_m(\omega)\sin(x-\varphi_2+\pi/6)}{\sqrt{(R_r + 4r'_a)^2 + (\omega L)^2}} + \frac{E_m(\omega)\sin\left(\frac{\alpha_r-\pi}{3}+\varphi_1\right)}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}} e^{-\frac{(R_r+4r'_a)}{L}t}$
$2/3\pi+\varphi_2 \le x \le \alpha_r$	φ_1	$\frac{E_m(\omega)\sin(x-\varphi_1)}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}} + \frac{\sqrt{3}E_m(\omega)\sin 2/3\pi}{\sqrt{(R_r + 4r'_a)^2 + (\omega L)^2}} e^{-\frac{(R_r+4r'_a)}{L}t}$
$\alpha_r \le x \le \pi+\varphi_1$	$\varphi_3 = arctg\frac{3\omega L}{R_r + 3r'_a}$	$\frac{E_m(\omega)\sin(x-\varphi_3)}{\sqrt{(R_r + 3r'_a)^2 + (\omega L)^2}} + \frac{E_m(\omega)\sin\pi}{\sqrt{(R_r + r'_a)^2 + (\omega L)^2}} e^{-\frac{(R_r+3r'_a)}{L}t}$

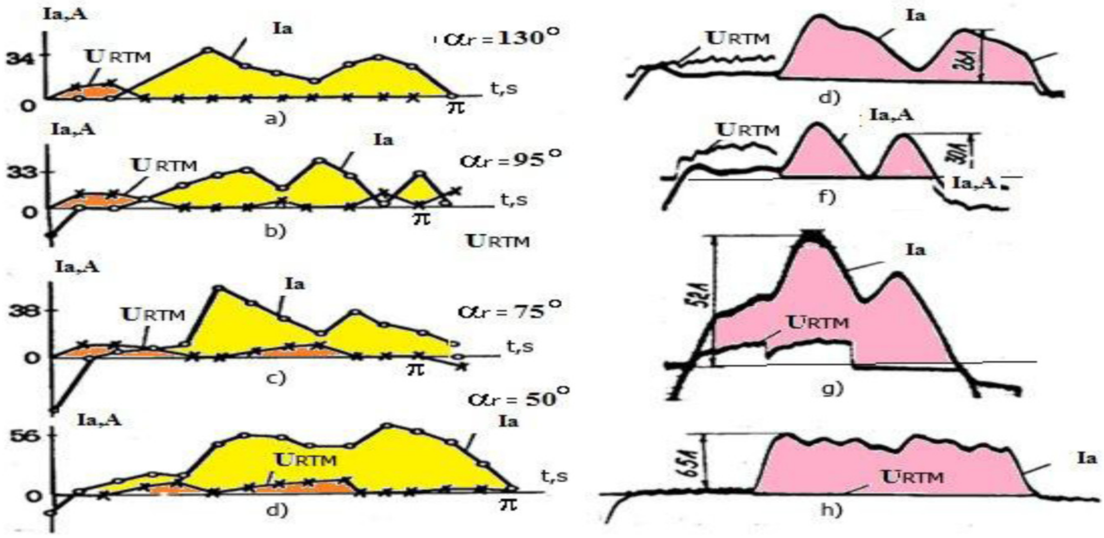


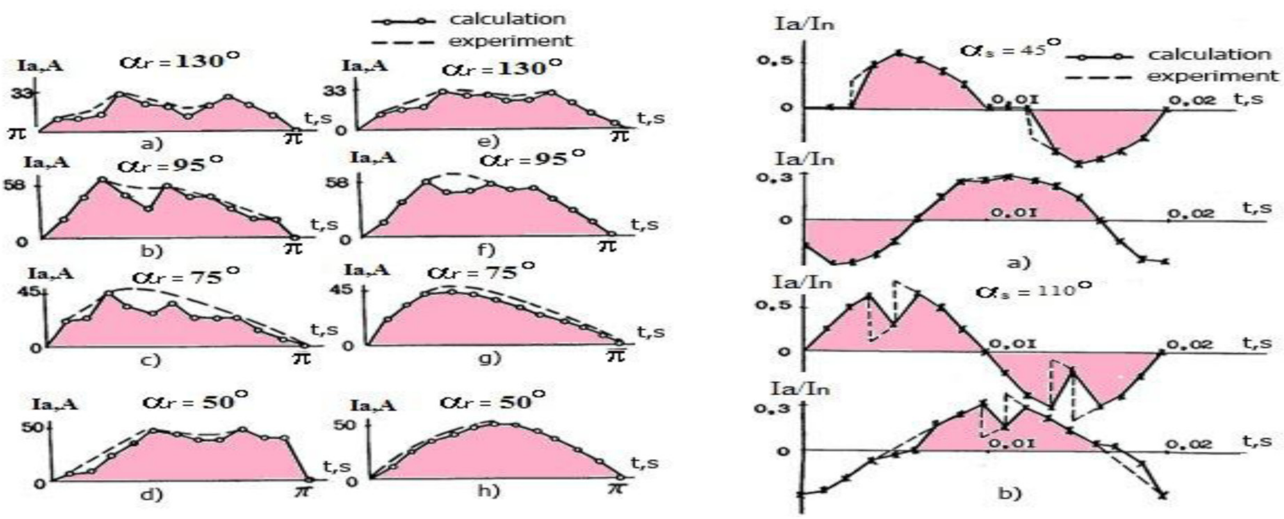
Figure 1. Oscillograms of rotor currents (Ia) and voltages (U_{RTM}) on RTM for the $S_{13}Z_KR_{32}$ scheme (a-d) - calculation; (e-h) – experiment.

RTM resistors. Wherein RC thyristors operates in groups of two or three. With large opening angles of the thyristors ($\alpha_r \geq 130°$), value of the rotor phase current noticeably reduces (fig. 1, a, e), because valves operate on their own and most of time rotor current flows through RTM resistors, wherein the line currents of the rotor have considerably smaller size.

After modeling of the static work-modes of the AM on computer and received experimental data we concluded, that rms value of the phase current of the rotor with change of the equivalent value of RTM resistors in $S_{11}Z_kR_{32}$ schemas is 25% less than rms value of the phase current.

This value is obtained by taking into account changes in the value of the inductive reactance of the rotor circuit. When adjusting the thyristors opening angle α_r from 0° to 60 ° average value of the phase current of the rotor is 1.5 times more as compared with modes of valve switch (pic. 2. d, h). The greatest distortion of the AM currents is observed with separate valve control in the rotor and stator circuit, and the absence of one, two, or with presence in the motor phases RTM resistors, values of which are different.

