DOI: 10.31897/PMI.2019.5.576

UDC 621.398

Improving the Energy Efficiency of the Electromechanical Transmission of an Open-pit Dump Truck

Anatoly E. KOZYARUK, Albert M. KAMYSHYAN ✉
Saint-Petersburg Mining University, Saint-Petersburg, Russia

The article analyzes the existing systems of electromechanical transmission of mining trucks BelAZ. The influence of the load nature created by the uncontrolled rectifier on the power factor and mass-dimensional indicators of the electromechanical transmission is assessed.

Variants of modernization of the AC-electromechanical transmission system are proposed, which provide power factor correction. The influence of the proposed options on the overall dimensions of the electromechanical transmission is considered. Based on the assessment, a modernization option was chosen that provides the required power factor with minimal impact on the overall dimensions of the electromechanical transmission.

The results of modeling the operation of the existing electromechanical transmission and the modernized electromechanical transmission system using the most promising modernization option are presented.

Key words: mining dump truck; electromechanical transmission; power factor; active filter; active rectifier

How to cite this article: Kozyaruk A.E., Kamyshyan A.M. Improving the Energy Efficiency of the Electromechanical Transmission of an Open-pit Dump Truck. Journal of Mining Institute. 2019. Vol. 239, p. 576-582. DOI: 10.31897/PMI.2019.5.576

Introduction. Automobile open-pit transport is the most effective and popular means of transporting rock mass [6, 7, 12]. The advantages of this type of transport are determined by high maneuverability, a reduction in the length of transport communications, and high operational efficiency.

On dump trucks with a carrying capacity of more than 90 tons, the use of electromechanical transmission has become most widespread. Although compared to hydromechanical, this type of transmission has lower efficiency, but it differs in layout flexibility and higher traction properties of the drive.

In Russia, the production of electromechanical transmission for mining dump trucks is carried out at the enterprise PJSC «Silovyye mashiny» (branch – Electrosila plant). The company has developed alternating current electromechanical transmission systems. Sets of electromechanical transmissions for heavy-duty dump trucks are also created by the Ruselprom Concern (PJSC «NIPTIEM») and HPE «NRU MEI» [4, 11].

In the electromechanical transmission developed by HPE «NRU MEI», induction motors with independent excitation are used as traction motors, however, as operating experience has shown, AC-transmission with frequency-controlled asynchronous traction motors powered by autonomous inverters voltage based on IGBT-transistors is the most effective solution due to the simplicity of manufacture, reliability, the ability to work in a wide range of speeds [5, 10, 13, 14].

Overview of the existing electromechanical transmission scheme. Figure 1 shows the scheme of the electromechanical transmission of alternating current of the BelAZ dump truck, which is most widely used on mass-produced dump trucks with a lifting capacity of 130 tons. A diesel engine (D) acts as an energy source in this scheme, with a synchronous generator connected to its shaft (SG) with a self-excitation system (B), feeding through two uncontrolled rectifiers (DR1, DR2) and autonomous voltage inverters (VI1, VI2) traction induction motors (IN1, IN2) of the right and left motor-count sa. At speeds (up to 8 km/h), braking is carried out by transferring the traction motors to the energy recovery mode and turning on the blocks of brake resistors (BR1, BR2) in the DC circuit.

DOI: *10.31897/PMI.2019.5.576*

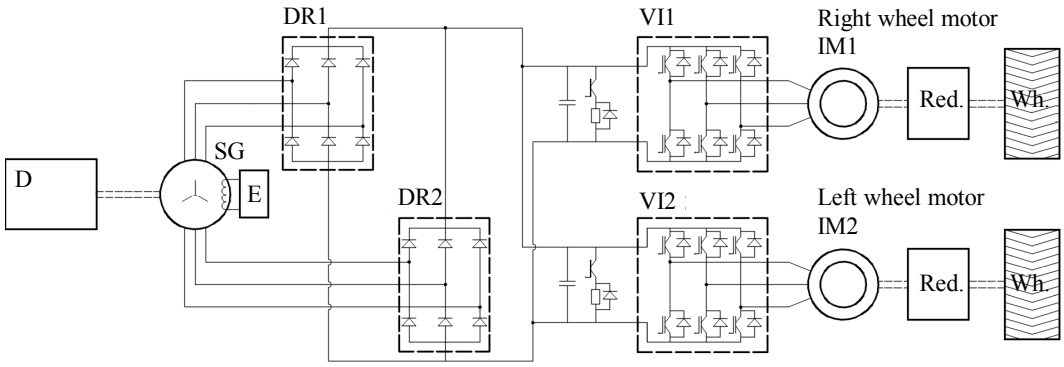


Fig. 1. Scheme of electromechanical transmission of AC/AC dump truck BelAZ

Parameters of electric transmission of a dump truck with a loading capacity of 130 t:

Rated power of the generator, kW	800
Generator rotation frequency, rpm	
rated	1500
maximal	1900
Power factor of generator in nominal mode	0,95
Rated power of IM, kW	610
Nominal rotation speed of IM, rpm	850
Rated power factor of IM	0,84
IM efficiency, %	93
Rated moment M_n, kNm	6,9
Nominal traction effort, kg	29400
Maximum traction effort, kg	75000
Rated rectified voltage U_n, V	1000

Figure 2 shows the voltages and currents in the system of the frequency converter with a diode rectifier and an autonomous voltage inverter in the steady-state mode of operation, where u_{sn} – three-phase network voltage system, i_{s1} – current of one phase of a network, i_d – rectified diode bridge current; u_{rc} – capacitor voltage; i_c – capacitor current, u_1 – voltage of one phase of the load, i_n – three-phase load current system, u_{ref} – reference voltage, u_{cn} – three-phase control voltage system [9].

The graphs in Fig. 2 show that the use of a two-link frequency converter of this design as part of an electromechanical transmission of a dump truck leads to non-sinusoidality of currents flowing through the windings of the generator [2, 5]. Distortion of the shape of the generator currents, in turn, leads to a significant increase in energy losses and a reduction in the service life of the generator stator windings (Report on research work «Development of an integrated system for optimizing power supply modes and improving the quality of electric energy in the distribution networks of mines of OJSC «Noril'skaya gornaya kompaniya». St. Petersburg: SPGGI. 2001. 123 p.). In addition, when working on an uncontrolled rectifier, the power factor of the generator-diode rectifier system decreases.

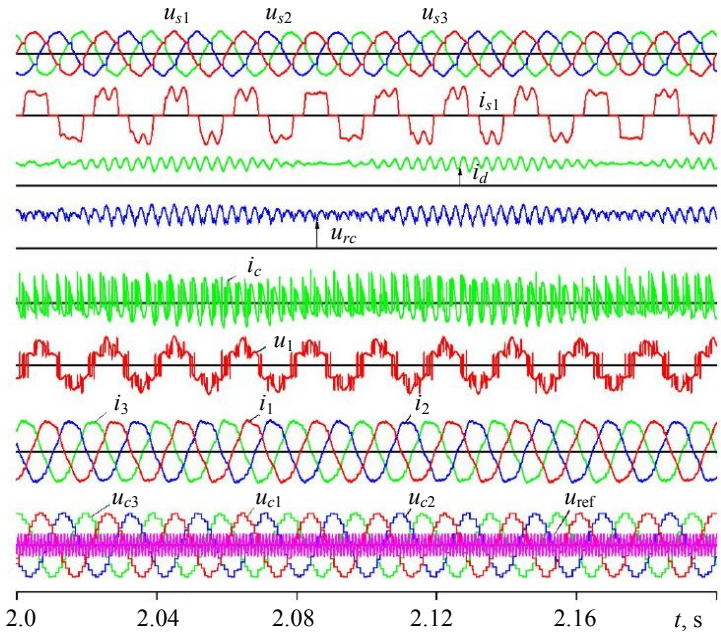


Fig. 2. Voltages and currents in a circuit with a diode rectifier and autonomous voltage inverter

DOI: 10.31897/PMI.2019.5.576

Dump trucks with a carrying capacity of 130 tons are equipped with a GST-800 synchronous traction generator with a rated power of 800 kW. When the generator is operating on an uncontrolled rectifier with a power factor of 0.84, the useful power of the generator-rectifier system will be equal to:

$$P_{gr} = P_g K_g K_r, \quad (1)$$

where P_{gr} – generator-rectifier system power; P_g – generator power; K_g – generator power factor, K_r – power factor of the generator when working on a diode rectifier.

