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Search and research of energy-efficient configuration of the power supply network

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Abstract

Model of main structure of power-supply is considered for research of states of working collections of induction motors. Model consists of separate electromechanic modules, which can contain different amount of motors. Modules are connected in different points to main cable, laid from transformer before remoted module. On base of this model is developed software program, intended for finding of optimum parameters of structure of network of power-supply with use the genetic algorithm.

Keywords: genetic algorithm, electric load, electric power distribution, electric power supply network, main structure, model, optimization, energy-efficient configuration

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1. Introduction

To date, many methods, models and algorithms have been developed, aimed at improving the efficiency, reliability and safety of power supply distribution networks, at optimizing power losses of industrial enterprises. In works [1-5] the optimization of the operating modes of the elements of power supply systems is described. This is achieved by a comprehensive account of the parameters and characteristics of the power supply system, rebuilding its structure, voltage regulation and reactive power.

Improving the energy efficiency of the power supply system can be achieved by introducing a frequency-controlled electric drive. In [6, 7] presents the experience of implementation and the problems of using a frequency-controlled asynchronous electric drive in the mining industry. In particular, the author in the article [8] proposed a method for improving the energy efficiency of multi-motor frequency-controlled electric drives of main belt conveyors, based on changing the speed of the conveyor and controlling the magnetic state of the electric motor. Despite the obvious advantages of the frequency-controlled electric drive, there are a number of nuances necessary to take into account when introducing it, as noted in [9]. At the same time, additional capital investments are required, which are repaid by the long trouble-free operation of the equipment, and there are electromagnetic drive compatibility problems. A long cable between the frequency converter and the motor leads to cyclically recurring significant overvoltages at the motor terminals, having a devastating effect on the insulation of the electrical machine [10]. Leakage currents, including currents through bearings, can cause rapid destruction of bearings and seizure of the rotor.

Based on the above, it can be noted that in many cases neither frequency converters nor soft starters are used. Therefore, in distribution networks with an electromotive load during the direct start-up of powerful motors, the problem of increasing the voltage at the terminals of the motors and reducing energy losses remains open.

2. Mathematical model of an asynchronous motor in the main power supply network

A structure of electric power supply with an electric load is known for search the energy-efficient configuration of the power supply network [11]. Its disadvantage when used in computer modeling is that in order to determine the optimal configurations of the power supply network and to research the operating modes of the set of N asynchronous motors, it is necessary to calculate repeatedly the 2^N electric motors.

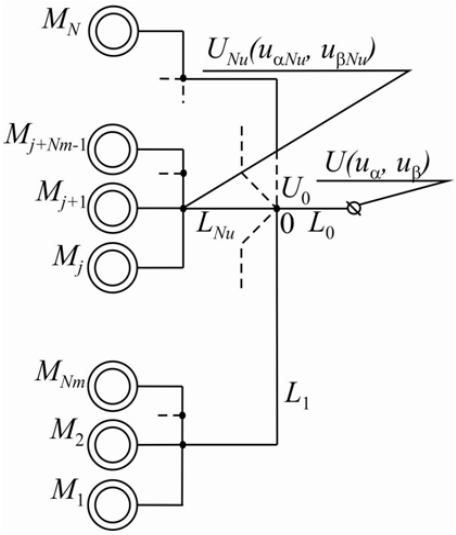

Figure 1. The scheme of power supply, consisting of separate electro-mechanical modules

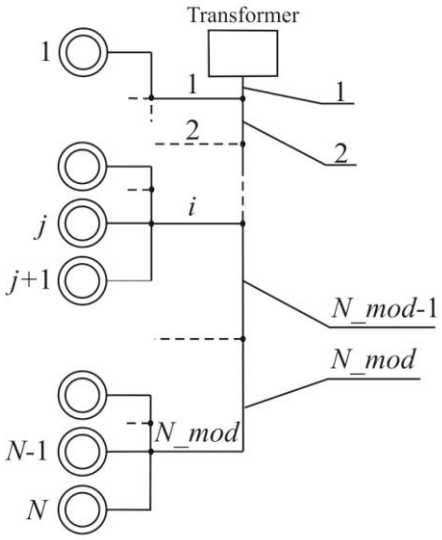

Figure 2. Backbone structure of the power supply network

This significantly increases the calculation time (up to $\frac{2^{N-1}}{N}$ times, $N \geq 2$). Therefore, in order to shorten the calculation time, we obtain a model of a power grid of a backbone structure with an electric load powered from a source of limited power, using which N motors are calculated.

A mathematical model of the electrical supply scheme is known, consisting of separate electromechanical modules (Figure 1) [12, 13].

