On improving the energy efficiency of electric mining excavators

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Abstract. The main directions of increasing the efficiency of using energy resources in mechatronic systems of mining excavators are considered. The main factors affecting the energy efficiency of excavators in quarries are the characteristics of the rock, the quality of the explosive preparation, the organization of the mining and transport complex, the characteristics and condition of the equipment, the geological conditions, the qualifications of the driver, etc. Improving circuit solutions and components allows to change ideological principles of the construction of mechatronic systems and provides the possibility of a significant increase in energy characteristics. The highest energy efficiency is achieved when using AC drives with asynchronous motors for excavators. The current issues of improving the power supply system and reducing the loss of electrical energy in the supply networks are considered.

1. Introduction
The effective use of all types of resources in all areas of society is a global challenge of the 21st century. Directions of its solution are the development of energy-efficient management systems, continuous monitoring and diagnostics of technical systems and their components during the life cycle in order to maximize the use of resources, reduce the cost of maintaining working condition, ensuring operational safety [1]. Excavators, drilling rigs, dump trucks, dredgers and other machines in open pits belong to the category of energy-intensive equipment: the installed capacity of electrical equipment reaches 1 MW or more. In this case, the machines operate in dynamic modes with large overloads and the recovery of a significant part of the energy (when braking mechanisms, actively counteracting the mountain massif, lowering the excavator bucket), and in severe climatic conditions [2].

Energy efficiency of excavators in quarries is usually estimated by the ratio of energy spent on loading a rock to the volume or mass of submerged rock for a fixed time interval, for example, the excavation cycle, shift, month [3]. This indicator depends on many factors and varies widely for different quarries and excavators. The main factors affecting the energy efficiency of excavators in quarries are the characteristics of the rock, the quality of the explosive mass preparation, the organization of the mining and transport complex, the characteristics and condition of the equipment, the geological conditions, the driver’s qualifications [4].
At the mining enterprises, energy efficiency measures are aimed at all aspects of the mining operations \cite{1, 5}. In this case, the main link in this process is a mining machine, the characteristics of which are laid during the design and must be maintained during operation.

The paper discusses the main directions of increasing the efficiency of using energy resources in mechatronic systems of mining excavators and examples of their implementation in equipment designed and manufactured by the “Joint Power” Company, Moscow.

2. **Increasing the energy efficiency of main drives**

Main drives – the main consumer of electrical energy of the excavator. The improvement of their circuit solutions and components allows changing the ideological principles of the construction of mechatronic systems and makes it possible to significantly improve the energy characteristics.

Achievement of the mechatronic technology of excavator drive system design can be considered the possibility of generating the desired drive characteristics for various types of engines due to special control algorithms implemented using microcontroller means.

“Joint Power” Company from 2012 to 2018 completed AC drive projects for Russian excavators with a bucket capacity from 10 m$^3$ to 35 m$^3$. The AC drives uses asynchronous motors of the special excavators series manufactured by the Safonovsky Electric Machine Building Plant (Concern “Ruselprom”). The drive control system is implemented using the vector principle of the subordinate speed control of an asynchronous motor with nonlinear current limitation, providing enhanced energy characteristics.

The use of a new AC drive system provides:

- increased reliability of electromechanical equipment, reduced operating costs due to the use of electric machines without sliding contacts;
- high electromagnetic compatibility of electrical equipment: the power factor is kept constant and equal to 1, the distortion factor of the current consumed does not exceed 5%;
- increased energy characteristics: specific energy consumption, measured during the excavation cycle, is 0.2 kWh/m$^3$;
- reduction of losses in the power supply network;
- the ability to work on “weak” networks.

With any structure of the system in cases of changes in control actions and mechanical loads, to ensure high energy efficiency, appropriate regulation of processes is necessary \cite{7}. Controlling an electromotive device in order to increase the efficiency of energy use is a classic task of the theory and practice of an electric drive. It consists in the search and implementation of motion control, which ensures minimum energy loss during the performance of a given work. Optimization of frequency-controlled asynchronous electric drives is carried out due to modern vector control algorithms of machines \cite{8, 9}. The tasks of optimizing the energy characteristics of the mechatronic system during the development of software motions are reduced to finding controls that deliver at least the specified functionality.

There is a practical interest in usage of nonlinear feedbacks in mechatronic systems of the excavator main drives. Such feedbacks on power or power losses in an electric machine together with special regulating devices provide current and speed waveforms in dynamic modes close to optimal according to the criterion of minimum power consumption and limiting drive power.

Recuperated energy in the excavation cycle reaches 30%. This energy is partially used by the drive of the machine, connected by a common local DC network, as well as electrical equipment of the excavator’s own needs. But the main part of it with the help of active rectifiers returns to the network. In this regard, a promising solution for mechatronic systems of an excavator is the use of electric energy storage devices based on supercapacitors for the efficient use of recovered energy on an excavator \cite{10}.