The electromechanical transmission system of a mining dump truck is an energy system with an autonomous source, therefore the power generated by a synchronous traction generator determines the maximum power consumed by the traction motors. With a low power factor and a high distortion coefficient of the generator currents and voltages, additional losses of active power occur.

The presence of active power losses in an electromechanical transmission system necessitates the use of an overpower generator, which, according to the Arnold machine constant, which relates the power of an electric machine, the number of revolutions per minute, the length and diameter of the rotor, leads to an increase in the dimensions of the synchronous traction generator:

$$D^2 l = \frac{C_A P}{n_1}, \quad (2)$$

where D – rotor diameter; l – rotor length; C_A – Arnold's machine constant; n_1 – synchronous rotor speed, rpm; P – active power of an electric machine, kW. In addition, power losses lead to a decrease in the overall power of the synchronous generator, defined as the ratio of active power to overall.

Modernization options. The above disadvantages can be eliminated by modernizing the existing electromechanical transmission system by providing correction of the power factor of the generator-rectifier system.

An increase in the power factor of the system can be achieved by adding electric devices to the composition of the electromechanical transmission, which make it possible to correct the power factor: an active filter or an active rectifier [8] (Fig.3).

The power factor correction in these topologies is ensured by the use of fully controllable transistor switches (IGBTs) and tuning of the key management system to minimize reactive power. In addition, the technical solutions presented above allow you to maintain the voltage in the DC link at a given level.

The existing electromechanical transmission system contains a single cabinet of the frequency converter, which includes uncontrolled rectifiers and autonomous inverters (Fig.4) and installed under the safety visor next to the dump truck cab. The converter cabinet has a liquid cooling system [10].

The upgrade option, including an active filter, is less expensive, since the semiconductor switches are not selected for the full generator current, as in the case of an active rectifier, but for the value of the reactive current and distortion current:

$$I_{AV} = \sqrt{I_a^2 + I_r^2 + I_d^2}, \quad (3)$$

$$I_{AF} = \sqrt{I_r^2 + I_d^2}, \quad (4)$$

where I_{AV}, I_{AF} – currents flowing through the active rectifier and active filter, respectively; I_a – active current; I_r – reactive current; I_d – distortion current value.

As shown in [1], the use of a parallel active filter with a common direct current link in the structure of an autonomous power supply complex for oilfield facilities makes it possible to reduce the harmonic coefficient of the current *THDi* and voltage *THDu* of the source from 22.99 and