In Figure 1 denotes: Nm – the number of electric motors in the module; N –the number of electric motors in the system; Nu – number of the module; j – number of the electric motor; M_j – j-th electric motor; L_0 – length of the common cable; L_{Nu} – cable length of the module Nu; U – voltage at the beginning of the common cable; u_α, u_β – the components of the voltage at the beginning of the common cable along the axes α, β; U_0 – voltage at the end of the common cable; U_{Nu} – voltage module Nu; $u_{\alpha Nu}$, $u_{\beta Nu}$ – the components of the module voltage along the axes α, β.

In Figure 2 shows the backbone structure of the power supply network, a particular case of which can be considered the structure in Figure 1. In Figure 2 denotes: *N_mod* – number of modules; i – the serial number of the module. In contrast to the scheme in Figure 1 scheme of power supply in Figure 2 consists of separate electromechanical modules that can contain a different number of motors connected at different points to the trunk cable laid from the transformer to the most remote module.

We introduce the following notation: the index M will refer to the parameters of the trunk cable, and the index K to the parameters of the cables laid from the trunk cable to the modules.

The state of the j-th electric motor is described by a set of differential and algebraic constraints [13-15]:

$$\begin{cases} \frac{d\psi_{s\alpha j}}{dt} = u_{s\alpha j} - R_{sj} i_{s\alpha j}; \\ i_{s\alpha j} = \frac{\psi_{s\alpha j}}{L'_{sj}} - \frac{k_{rj}}{L'_{sj}} \psi_{r\alpha j}; \\ \frac{d\psi_{s\beta j}}{dt} = u_{s\beta j} - R_{sj} i_{s\beta j}; \\ i_{s\beta j} = \frac{\psi_{s\beta j}}{L'_{sj}} - \frac{k_{rj}}{L'_{sj}} \psi_{r\beta j}; \\ \frac{d\psi_{r\alpha j}}{dt} = -R_{rj} i_{r\alpha j} - p_j \omega_j \psi_{r\beta j}; \\ i_{r\alpha j} = \frac{\psi_{r\alpha j}}{L'_{rj}} - \frac{k_{sj}}{L'_{rj}} \psi_{s\alpha j}; \\ \frac{d\psi_{r\beta j}}{dt} = -R_{rj} i_{r\beta j} + p_j \omega_j \psi_{r\alpha j}; \\ i_{r\beta j} = \frac{\psi_{r\beta j}}{L'_{rj}} - \frac{k_{sj}}{L'_{rj}} \psi_{s\beta j}, \end{cases} \quad (1)$$

with notation according to [13].

It is seen from (1) that the state of the j-th electric motor is characterized by the angular velocity of rotation of the rotor and the components of the stator motor voltages. Therefore, consider the algorithm for forming the stator voltage components in the power supply circuit in Figure 2, in order to obtain a mathematical model of an induction motor in the given power supply structure.

Knowing the number of motors *Nm(i)* in each i-th module, changing the module number i within the specified limits from 1 to *N_mod*, determine the j motor numbers of the i-th module from the following inequality:

$$\sum_{f=1}^{i-1} Nm(f) < j \leq \sum_{f=1}^{i} Nm(f). \quad (2)$$

We introduce some notation in order to simplify the form of the following expressions:

$$\begin{aligned} l_0 &= \sum_{g=1}^{i} Nm(g-1)+1; \\ l_1 &= \sum_{g=1}^{i} Nm(g); \\ b_0 &= \sum_{h=1}^{p} Nm(h-1)+1; \\ b_1 &= N, \end{aligned} \tag{3}$$

where p corresponds to the module number and varies from 1 to i.

Taking into account the last abbreviations, the required voltage on the stator winding of the j-th motor is determined as follows:

$$\begin{cases} u_{s\alpha j} = u_\alpha - R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\alpha l} - L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{di_{s\alpha l}}{dt} - \\ -\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\alpha b}\right) - \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{di_{s\alpha b}}{dt}\right); \\ u_{s\beta j} = u_\beta - R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\beta l} - L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{di_{s\beta l}}{dt} - \\ -\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\beta b}\right) - \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{di_{s\beta b}}{dt}\right). \end{cases} \tag{4}$$

Differentiating $i_{s\alpha j}$ and $i_{s\beta j}$ from (1), we obtain:

$$\begin{cases} \dfrac{di_{s\alpha j}}{dt} = \dfrac{1}{L_{sj}^{'}}\dfrac{d\psi_{s\alpha j}}{dt} - \dfrac{k_{rj}}{L_{sj}^{'}}\dfrac{d\psi_{r\alpha j}}{dt}; \\ \dfrac{di_{s\beta j}}{dt} = \dfrac{1}{L_{sj}^{'}}\dfrac{d\psi_{s\beta j}}{dt} - \dfrac{k_{rj}}{L_{sj}^{'}}\dfrac{d\psi_{r\beta j}}{dt}. \end{cases} \tag{5}$$

