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## The Current State of Excavators and Energy Efficiency Issues in The Process of Mining Rock Mass

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# The Current State of Excavators and Energy Efficiency Issues in The Process of Mining Rock Mass

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**Abstract.** This article analyzes the control systems of electric drives of quarry excavators currently used in mining operations, their dynamic and operating modes, as well as work aimed at increasing the efficiency of the electromechanical system. The main areas of research and development to improve excavator electric drive operating modes and enhance their energy efficiency are also analyzed. The relative energy consumption of excavator control systems used in mining environments is compared, and the factors influencing the efficiency of electromechanical systems are analyzed. The goals and objectives of the study were determined on the basis of an analysis of scientific literature and a study of scientific and practical work carried out in the divisions of the republican mining and metallurgical complex.

## INTRODUCTION

The most energy-intensive processes in the mining industry are ore extraction and ore transportation. In the process of excavating and loading the rock mass, single-bucket quarry excavators are widely used. During rock mass excavation, quarry excavators equipped with bucket mechanisms of various capacities are applied [1-4].

These types of quarry excavators are high-power and mechanically robust machines and are considered the most reliable equipment for excavating hard rock ores with a high degree of hardness and loading them onto transport vehicles. As a result of high mechanical friction and heavy loads, a high level of wear of excavator mechanisms is observed. Significant variations in load also lead to an increase in the number of mechanical failures [5-6]. It is well known that ore extraction is carried out using various types of quarry excavators, in which diesel engines, alternating current (AC) electric motors, and direct current (DC) electric motors are used as the main drives. In the mining industry, during ore excavation and loading processes, it is recommended to use high-performance excavation machines equipped with AC electric motors. Their advantages lie in lower power consumption and higher energy efficiency compared to other types of electric motors used in other industrial sectors. In such quarry excavators, diesel power plants or gas turbine generators are used as the main and backup sources of electrical energy. Reducing the electrical energy consumption of the electromechanical system leads to a decrease in fuel consumption at power plants [7-8]. Scientific studies devoted to the analysis of modern control methods for electromechanical systems are aimed at an in-depth investigation of the operating processes of mining excavators, the development of mathematical models to improve their efficiency, and the обеспечение of reliability. Various studies have produced complementary results. K. A. Kononenko and A. G. Shpagin analyzed the movements of the main mechanisms of a single-bucket excavator – the boom and the bucket – under different load conditions and developed mathematical models that take into account inertia forces, shifts in the center of gravity, and stresses in the structure. These models make it possible to optimize control algorithms under conditions close to real operating processes, prevent excessive mechanical stresses in structural units, and achieve resource savings. B. N. Petrov and I. P. Solovyov modeled the dynamics of electric drives for the main and auxiliary mechanisms of mining machines (bucket, stick, slewing platform), providing a comprehensive assessment of the effects of voltage–speed–harmonic relationships, torque, and load resistance. Their models are distinguished by high accuracy in both transient and steady-state operating modes and by their suitability for integration into automated control systems [9-10].

## METHODOLOGY

The reliability of mining excavators is a crucial criterion that ensures their continuous, safe, and efficient operation. Improving reliability is important not only for the main drives but also for pumps, compressors, auxiliary motors, and other components. To optimize this process, several key directions can be identified.Control of excavation and loading modes.The operation of the main mechanisms (bucket, stick, slewing platform) must be controlled in accordance with the load conditions. Dynamic loads acting on the working elements are monitored in real time, and control algorithms that ensure optimal speed and torque supply are implemented. Through automated control systems, motion characteristics are adjusted in response to load variations.Reliable operation of auxiliary equipment.Auxiliary systems such as pumps, compressors, and fans play a decisive role in excavator operation. To ensure their reliable functioning, backup power supply sources (batteries, diesel generators) are introduced. Potential failures are prevented through sensor-based monitoring and intelligent alarm systems for each auxiliary device.Intelligent control and monitoring.