DOI: 10.31897/PMI.2019.5.576

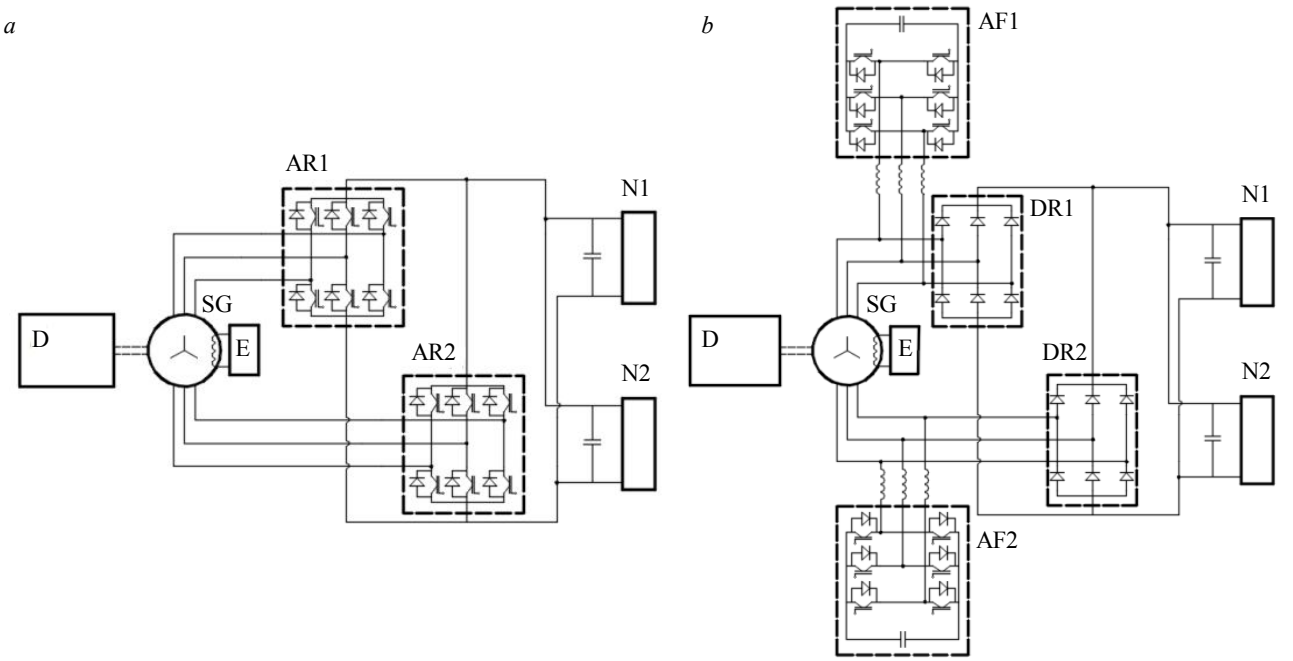


Fig.3. Options for modernization of the dump truck electromechanical transmission: *a* – using active filter (AF1, AF2); *b* – of active rectifier (AR1, AR2); N1, N2 – non-linear load (inverter, induction motor)

16.09 % to 0.43 and 1.43 %, respectively, and thereby increase the system power factor. In addition, this system allows to reduce the diesel fuel consumption of the primary engine by 12.47 % [1].

The most appropriate is the use of one active filter when working on a group of converters [3], but due to the fact that a six-phase synchronous generator is used in the electromechanical transmission of a dump truck, it becomes necessary to install an active filter in each of two three-phase branches and two additional capacitor banks (Fig.3, *b*), as well as an additional cooling system. This solution, in comparison with the modernization option using an active rectifier, will have a negative impact on the overall dimensions of the electromechanical transmission and increase the cost of maintenance and repair by increasing the number of components of the electromechanical transmission.

The modernization option using an active rectifier is the most promising solution, which allows to provide a power factor of the generator-active rectifier system close to 1. The implementation of this option will require the replacement of uncontrolled diode switch modules with power controlled IGBT transistors, which will not have a significant effect on mass and size parameters of the electromechanical transmission, while an additional cooling system is not required.

Mathematic modeling. To assess the influence of the operation of an asynchronous traction motor on the energy efficiency indicators of the traction generator, computer models of the electromechanical transmission of a mining dump truck were created, which allow one to adequately evaluate energy and electromechanical processes and synthesize control algorithms that provide the required static and dynamic modes of operation.