Using computer modeling it was determined, that in $S_{11}Z_2R_{32}$ type of scheme inrush of the rotor current can reach eleven times the rated current. The shape of the asynchronous machine rotor current may be improved using circuit design. A significant improvement of the form of a current is achieved in circuit of type Z_LR_{32} (fig. 2 a - d).



I

II

Figure 2. Currents in the AM rotor using circuit types Z_LR_{32} and Z_LR_{33} (I) and the waveform of the rotor and stator currents with control in stator circuits of AM (II)

The form of the AM rotor current may be improved by incorporating switch phase thyristor with different opening angles for anode and cathode groups of the bridge converter. The waveform in fig. 2. e –h not for the power circuit of type $Z_L R_{33}$, shows that in the curves of the rotor currents any oscillations and throws are practically absent. Here, the current form is quasi sine, and the average value of the rotor current increases up to 20%. When operating on stator circuit via RTM size and shape of the AM current changes in both, stator and rotor circuits. Fig. 2 shows the calculated and experimental waveforms of stator and rotor currents of asynchronous electric motor of MTF 411-8 type. Stator circuit of its machine contains RTM with resistances equal to $r_{2A} = r_A$, and rotor circuit – RTM with resistances $r'_{2a} = 5r'_a$.

As follows from analysis of the given waveforms, adjustment of the opening angle α_S of the thyristors in the RC leads to changes in the size and distortions of the form of rotor currents. This occurs because of the relationship between the phases windings of the stator and rotor. As a result, switching processes, which taking place in one phase, affects the other phase of the rotor and stator circuits. Moreover, with closed RC thyristors in disconnected from the network winding of the AM, induced EMF of the rotation that depends on the slip value. This EMF as well as the main voltage, significantly affects the size and shape of the rotor and stator currents of the asynchronous machine under parametric control. The smaller rotor rotation speed is, the smaller the effect of EMF of the rotor rotation on the values of the AM currents.

Conclusion

There proposed asynchronous electric drive for conveyor burning-machines, where in stator and rotor circuits of electric motor there is inverter, which uses resistor-thyristor modules for control.