One of the most effective ways to improve reliability is the use of intelligent monitoring algorithms. These algorithms analyze each motor or mechanism individually and create optimal start-up and shutdown conditions for them. Based on data collected from sensors, preventive maintenance strategies are developed.Maintenance and preventive strategies.Through statistical analysis, the operating periods and wear characteristics of pumps and compressors are evaluated. On the basis of these data, preventive maintenance intervals are determined. Continuous diagnostics is carried out to reduce inter-system dependencies and the probability of failures Improving energy efficiency during the operation of mining excavators is one of the most relevant directions in modern mining industry. Excavators, especially in large open-pit mines, operate as the main equipment for excavation and loading under constant loads, diverse geological conditions, and variable operating modes. This, in turn, leads to significant electrical energy consumption. Therefore, the need to apply adaptive, energy-saving, and optimal control solutions tailored to different operating conditions is steadily increasing Recent scientific research indicates that overall energy efficiency can be significantly improved by analyzing excavator operating modes, optimizing the load and speed characteristics of electric drives, and implementing additional energy-saving technologies. Special attention in these studies is given to real-time load monitoring, intelligent control algorithms, regenerative braking systems, and redundant power supply schemes.Research on improving the energy efficiency of mining excavators encompasses a wide range of innovative approaches and technical solutions. Using the methodology developed by T. S. Kamalov and O. Toirov, the fuel consumption and energy efficiency of excavators used in open-pit mines were evaluated based on specific indicators, enabling the selection of optimal operating modes [11-13].In the hybrid electrodynamic powertrain architecture proposed by Nguyen, the application of potential energy recovery and optimal control strategies resulted in efficiency improvements of up to 36–45% [14-16]. The electrohydraulic control and energy recovery system developed by Li and co-authors demonstrated energy savings of up to 92% according to simulation results [17].In developing a new generation of automated drives, it is necessary to fully account for the dynamic characteristics of electric machines, predict load variations occurring in the drive system, implement intelligent control algorithms, and use digital interfaces that ensure fast and reliable information exchange. At the same time, such drives increasingly incorporate energy-saving operating modes, regenerative braking systems, as well as remote monitoring and diagnostic capabilities via applications.The development of automated electric drives for mining excavators not only enhances energy and economic efficiency but also enables industrial digitalization, improves worker safety, and ensures long-term operational sustainability of excavators. Research and scientific-practical developments in this field play an important role in achieving technological advancement in the national mining sector.Studies published in the Journal of Mechatronix identified a relationship between operational performance and environmental efficiency through improvements in automation, layout of structural elements, and recovery systems [18-19]. Aliyev and Abdurazzoqov analyzed the kinetic and geometric parameters of excavators and proposed models for calculating energy consumption at each movement segment of the excavation process [20-21].In a study published in Energy Conversion & Management, an adaptive energy management method was applied to a hybrid hydraulic excavator, demonstrating the potential to reduce fuel consumption and emissions by 30–48% [22-23].The analysis of the reviewed scientific works confirms that reducing the specific energy consumption in ore excavation largely depends on the physical and mechanical properties of the ore – particularly density and hardness – as well as on the loading mechanisms of the excavator and their control systems.

Researchers have mathematically modeled variations in energy demand during the excavation process and determined cutting angles, trajectories, and pressure regimes corresponding to different ore types. To reduce energy consumption, the use of renewable energy resources, smart sensors, real-time control algorithms, and preventive diagnostic systems has been proposed.In an Industrial Automation article, optimal control solutions were developed through the analysis of operating parameters and cycle characteristics [24-25]. Overall, these studies and developments demonstrate that integrating hybrid technologies, automated control systems, and energy recovery methods can significantly improve the economic and environmental efficiency of mining excavators.