We substitute (5) into (4):

$$\begin{cases} u_{s\alpha j} = u_\alpha - R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\alpha l} - L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L_{sl}^{'}}\dfrac{d\psi_{s\alpha l}}{dt} + \\ +L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L_{sl}^{'}}\dfrac{d\psi_{r\alpha l}}{dt} - \sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\alpha b}\right) - \\ -\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L_{sb}^{'}}\dfrac{d\psi_{s\alpha b}}{dt}\right) + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L_{sb}^{'}}\dfrac{d\psi_{r\alpha b}}{dt}\right); \\ u_{s\beta j} = u_\beta - R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\beta l} - L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L_{sl}^{'}}\dfrac{d\psi_{s\beta l}}{dt} + \\ +L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L_{sl}^{'}}\dfrac{d\psi_{r\beta l}}{dt} - \sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\beta b}\right) - \\ -\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L_{sb}^{'}}\dfrac{d\psi_{s\beta b}}{dt}\right) + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L_{sb}^{'}}\dfrac{d\psi_{r\beta b}}{dt}\right). \end{cases} \tag{6}$$

Combining (1) and (6), we obtain for the j-th motor:

$$\begin{cases} \dfrac{d\psi_{s\alpha j}}{dt} + L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L_{sl}^{'}}\dfrac{d\psi_{s\alpha l}}{dt} + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L_{sb}^{'}}\dfrac{d\psi_{s\alpha b}}{dt}\right) = \\ = u_\alpha + L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L_{sl}^{'}}\dfrac{d\psi_{r\alpha l}}{dt} + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L_{sb}^{'}}\dfrac{d\psi_{r\alpha b}}{dt}\right) - \\ -R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\alpha l} - \sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\alpha b}\right) - R_{sj} i_{s\alpha j}; \\ \dfrac{d\psi_{s\beta j}}{dt} + L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L_{sl}^{'}}\dfrac{d\psi_{s\beta l}}{dt} + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L_{sb}^{'}}\dfrac{d\psi_{s\beta b}}{dt}\right) = \\ = u_\beta + L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L_{sl}^{'}}\dfrac{d\psi_{r\beta l}}{dt} + \sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L_{sb}^{'}}\dfrac{d\psi_{r\beta b}}{dt}\right) - \\ -R_{Ki}\sum\limits_{l=l_0}^{l_1} i_{s\beta l} - \sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1} i_{s\alpha b}\right) - R_{sj} i_{s\beta j}; \\ \dfrac{d\psi_{r\alpha j}}{dt} = -R_{rj} i_{r\alpha j} - p_j\omega_j\psi_{r\beta j}; \\ \dfrac{d\psi_{r\beta j}}{dt} = -R_{rj} i_{r\beta j} + p_j\omega_j\psi_{r\alpha j}. \end{cases} \tag{7}$$

We take into account the influence of the transformer on the process of electromechanical energy conversion. Transformer model:

$$\begin{cases} \dfrac{d\psi_{ts\alpha}}{dt} = u_{ts\alpha} - R_{ts} i_{ts\alpha}; \\ \dfrac{d\psi_{ts\beta}}{dt} = u_{ts\beta} - R_{ts} i_{ts\beta}; \\ \dfrac{d\psi_{tr\alpha}}{dt} = u_{tr\alpha} - R_{tr} i_{tr\alpha}; \\ \dfrac{d\psi_{tr\beta}}{dt} = u_{tr\beta} - R_{tr} i_{tr\beta}; \\ i_{tr\alpha} = \dfrac{\psi_{tr\alpha} - k_{ts}\psi_{ts\alpha}}{L_{tr}^{'}}; \\ i_{tr\beta} = \dfrac{\psi_{tr\beta} - k_{ts}\psi_{ts\beta}}{L_{tr}^{'}}. \end{cases} \tag{8}$$

The conjugation conditions for models (7) and (8) according to the Kirchhoff rules:

$$\begin{cases} u_\alpha + u_{tr\alpha} = 0; \\ u_\beta + u_{tr\beta} = 0; \end{cases} \tag{9}$$

$$\begin{cases} i_{tr\alpha} = \sum\limits_{b=1}^{b_1} i_{s\alpha b}; \\ i_{tr\beta} = \sum\limits_{b=1}^{b_1} i_{s\beta b}. \end{cases} \tag{10}$$

