RESEARCH OF DYNAMIC PROPERTIES OF ELECTRIC DRIVES OF MINING COMPLEXES

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ABSTRACT: In this article, the basic equations for mathematical modeling of the dynamic processes have been revised. The obtained equation allows defining the character of laws of changes in the managed variables, their derivatives and, as a result, the character of change of mode parameters of asynchronous engines at start-up, loss of energy, duration of process, complexity Regulatory law. The resulting expression establishes the relationship between dynamic indicators, machine and load parameters, and can be used to determine the dynamic properties of asynchronous motors.

KEY WORDS: electric drive, mathematical model, asynchronous engine, frequency control, phase control, dynamic mode, transient process, dynamic synthesis, generalized electric machine.

I. INTRODUCTION

The limitation of electrical and mechanical loads with permissible values is one of the most common and complex tasks to be solved in the design of an automated electric drive. Reliability, durability and performance of the mechanisms are directly dependent on the reliability and dynamic qualities of the electric drive system. Therefore, the study of the dynamic loads of the electric drive, the analysis of the impact of its parameters on the size of these loads, as well as the development of reliable and perfect automatic torque control systems are important practical value [1].
Dynamic processes make up a significant share of the entire working cycle of mining machines (MM). Electromechanical systems of MM in this case are in specific working conditions. Specificity consists in a way of change of energy condition of systems. For example, in start-up modes there is a sharp change in the flow of energy sent to the system from the side of the power transformer, and modes of locking, especially emergency, there is an intensive redistribution of stored energy between the elements electromechanical and mechanical systems of MM [2].
To reduce the level of variable load, acting on elements of transmissions of mountain machines, along with constructive solutions, allowing to optimize the design of mechanical gears [3], it is possible also to use the adjustable electric drive (ED).
Dynamic modes in the electric part of the actuator can lead not only to significant plemented overload of the elements of electrical equipment, but also to the occurrence of shock forces and breakages of mechanical transmission. Despite the presence of several types of protection in the preschools, it is not possible to completely exclude such regimes, so to improve the reliability of the drive it is advisable to investigate the dynamics of these processes at the design stage. [4].
Reduction of dynamic loading of elements of mechanical converters of electric drives of mountain cars in the course of their work is an important scientific problem.

II. RESEARCH METHODS

In order to obtain convenient solutions for practical use of equations of adjustable ED, we will consider the methods of research of transient processes in electric machines and electrical circuits containing valve converters.
To describe the processes in the systems uniting the display group, models based on the engine replacement scheme [5], differential equations recorded in the m-phase system of coordinates [6], the equation of the generalized converter of electrical energy [7, 8, 9].
Using engine substitution schemes, you can calculate the value of any energy parameter in static and dynamic modes.
Disadvantages of such modules is that the calculation of dynamic modes does not take into account the electromagnetic transient processes in the winding ad, the accuracy of calculations of dynamic modes is low.
m – phase models are the most accurate. By means of these equations it is possible to take into account practically all peculiarities of physical processes in electric machines. Disadvantages of them are the complexity, a significant length of computation on the computer. So on the RV preciseness with splitting between the pole space of the machine by the method of "grids" [10] the time of calculation of processes in an electric car make several hours.
Equations of the generalized electric machine in which coefficients are constant, are widely applied on practice at research and synthesis of control systems of asynchronous ED most often [6, 8,9,11]. They have the following form [11]:

$$
\left.
\begin{aligned}
&\overline{U} = r\bar{i} + p\overline{\psi} + j\omega_k\overline{\psi};\\
&\overline{U}_f = r_f\bar{i}_f + [p + j(\omega_k - \omega_p)]\overline{\psi}_f;\\
&\overline{\psi} = x\bar{i} + x_\mu\bar{i}_f;\\
&\overline{\psi}_f = x_f\bar{i}_f + x_\mu\bar{i};\\
&M = jP\omega_p + \mathrm{Re}[j(\psi\ \ i_f)]
\end{aligned}
\right\}
\quad (1)
$$

Where i-the current of the stator, i_f - the current of the rotor, ψ - derivative stator, ψ_f-derivative rotor, U - stator voltage, U_f - rotor voltage-complex conjugate value derivative, ψ^*- the electromagnetic moment, M - the moment of inertia of the engine, J- the frequency of rotation of the mouth, $\omega_p - rotor\ speed$, r, r_f – active resistance of stator and rotor, $p = d/dt$– symbol of differentiation, x, x_f – inductive resistance of stator and rotor respectively, x_μ- inductive resistance of reciprocal induction, ω_k – frequency of rotation of coordinates.