## EXPERIMENTAL RESEARCH

Various approaches exist to eliminate the shortcomings of excavator electric drives. Modernization of direct current (DC) electric drives is not a radical solution. At the present stage, the necessity of transitioning to alternating current (AC) electric drives with frequency control is becoming increasingly evident. At the same time, excavators operating with DC electric drives – especially those equipped with buckets having capacities from 5 m³ to 10 m³ – will continue to be operated for a long period [26]. These excavators are mainly intended for small open-pit mines, where rapid renewal of the excavator fleet is economically and organizationally difficult.

For controlling excavator electric drives, combined control systems based on the theory of optimal control have been found to be effective. Many researchers have conducted scientific studies aimed at improving the energy efficiency of electric drives used in mining excavators. Depending on the type of electric drive applied in mining excavators, the relevant literature can be classified as follows:

-Generator–motor electric drive systems;

-Thyristor rectifier–DC motor drive systems;

-Transistor rectifier–DC motor drive systems;

-Frequency converter–asynchronous motor electric drive systems.

One of the most effective methods for assessing the efficiency of excavators operating under mining conditions is evaluation based on specific electrical energy consumption. Taking this aspect into account, the specific electrical energy consumption of excavator mechanisms operating under different control systems in quarry conditions was analyzed in Table 1. Based on the table data, it can be concluded that the specific electrical energy consumption of excavator electric drives is directly dependent on the bucket capacity and the control method of the electric drive [27-29]. Relying on these data, and considering the factors affecting excavator productivity discussed above, there is potential to further improve the efficiency of electric drives.

**TABLE 1.** Values of specific electrical energy consumption during ore excavation under real operating conditions of excavators at the “Kalmakyr” mine of JSC AMMC

| Bucket capacity (m³) | Generator–Motor system | Thyristor rectifier + DC motor | Transistor rectifier + DC motor | Frequency converter + induction motor |
|---|---|---|---|---|
| EKG-8 | 1.4–1.6 kWh/ton | 1.2–1.3 kWh/ton | 1.0–1.1 kWh/ton | 0.8–1.0 kWh/ton |
| EKG-12 | 1.3–1.5 kWh/ton | 1.1–1.2 kWh/ton | 0.9–1.0 kWh/ton | 0.7–0.9 kWh/ton |
| EKG-15 | 1.2–1.4 kWh/ton | 1.0–1.1 kWh/ton | 0.8–0.9 kWh/ton | 0.6–0.8 kWh/ton |
| EKG-20–25 | 1.1–1.3 kWh/ton | 0.9–1.0 kWh/ton | 0.7–0.8 kWh/ton | 0.5–0.7 kWh/ton |

*Development of Alternating Current (AC) Electric Drives.* Currently, active research is being conducted in Russia and abroad on the creation of AC electric drives for excavators. In this field, the works of scientists such as V. I. Klyuchev, T. Z. Portnoy, L. M. Mironov, S. M. Postnikov, A. S. Sapelnikov, B. V. Olkhovikov, V. V. Berezin, M. B. Polinsky, A. V. Druzhinin, A. G. Babenko, B. M. Parfenov, and many other specialists are of particular significance. In addition, AC excavator electric drives proposed by companies such as ABB and Siemens have attracted considerable interest. Improvement of Direct Current (DC) Electric Drives. At the same time, the development of modern DC electric drives for excavators remains an urgent task [30-33]. These systems are primarily intended for the modernization of the existing excavator fleet, ensuring maximum preservation of electromechanical equipment. Furthermore, these systems can also be used to equip newly manufactured DC excavators that are still in production.

## RESEARCH RESULTS

The amounts of electrical energy consumed to excavate one ton of ore under real operating conditions for EKG-series excavators used at the “Kalmakyr” mine of Almalyk Mining and Metallurgical Complex (JSC) were analyzed according to the control systems of the excavator electric drives and summarized in the following table. In addition, separate measurements of the main mechanisms of the EKG-series excavators were conducted, determining the share of electrical energy consumed by each mechanism (Figure 1).