We unite (7) and (8) taking into account (9) and (10):

$$\begin{cases} \dfrac{d\psi_{s\alpha j}}{dt}+L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L'_{sl}}\dfrac{d\psi_{s\alpha l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\alpha b}}{dt}\right)+ \\ +\dfrac{d\psi_{tr\alpha}}{dt}=L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L'_{sl}}\dfrac{d\psi_{r\alpha l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\alpha b}}{dt}\right)- \\ -R_{Ki}\sum\limits_{l=l_0}^{l_1}i_{s\alpha l}-\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1}i_{s\alpha b}\right)-R_{sj}i_{s\alpha j}-R_{tr}\sum\limits_{b=1}^{b_1}i_{s\alpha b}; \\ \dfrac{d\psi_{s\beta j}}{dt}+L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L'_{sl}}\dfrac{d\psi_{s\beta l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\beta b}}{dt}\right)+ \\ +\dfrac{d\psi_{tr\beta}}{dt}=L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L'_{sl}}\dfrac{d\psi_{r\beta l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\beta b}}{dt}\right)- \\ -R_{Ki}\sum\limits_{l=l_0}^{l_1}i_{s\beta l}-\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1}i_{s\beta b}\right)-R_{sj}i_{s\beta j}-R_{tr}\sum\limits_{b=1}^{b_1}i_{s\beta b}. \end{cases} \quad (11)$$

Differentiating $i_{tr\alpha}$, $i_{tr\beta}$, in (8), we obtain:

$$\begin{cases} \dfrac{di_{tr\alpha}}{dt}=\dfrac{1}{L'_{tr}}\dfrac{d\psi_{tr\alpha}}{dt}-\dfrac{k_{ts}}{L_{tr}}\dfrac{d\psi_{ts\alpha}}{dt}; \\ \dfrac{di_{tr\beta}}{dt}=\dfrac{1}{L'_{tr}}\dfrac{d\psi_{tr\beta}}{dt}-\dfrac{k_{ts}}{L'_{tr}}\dfrac{d\psi_{ts\beta}}{dt}. \end{cases} \quad (12)$$

Where do we get:

$$\begin{cases} \dfrac{d\psi_{tr\alpha}}{dt}=L'_{tr}\dfrac{di_{tr\alpha}}{dt}+k_{ts}\dfrac{d\psi_{ts\alpha}}{dt}; \\ \dfrac{d\psi_{tr\beta}}{dt}=L'_{tr}\dfrac{di_{tr\beta}}{dt}+k_{ts}\dfrac{d\psi_{ts\beta}}{dt}. \end{cases} \quad (13)$$

Taking into account (5) and (10), we write:

$$\begin{cases} \dfrac{d\psi_{tr\alpha}}{dt}=L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\alpha b}}{dt}- \\ -L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\alpha b}}{dt}+k_{ts}\dfrac{d\psi_{ts\alpha}}{dt}; \\ \dfrac{d\psi_{tr\beta}}{dt}=L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\beta b}}{dt}- \\ -L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\beta b}}{dt}+k_{ts}\dfrac{d\psi_{ts\beta}}{dt}. \end{cases} \quad (14)$$

Using (11) and (14), we obtain the required model for research the processes of electromechanical energy conversion:

$$\begin{cases} \dfrac{d\psi_{s\alpha j}}{dt}+L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L'_{sl}}\dfrac{d\psi_{s\alpha l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\alpha b}}{dt}\right)+ \\ +L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\alpha b}}{dt}=L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L'_{sl}}\dfrac{d\psi_{r\alpha l}}{dt}+ \\ +\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\alpha b}}{dt}\right)+L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\alpha b}}{dt}- \\ -k_{ts}\dfrac{d\psi_{ts\alpha}}{dt}-R_{Ki}\sum\limits_{l=l_0}^{l_1}i_{s\alpha l}-\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1}i_{s\alpha b}\right)- \\ -R_{sj}i_{s\alpha j}-R_{tr}\sum\limits_{b=1}^{b_1}i_{s\alpha b}; \\ \dfrac{d\psi_{s\beta j}}{dt}+L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{1}{L'_{sl}}\dfrac{d\psi_{s\beta l}}{dt}+\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\beta b}}{dt}\right)+ \\ +L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\beta b}}{dt}=L_{Ki}\sum\limits_{l=l_0}^{l_1}\dfrac{k_{rl}}{L'_{sl}}\dfrac{d\psi_{r\beta l}}{dt}+ \\ +\sum\limits_{p=1}^{i}\left(L_{Mp}\sum\limits_{b=b_0}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\beta b}}{dt}\right)+L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\beta b}}{dt}- \\ -k_{ts}\dfrac{d\psi_{ts\beta}}{dt}-R_{Ki}\sum\limits_{l=l_0}^{l_1}i_{s\beta l}-\sum\limits_{p=1}^{i}\left(R_{Mp}\sum\limits_{b=b_0}^{b_1}i_{s\beta b}\right)- \\ -R_{sj}i_{s\beta j}-R_{tr}\sum\limits_{b=1}^{b_1}i_{s\beta b}; \\ \dfrac{d\psi_{r\alpha j}}{dt}=-R_{rj}i_{r\alpha j}-p_j\omega_j\psi_{r\beta j}; \\ \dfrac{d\psi_{r\beta j}}{dt}=-R_{rj}i_{r\beta j}+p_j\omega_j\psi_{r\alpha j}; \\ \dfrac{d\psi_{ts\alpha}}{dt}=u_{ts\alpha}-R_{ts}i_{ts\alpha}; \\ \dfrac{d\psi_{ts\beta}}{dt}=u_{ts\beta}-R_{ts}i_{ts\beta}; \\ \dfrac{d\psi_{tr\alpha}}{dt}=L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\alpha b}}{dt}- \\ -L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\alpha b}}{dt}+k_{ts}\dfrac{d\psi_{ts\alpha}}{dt}; \\ \dfrac{d\psi_{tr\beta}}{dt}=L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{1}{L'_{sb}}\dfrac{d\psi_{s\beta b}}{dt}- \\ -L'_{tr}\sum\limits_{b=1}^{b_1}\dfrac{k_{rb}}{L'_{sb}}\dfrac{d\psi_{r\beta b}}{dt}+k_{ts}\dfrac{d\psi_{ts\beta}}{dt}; \\ \dfrac{d\omega_j}{dt}=\dfrac{1}{J_j}\left(\dfrac{3}{2}p_j\dfrac{k_{rj}}{L'_{sj}}\left(\psi_{r\alpha j}\psi_{s\beta j}-\psi_{s\alpha j}\psi_{r\beta j}\right)-M_{cj}\right), \end{cases} \quad (15)$$

where J_j – the moment of inertia of the *j*-th electric motor; M_{cj} – the resistance torque of the *j*-th motor.

As a result, a mathematical model of an asynchronous motor has been obtained as part of a backbone power supply

network designed to determine the energy-efficient configuration of the power supply network and to research the operating modes of a set of asynchronous motors.

3. Energy-efficient configuration of the power supply network of the treatment site

Based on the above results, a software tool has been developed to determine the rational (close to optimal) power supply network configurations by various criteria using a genetic algorithm. The program also allows modeling transient processes in asynchronous electric motors operating in nominal modes as part of the power supply network, rational in terms of minimum power losses or minimum cable voltage loss.

A lot of works [16-19] were devoted to optimization of multi-extremal functions, to solving problems of nonconvex optimization, nonlinear programming, and forecasting using evolutionary-genetic algorithms. When the genetic algorithm is working, the search process ends when you find a solution close to the optimal one, and not an absolutely exact solution. Therefore, such a solution of the problem can be called rational.

Consider the operation of this software for the example of searching for a rational configuration of the power supply network for the treatment site, and also analyze the results.

In Figure 3 shows the scheme of power supply for the treatment site. Electricity supply of the conveyor, the reloader and the crusher is provided from the power train with the transformer BRUSH 1250-6/1,2. In Table shows the parameters of the consumers of the site.

The scheme in Figure 3 corresponds to the layout of the electrical equipment of the treatment site, shown in Figure 4.

Table. Parameters of the consumers of the site

Name of the consumer	Motor type	Un, V	Pn, kW	Operating mode
Conveyor A35	DKV355LB4	1140	2x315	S3
Reloader PSP-308	DKV315L4	1140	200	S3
Crusher DU-910	AVR280L4	1140	160	S3

As a result of the search for a rational configuration of the power supply network in terms of minimum energy losses in the cable network, a scheme is obtained (Figure 5), in which the energy losses are reduced by 17%, and the average value of the voltage practically does not change.