For research and calculation of dynamic properties of adjustable electric drives MM is convenient to use the method of dynamic synthesis [12.13], which allows to simplify the finding of the law of regulation asynchronous engines.

This method is based on the principle features of the regulated electric machines, which consists in that, in them any and not changing abrupt variable characterizing a mode of work, can be accepted as controlled [12, 14]. The advantage of this method is the possibility of simply obtaining direct analytical expressions that connect the parameters of energy in a transient process with the parameters of the machine and the load. At the same time, the law of regulation of Hell, close to the optimal, is expressed in general terms through parameters, as well as the law of changing the controlled variables of hell, associated with its electromagnetic and mechanical inertia. The limitation in the study of the method of dynamic synthesis is that, with its help it is possible to define laws of change of control influences not optimal, but only close to them. To eliminate this deficiency it is rational to use methods of mathematical synthesis, variation calculus, optimal control theory when defining laws of change of controlled variables.

Thus, in the study of electric drives of mining machines, we use a method that takes into account the parameters of the power transmission line, the source of power supply and the electric motor, the method of dynamic synthesis, the methods of the calculus of variations, and the theory of optimal control.

III. RESULTS AND DISCUSSIONS

To study modes of operation, definition of control algorithms, investigation of peculiarities of interaction of ED in the composition of the mining complex, it is necessary to establish a relationship between the individual values characterizing the state Operating machines, process parameters. This relationship is based on the display equations, consisting of the equations of its elements and expressions for the coefficients of the relationship between them. The control system of the complex has a multilevel hierarchy. As a result of structuring the elements of technological

Control. The output variables of the control devices are signals informing the service personnel or higher level of management about the state of the system and running processes.

For simplification of further analysis the multilevel structure of the complex is expedient to simplify, conditionally replacing numerous ED at different levels of automation of one-m EP ($i \geq 1$), one j-th ($j \geq 1$) control system (Fig. 1). As $i -$ th ED we consider one of the EDs: regulated or unregulated. The described approach in the future will allow to use the obtained results for Research and Development of ED of various mechanisms used in mining production.

Thus, the structure of similar systems can be organized on the modular principle that will allow to choose a concrete set of models (engines, blocks of the sewn, regulators of voltage, frequency, control units etc.) depending on Characteristics of the object, both simple and complex systems of equipment management with the solution of problems of optimization of modes. This principle of organization of the structure of the electric part of the complex allows to build its mathematical models, calculation programs also on the modular principle, considering individual elements of systems as modules.

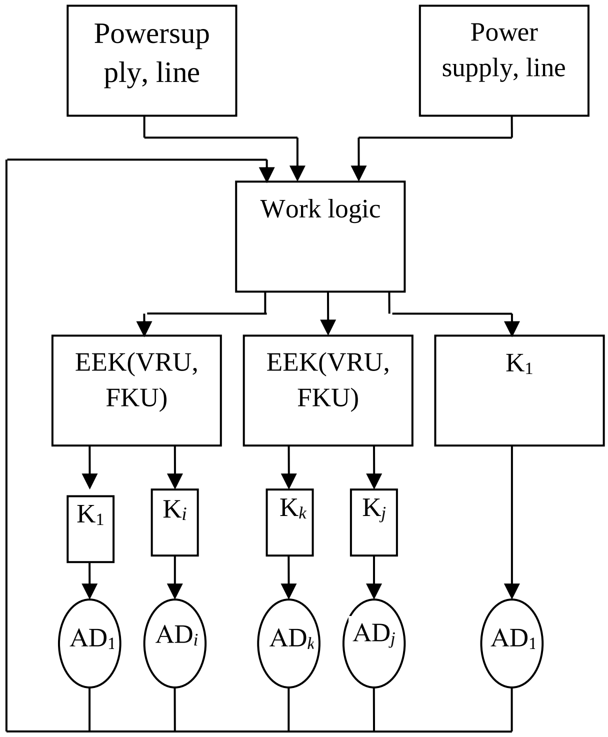

Fig. 1. Structure of mathematical model of ED MOC
EEK – electrical energy converter; VRU– voltage regulating unit; FKU – Frequency control unit; k_i - coupling coefficients; AM – Asynchronous motors.

