On the use of compensators in electric networks of mining enterprises

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Abstract. The electric power processes in the electric networks of the quarries during the work of excavators with various electric drive systems are considered. In the conditions of power supply of excavators from long cantilever lines, constantly changing network topology and a very uneven load schedule, an urgent task is to ensure the quality of electricity at the consumers’ inlets. Fluctuations and voltage deviations adversely affect the operation of excavators, the reliability and durability of electrical equipment, the functioning of protection, etc. Therefore, to effectively use the energy resource, it is necessary to use a set of methods and means aimed at reducing voltage and power losses in power networks, improving the quality of electricity and providing electromagnetic compatibility. Improving the efficiency of power supply to mining machines is provided by regulating the voltage and flow of reactive energy.

The features of the use of fast-acting reactive power compensators to maintain the quality of electricity in quarry networks are considered.

1. Introduction

Electricity distribution systems used to power mining machines in open pits consist of medium-voltage overhead lines, usually 35 kV, step-down transformers (mainly with a secondary voltage of 6 kV) and long three-phase cables (in many cases more than one kilometer) [1]. Excavators and other machines in open pits are classified as energy-intensive equipment: the installed capacity of electrical equipment reaches 1 MW or more. At the same time, the machines operate in dynamic cyclic modes with large overloads and recovery of a significant part of the energy (when braking mechanisms, actively counteracting the rock massif, lowering the excavator bucket) [2, 3]. Peak power consumption typically exceeds 1.6 times the average value. The operation of the excavator leads to deviations, fluctuations and distortions of the voltage, a decrease in the power factor, i.e. reducing the quality of electricity [4].

In the twentieth century, mining excavators were equipped with electric drives based on the generator – DC motor system (Ward Leonard). The traditional generator-motor system (Ward Leonard), by the principle of operation, is reversible with simple bidirectional energy transfer, automatically provides the required four-quadrant mechanical characteristics and, with modern microcontroller control, has high technical characteristics. A feature of such a system is the use of a
synchronous drive motor, which consumes an advanced current during overexcitation. Due to the capacitive current in the network, an increase in voltage at the input of the excavator is achieved. The Ward Leonard drive system is being actively superseded by other progressive technical solutions, including those made on the basis of AC motors [5, 6]. The use of thyristor controlled rectifiers for controlling motors, for example, in P&H excavators, leads to a distortion of the shape of the consumed current and a phase shift of the fundamental harmonic with respect to voltage. The operation of such excavators is impossible without compensating and filtering devices [7, 8].

In modern excavators, transistor converters with pulse-width modulation are used to control DC and AC motors [9]. A new element of such a drive system - an active rectifier, is an adjustable voltage source that feeds the excavator's local DC network [10]. The control of the components of the current vector consumed from the network or delivered to the network provides an almost sinusoidal current shape, which ensures the best conditions for the electromagnetic compatibility of the equipment. Using vector control algorithms allows you to adjust the power factor and thus compensate for reactive power in all modes [11].

The paper discusses the current issues of the use of compensating devices to increase the efficiency of energy resources use in mechatronic systems of mining excavators and examples of their implementation in equipment designed and manufactured by the “Joint Power” Company, Moscow.

2. Electrical power processes in the power systems of excavators

In figure 1 are shown a simplified equivalent single-line circuit of an electric line with active resistance \( r \) and inductive resistance \( x \), which provides power for a mining excavator. In fig. 1 is denoted: \( \dot{E} \) – power center voltage; \( \Delta \dot{U} \) – voltage drop in the supply network; \( \dot{I} = I_a + j I_r \) - mains current; \( I_a \) – mains active current; \( I_r \) – mains reactive current; \( \dot{U} \) - voltage at the load node; \( x_c \) – equivalent reactance of the compensating device; \( z_l \) – complex load resistance. The reactive load current may be inductive or capacitive. The excavator can both consume electrical energy and recuperate it into the mains.

![Figure 1. Simplified electrical system diagram.](image)

In figure 2 are shown the vector diagrams of currents and voltages in the load node in the consumption mode of the active-inductive current. In the drawing are denoted: \( I_{rl} \) – load reactive current; \( I_c \) – reactive current compensation device. The active current of the supply network is equal to the active current of the load \( I_a = I_{al} \). The sign of the reactive current is determined by its nature: inductive (lagging behind voltage) current is negative, capacitive (leading voltage) positive. A positive active current corresponds to energy consumption, a negative active current corresponds to the recovery of energy into the supply network.