Now there is practical interest in the development of a hybrid drive for mining excavators. For the accumulation of recovered energy produced by lowering the boom and arm under its own weight, as well as a result of braking the turntable, supercapacitors are used. This energy then provides power
to the hydraulic system when the machine is operating at peak power. Diesel-electric hybrid recovery technology reduces fuel consumption per ton by up to 25%. The P&H 2650CX hybrid excavator reduces the cost of loading a ton of rock by 15% compared to diesel hydraulic excavators by combining lower fuel consumption, increased availability and lower maintenance and repair costs [11].

For power converters, energy efficiency is achieved by using new electronic components with improved characteristics, for example, silicon carbide-based semiconductor devices [12], special energy-saving circuit solutions [13].

High energy characteristics of electric drives are the basis, but not a guarantee of efficient energy conversion. Processes in mechatronic systems are determined by the interaction of all their elements and technological processes. Therefore, improving energy efficiency involves the improvement of the structural organization of systems and includes the following methods:

1. Improvement of technological processes aimed at reducing their energy intensity. In the mining industry with the traditional mining of mineral resources by the open method, the change in technology is mainly due to the rational choice of parameters of the transport and technological complex. In world practice, there is a tendency to increase the volume of the excavator bucket and the load capacity of dump trucks.

2. Rational construction of the system through the optimal choice of the type of current, types of motors, converter and transfer devices, coordination of the characteristics of the elements, etc.

3. The optimal choice of elements by power. Analysis of statistical data on the operating modes of electrical equipment, including drive engines, suggests that the engines, as a rule, operate with incomplete loading and, therefore, with reduced energy performance.

4. The use of monitoring to obtain objective information about the operation of the machine during the work [14]. The results of monitoring an excavator can significantly improve the efficiency of equipment operation, primarily by increasing its reliability in specific geological conditions, the coefficient of technical use, the timely implementation of preventive measures, and energy saving.

3. Reducing power losses in the supply network
Losses in the network depend on its frequency response and current spectral density. With a constant network characteristic, they are minimal if the effective current has a minimum value for a given active power.

The main directions and methods of improving the efficiency of energy transfer from the source to the consumer:
- the use of compensating devices to increase the power factor and quality of electrical energy;
- reduction of currents consumed by electric drives and other equipment;
- the use of electric drive control algorithms that provide increased electromagnetic compatibility of equipment.

An effective element of the electrical system - an active rectifier, is an adjustable voltage source that feeds the excavator’s local DC network [6]. The voltage in the DC link is kept constant and practically does not depend on the voltage in the network, both during consumption and in the recovery mode. Control of the components of the current vector consumed from the network or delivered to the network provides a virtually sinusoidal current, thereby achieving the best conditions for electromagnetic compatibility of equipment. The use of vector control algorithms allows you to adjust the power factor and thus compensate for the reactive power in all modes.

4. Conclusion
The efficient operation of open-pit excavators is ensured by the rational use of the energy resource, high electromagnetic compatibility of all components, complete control of electric power processes and the use of multifunctional protection devices. The considered directions and methods of increasing the energy efficiency of electric excavators are implemented in control systems offered by “Joint Power” Company. Due to the use of new element base of mechatronic control systems on excavators
(special AC motors, transistor converters, active rectifiers, etc.) and special intelligent control algorithms using nonlinear feedback and energy watches, the specific energy consumption of excavation was reduced to 0.2...0.4 kWh/m³. The power factor of mining machines has been increased from 0.3 (Ward Leonard system) to 0.9 due to the use of active rectifiers. The losses of electricity in the power supply networks are reduced by 3...4 times due to the maintenance of a high power factor.

References

[1] Awuah-Offei K 2016 *Journal of Cleaner Production* vol 117 89–97
[2] *Modern American coal mining. Methods and Applications* 2013 (Society for Mining, Metallurgy and Exploration, Inc.) ed C J Bise p 563
[3] Vukotic I and Kecojevic V 2014 *International Journal of Mining Science and Technology* 24 259 – 268
[4] Awuah-Offei K, Osei B and Askari-Nasab H 2011 *Transactions of the Society for Mining, Metallurgy and Exploration* 330 673–584
[5] Levesque M, Millar D and Paraszcak J 2014 *Journal of Cleaner Production* 84 233-255
[6] Malafeev S I and Novgorodov A 2016 *Russian Electrical Engineering* vol 87 10 560–565
[7] Malafeev S I and Zaharov A V 2008 *Russian Electrical Engineering* vol 79 7 349–352
[8] Vas P 1998 Sensorless Vector and Direct Torque Control (Oxford University Press) p 729
[9] Bose B K 2002 *Modern Power Electronics and AC Drives* (Prentice Hall PRT) p 738
[10] Kolner W 2013 *Peak Shaver* (Siemens AG) p 8
[11] P&H 2650 CX Hybrid Shovel. Joy Global 2016 p 7
[12] Melkonyan A 2007 *High Efficiency Power Supply Using New SiC Devices* (Kassel University Press) p 157
[13] Pandit P, Mazumdar J, May T and Koellner W G *IEEE Transactions on Industry Applications* vol 46 5 1755–63
[14] Malafeev S I, Malafeev S S and Tikhonov Y V 2018 *Advances in Neural – Computation, Machine Learning and Cognitive Research. NEUROINFORMATICS 2017. Studies in Computational Intelligence* vol 736 110–116