From the analysis of Fig. 1 It follows that the mathematical model of the electrical part of the complex is a system of differential equations of the ED, coordinated by the coefficients of communication (K_u, K_i, K_p) elements of switching logic and establishes the interrelation of parameters Elements of the complex, mode parameters, disturbance parameters, algorithms and control constants. Often at work of a complex influence of parameters of a feeding line, a power supply source on characteristics of a display essentially: a drop of voltage on a line, proportionality of capacities of a source of power supply and receivers of a complex can cause Deterioration of the characteristics of the ED and the complex as a whole. In this connection, in the mathematical model of the electrical part of the complex should be introduced modules describing the power supply and feeding line.

The considered dependencies when specifying the elements of the electrical part of the complex, choosing the laws of changing the managed variables, as well as specifying the corresponding initial conditions describe any process occurring in the system.

The general solution of these equations can be presented in the following way [15]:

$$\left.\begin{aligned} U &= f(Z_{í} .Ï \ ,F,t); \\ i &= f(Z_{í} ,Ï \ ,F,t); \\ M &= f(Z_{í} ,Ï \ ,F,t); \\ \omega_0 &= f(Z_{í} ,Ï \ ,F,t) \end{aligned}\right\} \quad (2)$$

where $Z_{í}$ – characteristics of the load of the display; P – parameters of elements of the complex; F - laws of changing managed variables; t - time.

In addition, these equations together with the original system (1) Allow to determine the nature of change in time of any parameter of the energy of ED mining complexes (MC

The following values of energy parameters [12, 16] are used as basis: amplitude of the nominal values of the phase voltage, phase current, rated power, nominal speeds of rotors of electric machines.

When describing transient processes in electric machines it is expedient to apply the equations of the generalized electric machine. The equations for the asynchronous motor with the squirrel rotor are as follows [13]:

$$\left.\begin{aligned} &\overline{U} = r\bar{i} + p\overline{\psi} + j\omega_k\overline{\psi}; \\ &0 = r_f\,\bar{i}_f + [p + j(\omega_k - \omega_p)]\overline{\psi}_f; \\ &\overline{\psi} = x\bar{i} + x_\mu\bar{i}_f; \\ &\overline{\psi}_f = \bar{i}_f x_f + \bar{i}x_\mu; \\ &M = jP\omega_p - i_y\psi_{fz} + i_z\psi_{fz} \end{aligned}\right\} \quad (4)$$

where - z, y are the indices to indicate the projections of vectors z, y .
The solution of the display equations is to minimize the power losses for phase and frequency control.

A). Phase control

Let's consider transient processes at the start of ad with squirrel rotor by voltage regulation. In order to simplify the initial equation (3) We write in "vibrating " coordinate system y, z, associated with the vector of the full derivative of the rotor (ψ_f). We select (ψ_f) andω_k as the managed variables, and the vector (ψ_f)with the actual coordinate axis (z) is compatible. Then the second, fourth and fifth equations of the system (3) will take the following form [13]:

$$0 = r_f \bar{i}_f + j(\omega_k - \omega_p)\psi_{fz} + p\psi_{fz} \tag{5}$$

$$\psi = x_\mu \bar{i} + x_f \bar{i}_{fz}, \tag{6}$$

$$M_c = jp\omega_p + \psi_{fz} i_y, \tag{7}$$

Consider the change of the rotor speed according to the exponential law, derivative of the rotor-according to the exponential law and the law of technical Optimum:

$$\psi_{fz} = \psi_{fz0} + (\psi_{fz\infty} - \psi_{fz0})(1 - \varepsilon^{-\alpha t})$$
$$\psi_{fz} = \psi_{fz\infty} - (\psi_{fz\infty} - \psi_{fz0})(\sin \alpha t + \cos \alpha t)\varepsilon^{-\alpha t},$$