Fig.4. Transmitter cabinet placement on a mining truck

DOI: 10.31897/PMI.2019.5.576

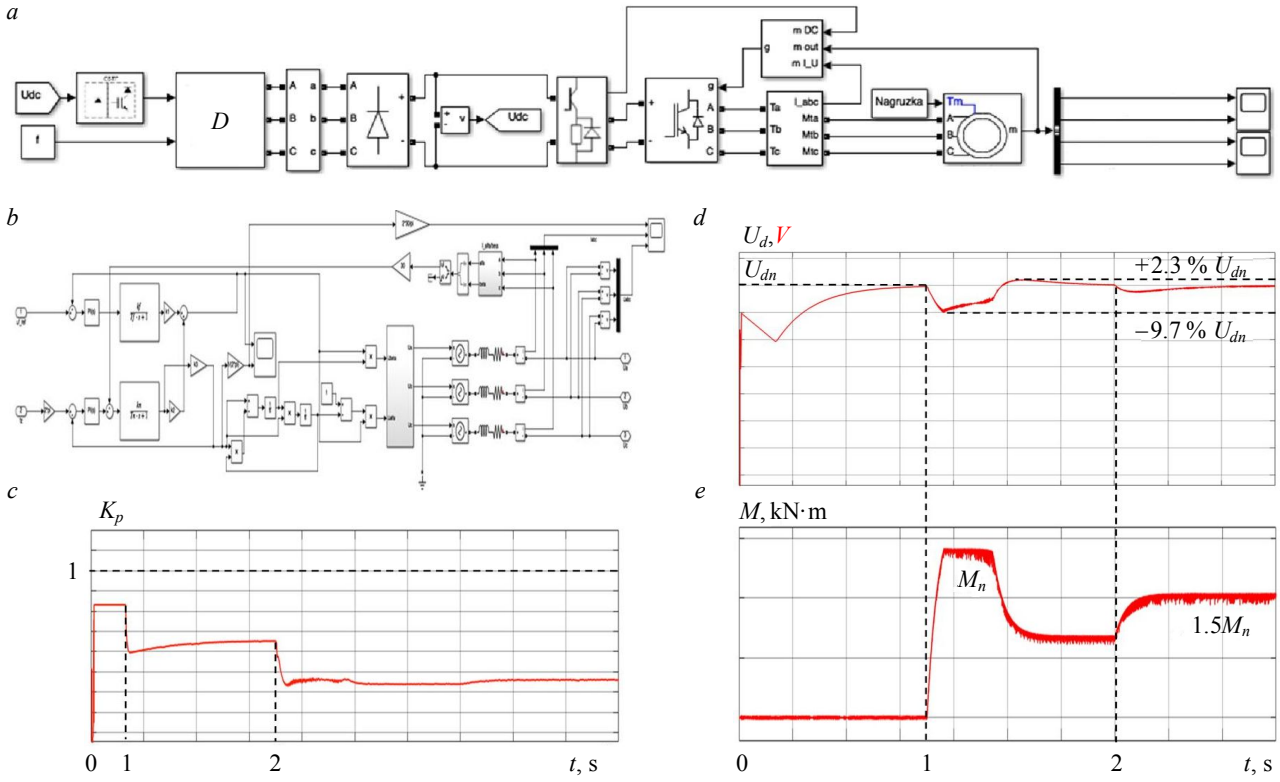


Fig.5. The mathematical model of the electric drive system: *a* – block diagram of the model; *b* – block diagram of diesel generator; *c* – power factor K_p of system generator – uncontrolled rectifier; *d* – DC link voltage U_d; *e* – electromagnetic torque of a traction induction motor *M*

The first model (Fig.5, *a*) is made according to the scheme developed by PJSC «Silovyye mashiny» and used on mass-produced models of dump trucks, which includes a model of a traction generator, an uncontrolled diode rectifier, and a vector-controlled traction induction motor. Maintaining a given voltage in the DC link in this model is carried out by voltage feedback, taking into account the time constant of the generator exciter.

The generator model is based on the passport data of the synchronous generator and the dependence of the output voltage on the rotation speed obtained from the test report of the prototype of the BelAZ asynchronous traction electric drive of the dump truck (Report on the test results of the prototype of the BelAZ asynchronous electric drive for the dump truck with a carrying capacity of 136 t. St. Petersburg: SPSMU, 2006. 62 p.) (see Fig.5, *b*).

The experiments with the model shown in Fig.5 were performed in the start-up mode of the diesel generator (*D*) until the DC link voltage reached the nominal value U_{dn} (Fig.5, *d*) (time 0-1 s) with the subsequent start of the induction motor under rated load M_n (Fig.5, *d*) (time moment 1-2 s) and its further increase to a double nominal value of 1.5 M_n (time moment 1-3 s). The power factor K_p calculated during the simulation is presented in Fig.5, *c*. It can be seen that when the induction motor was operating at rated load (time instant 1-2 s), the power factor of the generator-uncontrolled rectifier system was 0.76, and when the load was increased to double the rated value (time instant 2-3 s) – 0.68.

In addition, a Fourier analysis of the harmonic composition of the voltage of the generator system – an uncontrolled rectifier was performed and the coefficient of non-sinusoidality was calculated, which amounted to 13.94 %.

The second model (Fig.6, *a*) was developed on the basis of the proposed scheme for the modernization of electromechanical transmission using an active rectifier with a vector control system (*V*) with orientation along the voltage vector.