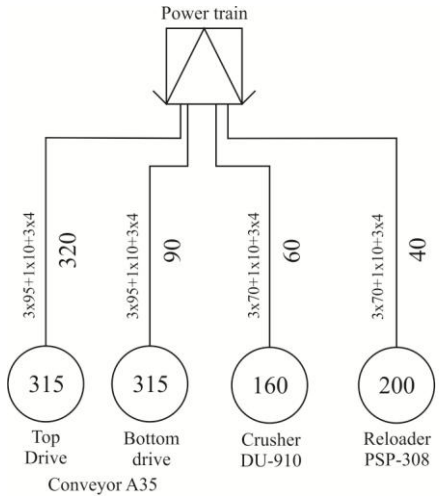

Figure 3. Scheme of power supply for the treatment site

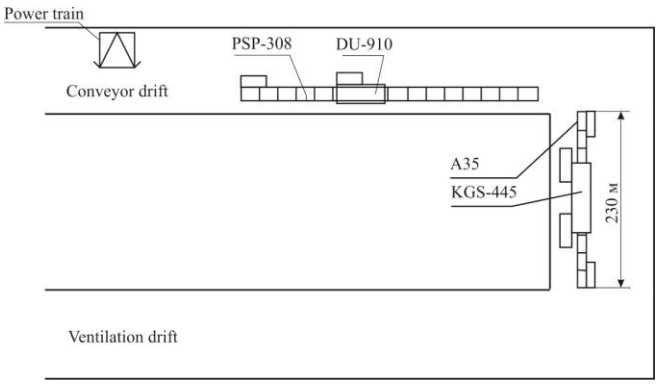

Figure 4. Scheme of the location of the electrical equipment of the treatment site

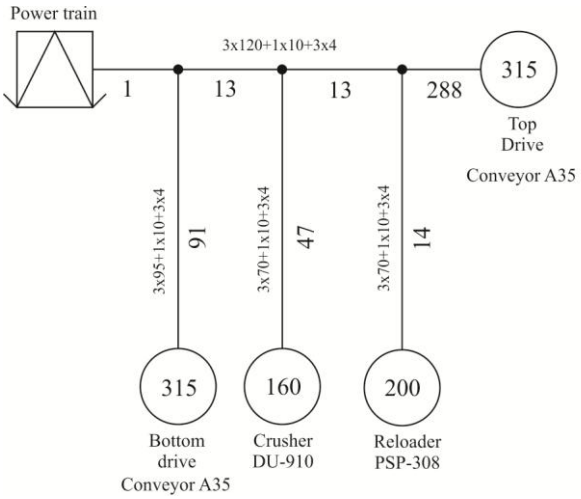

Figure 5. Rational configuration of the power supply network in terms of minimum energy losses in the cable network

4. Research of dynamic characteristics of electromechanical system at start-up of electric motors in the power supply system of the treatment site

The operability and adequacy of the mathematical model of the mains supply network with a motor load powered by a limited power source is confirmed by the following computational experiment. In the experiment, the configuration of the power supply network of the treatment site, which was rational for the minimum energy loss in the cable network, was modeled.

As a load on the electric motors of the conveyor, the reloader and the crusher, the torque of resistance was simulated, the value of which was set by the analytical expression:

$$M_s = M_{nom} + 0,4M_{nom}\sin(12\pi t) + 0,4M_{nom}\sin(26\pi t), \quad (16)$$

где M_s – calculated torque of resistance on the executive organ; M_{nom} – nominal electromagnetic torque motor.

In Figures 6, 7, 8 and 9 show the dynamic characteristics of the main indicators of the electromechanical system when starting the electric motors in the power supply system of the treatment site. With the simultaneous start-up of the reloader motors and the crusher from Figure 6 shows that the voltage drop at the motor terminals is approximately 12 %. After the acceleration of the motors, their currents are reduced (Figure 7), and the voltage is restored after 0,5 s to a level lower than the previous value by approximately 20 V, that is, the voltage loss in the network cables and in the transformer. The latter adversely affects the start up electric motors of the conveyor at the time 1 s. When starting the conveyor motors, their currents form voltage drops on the common sections of the main cable with the motors running. There is a decrease in the voltage at the terminals of the motors already running, depending on the length of the common sections of the motor cables, and also due to an additional drop in the resistance of the secondary windings of the transformer. This has an effect on the speed (Figure 8) and the electromagnetic torque (Figure 9) of the crusher motor and the reloader. The torque of the top drive motor of the conveyor is less than that of the lower drive motor, because of the greater distance from the transformer. So for the most remote of the top drive motor of the conveyor, the voltage drop is approximately 30 % of the nominal value. When working under load, this can lead to a prolonged start-up and, in the worst case, to "overturn" the electric motor. Then, the voltage is restored after 0,5 s to a level lower than the previous one by about 25 V. At the time of 2 s, the motors are subjected to an alternating load, which leads to voltage fluctuations at the motor terminals and adversely affects their operation. Voltage fluctuations in the network lead to the appearance of electromechanical oscillations on the shafts of the motors (Figure 9). When the crusher and the reloader motors are switched off at a time of 3 s, the voltage on the connected conveyor motors is increased by approximately 25 V. At the time of 4 seconds, the conveyor motors are switched off. From the time 5 s, the above cycle is repeated, since the motors operate in an intermittent S3 mode with a duty cycle of 60 %.

The reliability of the results obtained is confirmed by the fact that the characteristics described above fully correspond to the oscillograms of the starting of an induction motor with power supplied from a limited power source presented in [20-22].