where α -coefficient characterizing the law of change of derivative rotor; $\psi_{fz0}, \psi_{fz\infty}$ -the initial and final value ψ_{fz} (determined from the equations established mode AE). In order to reduce the current start-up ad it is expedient to produce from non-zero initial conditions, feeding on the phase discrete pulses of voltage. In this case, the initial value of the derivative rotor should be equal to potokosctepleniju at steady short-circuit ad at low voltage, providing the necessary value of the starting torque.
The current of the rotor ad find from equations (5) and (7)

$$\bar{i}_f = -\frac{p\Psi_{fz}}{r_f} + \frac{j(Jp\omega_p - M)}{\Psi_{fz}} \tag{8}$$

Using the last expression, as well as the equation (5,6), we get;

$$\bar{i} = \frac{(\Psi_{fz} + \frac{x_f}{r_f} p\Psi_{fz}) + jx_f (Jp\omega_p - M_c)}{x_\mu \Psi_{fz}} \tag{9}$$

On the basis of equation (5) we find the frequency of rotation of coordinates:

$$\omega_k = \frac{\omega_p - r_f (Jp\omega_p - M_c)}{\Psi_{fz}{}^2} \tag{10}$$

The linkage of the stator is determined from the third equation of the system (4). Substituting expressions i, ω_k, ψ for in the first equation of the system (4) We get the dependence of the stress on the time at the start of asynchronous motor [13]:

$$\begin{aligned} U = {} & \frac{r}{x}\Psi_{fz} + (\frac{rx_f + r_f x}{x_\mu r_f})p\Psi_{fz} + \frac{xx_f - x_\mu{}^2}{x_\mu r_f} p^2\Psi_{fz} - \frac{xx_f - x_\mu{}^2}{\Psi_{fz0} x_f}(Jp\omega_p - M_c)x \\ & x[\omega_p + \frac{x_\mu r_f}{\Psi^2{}_{fz} x_f}(Jp\omega_p - M_c)] + j[\frac{x}{x_\mu}\omega_p \Psi_{fz} + \frac{rx_f + r_f x}{\Psi_{fz} x_f}(Jp\omega_p - M_c)] + \\ & + \frac{xx_f - x_\mu{}^2}{x_\mu r_f}\omega_p p\Psi_{fz} + \frac{xx_f - x^2{}_\mu}{\Psi_{fz} x_f}(Jp^2\omega_p - pM_c) \end{aligned} \tag{11}$$

In the last expression, all the values, except the coefficients that characterize the laws of changing the managed variables, are set. The nature of the laws of change of the controlled variables, their derivatives depends on the values of these coefficients and, as a consequence, the character of change of regime parameters ad at start-up, energy loss, process duration, complexity of the law

B). Frequency control

Frequency control is the most economical way of smooth regulation of rotation speed ad, as it in the whole range of regulation works with a small amount of sliding of the rotor (small sliding losses), has high efficiency and good rigidity of mechanical characteristics.
We use the method of dynamic synthesis together with methods of variation calculus, as the method of dynamic synthesis does not allow to define optimal laws of change of control influences [11.]. Consider the electromagnetic

transient process, which occurs at the initial stage, when the speed of the engine has not had time to significantly change. It is more convenient to analyze such process α , β , on axes.

For the investigation of asynchronous machines it is expedient to apply a system of α , β ,coordinates, allowing simplify equations and get constant coefficients before variables.

First we solve the problem in general. We will find the laws of control that ensure the transition of hell from one established mode ($U_0, i_0, i_{f0}, U_{f0}, M_0, \omega_{p0}$) to another established mode ($U_\infty, i_\infty, i_{f\infty}, U_{f\infty}, M_\infty, \omega_{p\infty}$). Specification of the boundary conditions according to the given criterion of quality will allow to use the received results at consideration of any mode of work asynchronous motor.

For ad with squirrel rotor as a managed variable it is convenient to take the vector (ψ_f).Equation (3) write in the coordinate system, stationary relative to the rotor ($\omega_k = 0$).