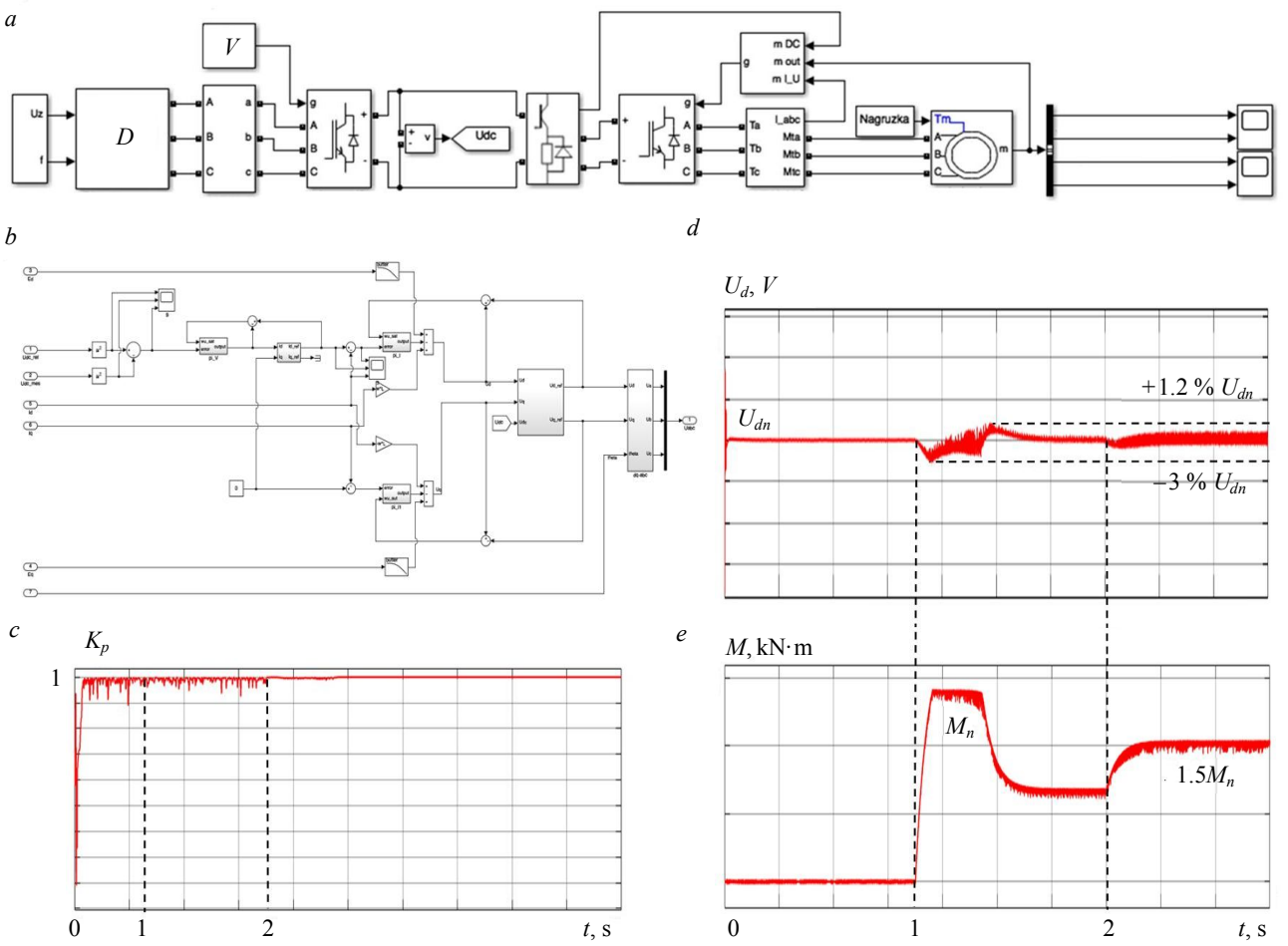


Fig. 6. The mathematical model of the modernized electric drive system: *a* – structural diagram of the model; *b* – structural diagram of a vector control system of an active rectifier; *c* – power factor K_p of the generator-active rectifier system; *d* – DC link voltage U_d; *e* – electromagnetic moment of the traction induction motor *M*

The simulation results of the upgraded circuit in the similar operating modes used in the first model are presented in Fig.6.