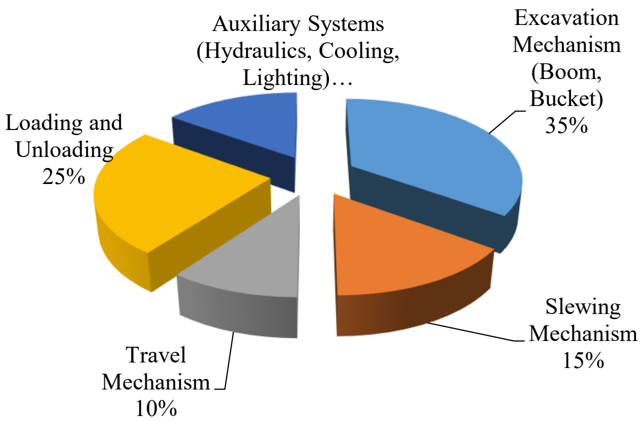


**FIGURE 1**. Distribution of Electrical Energy Among the Main Components of an EKG-Series Excavator

In our country, the Almalyk Mining and Metallurgical Complex was the first to abandon the use of rotating electromechanical amplifiers in the power chains of excavator electric drives. The main mechanisms of the powerful EKG-15 open-pit excavator, manufactured by KARTEX, were equipped with electric drives based on the TP-D system, and these machines began to be used in our mines. At the same time, in Russia, four modifications of thyristor amplifiers produced by the KARTEX association (KTP-E type amplifiers) have successfully passed industrial trials

Impulse phase control systems have been developed for the control devices of frequency converter units. In these systems, the opening degree of the semiconductor is controlled through pulses of varying values and shapes, allowing the delivery of the required power to the motor. The complexity lies in accurately analyzing variable loads on the excavator, modeling control systems corresponding to these loads, and determining optimal parameters for energy-saving operating modes, which remains a critical challenge today.

## CONCLUSIONS

In conclusion, modern mining excavators are one of the primary working mechanisms in the mining and construction sectors, and their operational efficiency, energy savings, and service life directly depend on the capabilities of their electric drives and control systems. Research results indicate that by using frequency converter-driven asynchronous motors, thyristor generator–motor systems, hybrid energy recovery solutions, and intelligent sensor complexes, it is possible to reduce energy consumption by 15–40%, improve control accuracy by up to 30%, and significantly extend the service life of main mechanisms. Overall, the integrated application of modern control and energy-saving technologies is essential for optimizing the operation of mining excavators, reducing operational costs, and enhancing the competitiveness of the industry. Furthermore, scientific and practical developments in this area can be widely applied not only in mining but also in large-scale energy and mechanized production sectors. Such approaches have strategic importance for rational resource use, ensuring environmental sustainability, and achieving economic efficiency in our country.

Based on the relevant literature, published scientific works, and scientific-practical studies conducted in the divisions of the national mining and metallurgical complex, the following research tasks have been identified:

- Develop energy- and resource-efficient operating modes for mining excavators based on controllable electric drives;
- Improve the performance of mining excavators through modernization of control systems and electrical equipment;
- Mathematically model the control system of the excavator and the dynamic modes of its electromechanical systems;
- Develop a mathematical model for determining electrical energy consumption, taking into account the main energy, operational, and technological factors affecting energy efficiency;
- Develop a comprehensive methodology for assessing energy efficiency during the operation of excavators;
- Model adaptive operating modes of electric drives depending on ore type, hardness, and the excavator's loading mechanisms to reduce specific energy consumption during ore excavation;
- Develop methods for calculating and improving the energy efficiency of electric drives in mining excavators;
- Develop algorithms for selecting electric drives, frequency converters, and control laws for excavator equipment during the ore excavation process;
- Develop control algorithms using frequency converters based on software methods to ensure optimal operating parameters adapted to the excavator's working conditions.

The energy- and resource-efficient modes developed will allow reducing expenditures during ore excavation and loading, conserving energy resources, and increasing labor productivity by ensuring the effective use of electrical equipment in mining excavators.

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