Then the second equation of the system (4) will take the following form:

$$0 = r_f \bar{i}_f + p\overline{\Psi}_f \qquad (12)$$

Taking into account the fourth equation of the system (4.) We will get:

$$\bar{i}_f = -\frac{p\overline{\Psi}_f}{r_f}$$

$$\bar{i} = \frac{(\overline{\Psi}_f + \frac{x_f}{r_f} p\overline{\Psi}_f)}{x_\mu}$$

Using the obtained dependencies, we write the expression (1,4):

$$W = \int_{t_0}^{t_\infty} [a_1(\Psi'^2{}_{f\alpha} + \Psi'^2{}_{f\beta}) + a_2(\Psi_{f\alpha}\Psi'_{f\alpha} + \Psi_{f\beta}\Psi'_{f\beta}) +$$

$$+ a_3(\Psi^2{}_{f\alpha} + \Psi^2{}_{f\beta})]dt, \qquad (13)$$

where $a_1 = \frac{(1 + a_3 \frac{x^2{}_f}{r_f})}{r_f}$; $a_2 = 2a_3 \frac{x_f}{r_f}$; $a_3 = \frac{r}{x^2{}_\mu}$

Euler-Lagrange equations [5]:

$$\Psi''_{f\alpha} + a_4\Psi_{f\alpha} = 0$$

$$\Psi''_{f\beta} + a_4\Psi_{f\beta} = 0$$

where $a_4 = -\frac{a_3}{a_1}$

The permissible Jekstremali of these equations are:

$$\Psi_{f\alpha(\beta)} = C_{1\alpha(\beta)}\varepsilon^{-\sqrt{a_4 t}} + C_{2\alpha(\beta)}\varepsilon^{-\sqrt{-a_4}t}, \qquad (14)$$

where $C_{2\alpha(\beta)} = \Psi_{f\alpha(\beta)1} - \Psi_{f\alpha(\beta)0}\varepsilon^{-\sqrt{-at_{14}}/\varepsilon\sqrt{-a_4 t_1}}$ $C_1 = \Psi_{a\alpha(\beta)0} - C_{2\alpha(\beta)}$;

$\Psi_{f\alpha(\beta)0(\infty)}$ - accordingly, the initial and final values $\Psi_{f\alpha}, \Psi_{f\beta}$

The Legendre condition is fulfilled in strict form:

$$W''_{\Psi_{f\alpha}{}'\Psi_{f\alpha}{}'} = 2a_4$$

$$W''_{\Psi'_{f\beta}\Psi_{f\beta}{}''} = 2a_1 \rangle 0$$

The Jakob equation has the form of z"-a4 z = 0. Its solution (under the initial conditions Z (0) = 0; z/(0) = 1), the conjugate points does not. Thus, function (14) gives minimum functionality (13) for all values t.

From (4) you can get the dependencies of the change in time of all the energy parameters of hell, including the control effects. For example

$$M=\frac{2\sqrt{-a_4}}{r_f x_\mu}[C_{1\alpha}C_{1_\beta}(1-\sqrt{-a_4\frac{x_f}{r_f}})e^{-2\sqrt{-at_4}}+C_{2\alpha}C_\beta(1+\sqrt{-a_4\frac{x_f}{r_f}})e^{2\sqrt{-a_4 t}}]$$

The rotor speed is determined from the equation:

$$P\omega_p=P\omega_p+\frac{M_i\,dt}{J}-\frac{1}{2r_f x_\mu J}[C_{1\alpha}C_{1\beta}(1-\sqrt{-a_4\frac{x_f}{r_f}})e^{-2\sqrt{-a_4 t}}+$$
$$+C_{2\alpha}C_{2\beta}(1-\sqrt{-a_4\frac{x_f}{r_f}})e^{2\sqrt{-a_4 t}}$$

Losses during dynamic mode are ($t_0=0$)

$$W=\frac{1}{2\sqrt{-a_4}}(C_{1\alpha}{}^2+C_{1\beta}{}^2[a_3+\sqrt{-a_4}(a_2\sqrt{-a_4}+a_2)](1-e^{2\sqrt{-a_4 t_m}})-(C_{2\alpha}{}^2+C_{2\beta}{}^2)$$
$$[a_3+\sqrt{-a_4}(a_2\sqrt{-a_4}-a_3)](1-e^{-2\sqrt{-a_4 t_m}})+2(C_{1\alpha}C_{2\alpha}+C_{1\beta}C_{2\beta})(a_3-a_2a_4)t_\infty$$

Thus, in the considered statement of the problems of dynamic regimes ad with squirrel rotor is reduced to the problem of variation calculus.