Conclusion. It can be seen from the results that the use of an active rectifier with a vector control system with a voltage vector orientation as part of an electromechanical transmission of a mining dump truck allows you to ensure the power factor of the generator-active rectifier system close to unity (0.95-0.99) in all asynchronous operation modes engine, with rated and double rated load (time 1.2 s).

Analysis of the voltage of the generator-active rectifier system showed a decrease in the non-sinusoidal coefficient to 8.4 %, which in turn will increase the service life of the synchronic machine.

REFERENCES

1. Abramovich B.N., Sychev Yu.A., Zimin R.Yu. Evaluation of the effectiveness of hybrid systems for correcting the shape of current and voltage curves in electric networks with distributed generation. *Promyshlennaya energetika*. 2018. N 1, p. 45-54 (in Russian).

2. Kazovskii E.Ya., Danilevich Ya.B., Kasharskii E.G., Rubisov G.V. Abnormal operating modes of large synchronous machines. Leningrad: Nauka, 1969, p. 429 (in Russian).

3. Emel'yanov A.P., Vershinin V.I., Kozyaruk A.E. Machine electric drive and equipment. Sankt-Peterburgskii gornyi universitet. St. Petersburg, 2017, p. 297. URL: http://www.iprbookshop.ru/78137.html (Access date: 14.01.2019) (in Russian).

4. Kozachenko V.F., Ostrirov V.N., Lashkevich M.M. Electric transmission based on a valve-induction motor with independent excitation. *Elektrotekhnika*. 2014. N 2, p. 54-60 (in Russian).

DOI: *10.31897/PMI.2019.5.576*

5. Kozyaruk A.E. Energy-efficient electromechanical complexes of mining and transport vehicles. *Zapiski Gornogo instituta*. 2016. Vol. 218, p. 261-269 (in Russian).

6. Mariev P.L., Anistratov K.Yu. «BelAZ» and current trends in the development of mining vehicles. *Gornaya Promyshlennost'*. 2001. N 6, p. 29-32 (in Russian).

7. Overview of global manufacturers of mining trucks. Development trends. URL: https://maxi-exkavator.ru/articles/trucks/~id = 626 (Access date: 25.02.2000) (in Russian).

8. Kozyaruk A.E., Kamysh'yan A.M. Patent N 2653945 of the RF. Energy-efficient traction electric drive of an autonomous vehicle. Opubl. 19.05.2018. Byul. N 14 (in Russian).

9. Pronin M.V., Vorontsov A.G. Power fully controllable semiconductor converters (simulation and calculation). St. Petersburg: Elektrosila, 2003, p. 172 (in Russian).

10. Pronin M.V., Vorontsov A.G. Electromechanotron complexes and their modeling according to interconnected subsystems. St. Petersburg: Ladoga, 2017, p. 177 (in Russian).

11. Vinogradov A.B., Sibirtsev A.N., Chistoserdov V.L., Gnezdov N.E., Korotkov A.A. AC traction electrical equipment for BelAZ mining dump trucks with a loading capacity of 90 and 240 t. Sbornik materialov III Vserossiiskoi nauchno-prakticheskoi konferentsii «Energetika i energosberezhenie: teoriya i praktika». Kemerovo: KuzGTU, 2017, p. 303-309 (in Russian).

12. Yasyuchenya S.V. On increasing the operational efficiency of open pit mining at OJSC «SUEK». *Gornaya Promyshlennost'*. 2013. N 6, p. 23-28 (in Russian).

13. Aspalli M.S., Asha R., Hunagund P.V. Three phase induction motor drive using IGBTs and constant V/F method. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*. 2012. Vol. 1, p. 463-469.

14. Rachana G., Priya M., Parmod K., Rohit G. Design of unity power factor controller for three-phase induction motor drive fed from single phase supply. *Journal of Automation and Control Engineering*. 2014. Vol 2. N 3, p. 221-227.

***Authors*: Anatoly E. Kozyaruk**, *Doctor of Engineering Sciences*, *Professor*, *kozjaruk@mail.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Albert M. Kamyshyan**, *Postgraduate Student*, *dvorff@ya.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

The article was received on 15 January, 2019.

The paper was accepted for publication on 26 May, 2019.