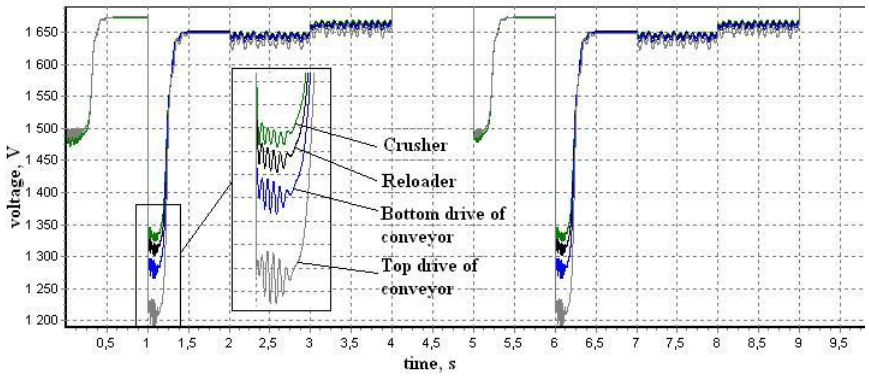

Figure 6. Amplitudes of voltages on the windings of stator motors

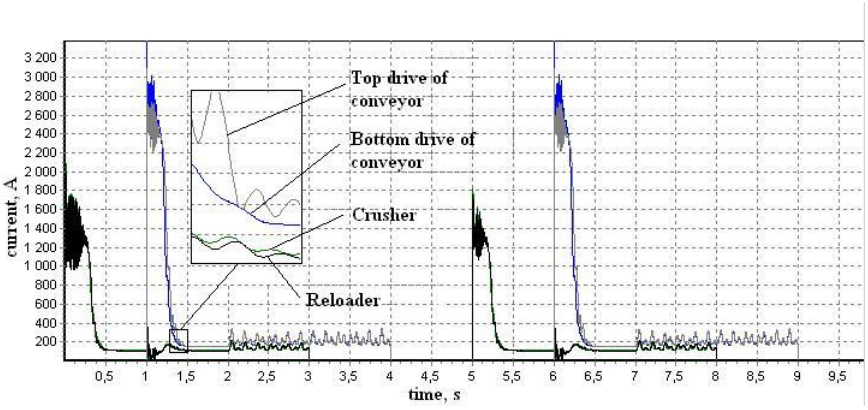

Figure 7. Amplitudes of currents on windings of stator motors

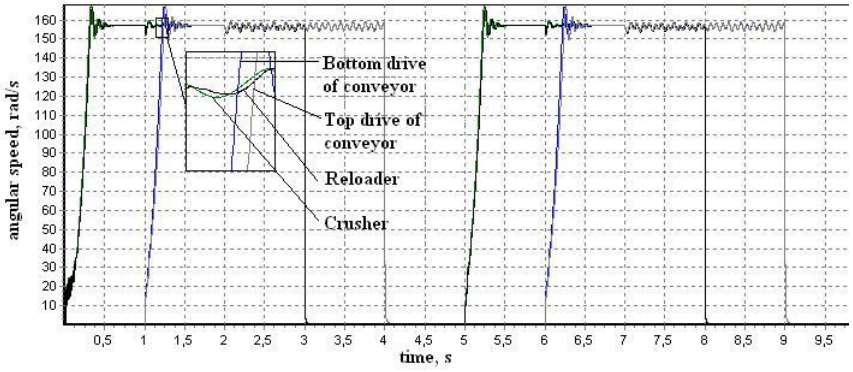

Figure 8. The motor angular speed

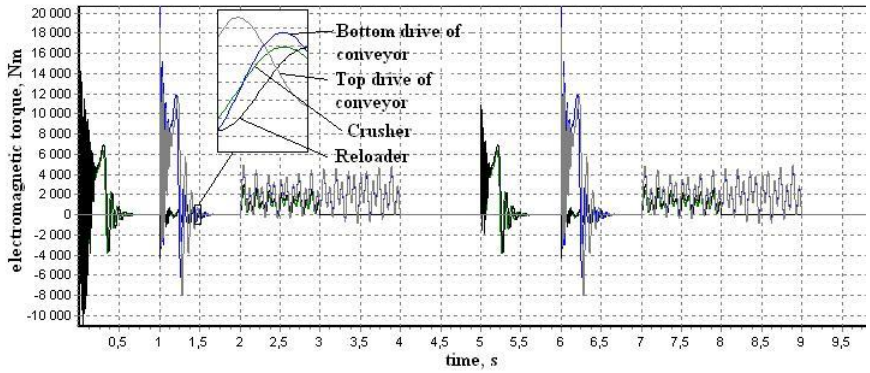

Figure 9. Electromagnetic torque of motors

5. Conclusions

1. The mathematical model of an asynchronous motor in the structure of the main power supply network, taking into account the influence of the transformer on the process of electromechanical energy conversion, is obtained.