For ad with a phase rotor (dual-power machine mode, asynchronous machine-valve cascade) as a manageable to take the vector, and equations (4) write in a stationary coordinate system. *(u,y)* Then from the first and third equations of the system (5), taking into $\omega_k=0, U=\cos t+j\sin t$ account that when, it is possible to write:

$$\bar{i}=\frac{\cos t+j\sin t-p\overline{\Psi}}{r};$$

$$\bar{i}_f=\frac{\overline{\Psi}-\frac{x}{r}(\cos t+j\sin t-p\overline{\Psi}}{x_\mu}$$

Having performed similar above for hell with squirrel rotor conversion, get:

$$W=\int_{t_0}^{t_\infty}a_5[\Psi\ {}^2{}_u+\Psi'^2{}_y-$$
$$-2(\Psi_u'\cos t+\Psi_y'\sin t)+1]+$$
$$+a_6(\Psi_u\Psi_u'+\Psi_y\Psi_u'-\Psi_u\cos t-$$
$$-\Psi_y\sin t)+a_7(\Psi^2{}_u+\Psi^2{}_y)dt,\quad (14)$$

where $a_5=\frac{1-a_7\frac{x^2}{r}}{r};a_6=2a_7\frac{x}{r};a_7=\frac{r_f}{x^2{}_\mu}.$

Euler-Lagrange equations [13]:

$$\Psi'{}_u+a_8\Psi_u=a_9\cos t+\sin t;$$

$$\Psi_d{}'+a_8\Psi_v=a_9\sin t-\cos t,$$

where $a_8=-\frac{a_7}{a_5};a_9=\frac{a_6}{a_5}$

Permissible ekstremali of these equations

$$\Psi_{u(y)}=C_{3u(y)}e^{-\sqrt{-a_8}t}+C_{4u(y)}e^{\sqrt{-a_8 t}}+A_{u(y)}\cos t+B_{u(y)}\sin t,\quad (15)$$

where

$$C_{4u(y)}=\frac{\Psi_{u(y)\infty}-\Psi_{u(y)0}e^{-\sqrt{-a_8 t}}+A_{u(y)}\cos t_1+B_{u(y)}\sin t_1}{e\sqrt{-a_8 t_1-e^{-\sqrt{-a_8 t_1}}}};$$

$$A_u=B_y=-\frac{-a_9}{-a_8};A_y=B_u=\frac{1}{1-a_8};C_{3u(y)}=\Psi_{u(y)0}+A_{u(y)}-C_{4u(y)};$$

where $\Psi_{u(y)0\infty}$ the starting and ending values are, respectively, $\Psi_{u(y)}$

The Legendre condition for this task is done in strict form

$$W''_{\Psi'_u\Psi'_u} = 2a_5\rangle 0$$
$$W''_{\Psi'_v\Psi'_v} = 2a_5\rangle 0$$

Jacob's equation $z'' - \frac{a_7}{a_5} = 0$ has a look. Its solution (under the initial $z(0) = 0; z'(0) = 1$ conditions, conjugate points does not have. Thus, the function (15) gives the minimum functionality (14) for all values t. Substituting (15) in the original equations (3), you can get the analytical dependencies of the change of the ad mode parameters in the Time. In the present statement the task of research of dynamic modes in hell with a phase rotor is reduced to variation task with movable borders.

The resulting expression establishes the relationship between dynamic indicators, machine and load parameters, and can be used to determine the dynamic properties of asynchronous motors.

IV. CONCLUSIONS

1. The basic equations for mathematical modeling of the dynamic processes have been developed;
2. The algorithm and the program of calculation of processes in electric drive on the computer, enabling to execute calculations and researches of work of ED MC have been developed.
3. The program of direct start simulation has been developed taking into account the resistance of the line and simulation of the start of hell by the consideration of the electromagnetic transient processes.
4. The graphics of the change of the derivative rotor are received in time, the dependence of losses in Hell in time, the calculation curves of the start of hell, the waveforms of the start.
5. Algorithms and programs of Optimal control of the ED at minimum losses at phase and frequency regulation are developed.

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