For industrial use, taking into account technical requirements for this type of mechanism there developed an analytical method for determining the voltages and currents while RTM in charge. The calculations showed that modeling of these flow modes depends on the type of modules power circuit and type of control of them. Voltages and currents of the electric motor change most efficiently with the help of adjusting the opening angle of the thyristors, in other words - by changing the equivalent resistance values, which are included in the RTM. The proposed analytical method of calculation allows choosing the most efficient power converter circuit with resistor-thyristor modules and the simplest control laws for the electric motor of the conveyor burning-machines, so it is has practical importance. The calculations using this method indicate that their values of voltages and currents of the AM depend on type of RTM power circuit and valves control method. Moreover, current value is most effectively limited by controlling the opening angle of the thyristors, in other words - by changing the equivalent value of the RTM.

References

1. Chilikin M.G. Sandler A.S. *Obshhij kurs elektroprivoda: Uchebnik dlya vuzov* [Guideline of electric drive. College textbook]. Moscow, Energoizdat, 2007, 576 p.
2. Vyacheslav Lobov (2015). Method for research of parametric control schemes by asynchronous motor. *Metallurgical and Mining Industry,* No. 6, p.p. 102-108.
3. Vyacheslav Lobov. Research of launcher and braking regimes of asynchronous electric drive with teristor parametric control. Abstract of thesis for the degree of PhD. tehn. Sciences. Moscow. VNYY electric drive, 1983.
4. Petrushin V.S., Yakimets A.M., Bangula V.B (2012). Analysis of starting an induction motor with a thyristor converter voltage. *Elektrotekhnika i elektromekhanika – Electrical engineering & electro mechanics,* No.6, p.p. 31-33.
5. Figaro B.I. (2011). Primenenie ustroistv plavnogo puska i tormozheniya asinhronnyh elektrodvigatelei s korotkozamknutym rotorom v elektroprivodah kranovyh mexanizmov peredvizheniya [Application of devices of smooth start-up and braking of asynchronous electric motors with square-cage rotor in electric drives of crane mechanisms of movement]. *Elektrotehnicheskie i kompyuternye sistemy*. No 4, p.p. 30-38
6. Krasnoshapka N.D. Zmenshennya pohibki rozrahunku puskovih rezhimiv asinhronnih elektroprivodiv za statichnimi harakteristikami [Reduction of an error of calculation of starting modes of asynchronous electric drives behind direct current characteristics]. *Problemi informatizatsii ta upravlinnya*. Collection of scientific papers. Kyiv, NAU, -2011. No 3 (35), p.p. 62–67.
7. Vasilev D.S. (2010). Issledovanie elektromehanicheskih processov pri pryamom puske i tormozhenii asinhronnyh dvigatelei s uchetom peremennyh parametrov i sravnenie ih s plavnym puskom i tormozheniem [Research of electromechanical processes at direct launch

and braking of asynchronous engines taking into account variable parameters and their comparison with smooth start-up and braking]. *Bulletin of Kremenchuk Mykhailo Ostohradskyi National University*. No 4, p.p. 43-49.

8. *Vladimir Morkun, Natalia Morkun, Vitaliy Tron (2015).* Distributed closed-loop control formation for technological line of iron ore raw materials beneficiation. *Metallurgical and Mining Industry,* No.7, p.p.16-19.

9 Marynych I.A. (2014). Reason for application of intelligent systems for disintegrating complex control. *Metallurgical and Mining Industry*, No 6, p.p. 25–29.

10. Kovalov V.I. *Patent of Ukraine for utility model No 67058. Way of formation of starting modes of asynchronous drive with phase-wound rotor.* UA MPK (2011.01) E21B 4/00, E21B 44/00, Published 25.01.2012, Bulletin No 2, 2012.

11. Potapenko E.M., Potapenko E. E. Patent of Ukraine for utility model No 53315. *Way of formation of desirable stator currents of asynchronous three-phase electric motor with the square-cage rotor.* UA MPK (2009) H02P 21/00. Published 11.10.2010, Bulletin No 19, 2010.

12. Popovich M.G., Lozinsky O.Yu., Klepikov V.B. *Elektromehanichni sistemi avtomatichnogo keruvannya ta elektroprivodi: Navch. posibnik* [Electromechanical systems of automatic control and electric drives]. Kyiv, Libid, 2005, 680 p.