2. Based on the received model, a software tool was developed to search and research the rational configuration of the power supply network using a genetic algorithm.

3. The efficiency of the software is shown in the example of searching a rational configuration of the power supply network in terms of minimum energy losses in the cable network.

4. The dynamic characteristics of the electromechanical system during the start-up of electric motors in the power supply system of the treatment site are researched.

References

[1] Balametov, A. B., Mamedov, S. G., Aliev, Kh. T., Khalilov, E. D. (2011) The method of calculating electricity losses in distribution networks by simulating load graphs. *Electricity* **№8**: 15-22.

[2] Timchuk, S. A., Derenko, N. S. (2013) Optimization of the power supply system of an industrial enterprise when it is being reconstructed. *East-European Journal of Advanced Technologies* **№8**: 4-8.

[3] Artyukhov, I. I., Arshakyan, I. I., Korotkov, A. V., Pogodin, N., Stepanov, S. F. (2006) The autonomous system of power supply of a technological complex with a multi-motor electric motor, which is being reconstructed in structure. *Vestnik SSTU* **№1**: 20-28.

[4] Sadkov, E. V. (2006) Optimization of the structure of the power supply system of an industrial enterprise due to the complex accounting of parameters and characteristics of its elements. *Energy security and energy saving* **№3**: 6-10.

[5] Erkhan, F. M., Voinesko, D. A., Lupushor, I. N., Bantash, R. G. (2014) Principles of developing algorithms for optimizing the functional reliability of distribution systems, taking into account the influence of probabilistic factors. *Energetika. Izvestiya of higher educational institutions and energy associations of the CIS* **№2**: 40-50.

[6] Malcher, M. A, Anikin, A. S. (2011) Problems of introduction of frequency regulation in the mining industry. *Mining equipment and electrical engineering* **№4**: 40-46.

[7] Egorov, A. N., Semenov, A. S., Fedorov, O. V. (2017) Practical experience of using frequency converters Power Flex 7000 in the mining industry. *Proceedings of NSTU. R.E. Alekseeva* **№4**: 86-93.

[8] Semykina, I. Yu., Negadaev, V. A. (2017) Methods of improving the energy efficiency of multi-motor frequency-controlled electric drives of main belt conveyors. *Vestnik KuzGTU* **№3**: 134-143.

[9] Pustovetov, M. Yu. (2016) The condition of effective operation of the frequency-controlled electric drive. *Scientific Review* **№26**: 107-115.

[10] Kalashnikov, B. Ye. (2002) The problem of "long cable" in electric drives with IGBT-inverters. *Electrical Engineering* **№12**: 24-26.

[11] Negadaev, V. A. (2017) Optimization of the backbone network of electrical power supply of limited power. *Vestnik KuzGTU* **№3**: 143-154.

[12] Eshin, E. K. (1999) Calculations of electromechanical transients in the power supply system of mining machines. *Elektrotekhnika* **№3**: 41-44.

[13] Eshin, E. K. (2003) Electromechanical systems of multi-motor electric drives. Modeling and control. (Kemerovo: KuzGTU).

[14] Kovach, K. and Rat. I. (1963) *Transient processes in alternating current machines.* (M.-L.: Gosenergoizdat).

[15] Kononenko, E. V. and Sipailov, G. A. and Khorkov, K. A. (1975) *Electric Machines.* (M.: Vysshaya shkola).

[16] Batishchev, D. I. (1995) Genetic algorithms for solving extreme problems: proc. allowance. (Voronezh).

[17] Tenenev, V. A. (2006) Solution of the problem of multicriteria optimization by genetic algorithms. *Intellectual systems in production* **№2**: 103-109.

[18] Adeli, H., Cheng, N. T. (1994) Concurrent genetic algorithms for optimization of large structures. *Journal of Aerospace Engineering* **Vol.7, №3**: 276-296.

[19] Chiraphadkanakul, S. (1997) *Genetic forecasting algorithm.* (Thailand: Assumption University Bangkok).

[20] Eshin, E. K. (1999) Modeling of electromechanical processes of multi-motor electric drives of mining machines. (Kemerovo: KuzGTU).

[21] Petrov, I. I. and Meistel, A. M. (1968) Special modes of operation of an asynchronous electric drive. (M.: Energia).

[22] Venikov, V. A. (1978) Transient electromechanical processes in electrical systems. (M.: Vysshaya shkola).