Based on the vector diagram shown in fig. 2, it is possible to make an equation for the effective voltage values:

\[
E^2 = (U + rI_{al} - xI_r)^2 + (rI_r + xI_{al})^2, \tag{1}
\]

where \( E \) is power center voltage.
The solution of equation (1) regarding the voltage at the input of the excavator gives the expression

\[ U = \sqrt{E^2 - (rI_r + xI_{al})^2 + (rI_{al} - xI_r)^2}. \]

The power loss in the supply line during the flow of current is

\[ P_n = r^2 (I_{al}^2 + I_r^2). \]

The power factor at the input of the excavator is determined by the formula

\[ \lambda = \cos \varphi \approx \frac{|I_{al}|}{\sqrt{I_r^2 + I_{al}^2}}. \] (2)

Equation (2) determines the power factor module. The current in the line in this case can be leading or lagging in phase from the voltage.

When working excavators with drives using the Ward Leonard system, a large leading current is consumed. Due to this, the voltage at the input of the excavator is maintained too high. In figure 3a shows the waveforms of active and full power recorded during the operation of the EKG-1500R excavator. For comparison, in figure 3b shows similar waveforms for the ECG-18R excavator, at the input of which the power factor is maintained equal to 1.
Figure 4 shows the calculated dependence of the voltage at the input of the excavator on the active load current $I_a$ under different conditions of consumption of reactive current $I_r$. In the calculations, the following network and supply line parameters were adopted: The voltage at the substation is 6 kV; active and inductive reactance of the line are equal $r=1$ Ohm; $x=1$ Ohm. Line 1 corresponds to the load operation mode with lagging current at a power factor $\lambda = 0.7$. Line 2 shows the dependence of voltage on the active current at a constant capacitive component of the load current equal to 100A. Line 3 corresponds to processes with power factor $\lambda = 1$. The slopes of the lines are proportional to the sensitivity of voltage changes to changes in the active current. Shown in fig. 4 dependencies show that the additional consumption of reactive (leading) current allows you to increase the voltage and reduce voltage fluctuations at the input of the excavator.

The flow of reactive current in the supply line causes additional power loss. In figure 5 shows the dependences of the active power of the line losses at various values of the power factor.

3. The use of compensating devices in power supply systems for mining excavators

Reactive power control in the power systems of mechatronic complexes of modern excavators can improve the quality of electricity and the efficiency of mining machines [11]. The main technical means for this purpose are active rectifiers of the main drive drives and additional high-speed reactive power sources (STATCOMS). The use of active rectifiers to regulate reactive power over a wide range is not advisable, since it leads to an increase in losses in all power components of the mechatronic complex. In [10], it was proposed to set the power factor of active rectifiers equal to 0.96 (leading current) when energy are consumed from a network and $\lambda = 1$ when recuperating energy to a network. In figure 6 are shown the dependences of voltage and power loss on active current for such a case.

Fast-acting reactive power compensators, for example, thyristor-reactor ones, provide effective voltage regulation and control of the reactive power mode during operation of excavators, both when consuming and recovering active energy [11]. It is possible to use various control algorithms. A simple way is to control the reactive current in the supply network in accordance with equation [12]

$$I_r \approx \frac{r}{x} I_{al}.$$  

(3)
It follows from equation (3) that if the reactive current \( I_r \) in the line is maintained in proportion to the active load current \( I_{al} \), the voltage loss in the supply network is compensated. The coefficient of proportionality is equal to the ratio of the active and reactive resistances of the supply line and does not depend on its length. To implement the control system, it is sufficient to measure only the active and reactive load currents. The power factor for controlling the reactive current in accordance with Eq. (3) is determined by formula

\[
\lambda = \cos \varphi = \frac{I_{al}}{\sqrt{I_r^2 + I_{al}^2}} = \frac{I_{al}}{\sqrt{\left(\frac{r}{x} I_{al}\right)^2 + I_{al}^2}} = \frac{x}{\sqrt{r^2 + x^2}}.
\]

In figure 7 are shown the dependences of the voltage at the inlet of the excavator and the power loss in the supply line from the active current for the case of regulation of the reactive current in accordance with equation (3).

**Figure 6.** The dependence of the voltage at the input of the excavator and the power loss in the line from the active load current at \( \lambda = 0.96 \) (leading current) when energy are consumed from a network and \( \lambda = 1 \) when energy are recuperated to a network.

**Figure 7.** Dependences of the voltage at the input of the excavator and the power loss in the line from the active load current for reactive power compensation according to the algorithm (3).

The considered dependencies between the components of the load current, voltage and power losses in the supply network reflect the contradiction between the quality of electricity and losses during transmission of electricity. Rational solutions in the conditions of this contradiction are achieved using special algorithms for controlling compensating devices.

**4. Conclusion**

Power consumption in mechatronic systems of excavators is characterized by cyclical and uneven processes of energy consumption and recovery. For excavators with drives using the traditional Ward Leonard system, the large reactive current of the synchronous motor in the energy consumption mode provides low sensitivity of voltage fluctuations to changes in the load current. During recovery, on the contrary, a large reactive current causes an increase in voltage loss in the network. Losses in the network with a decrease in the load power factor increase inversely with its square. In mechatronic systems with semiconductor energy converters, a constant power factor, for example, 1.0, is maintained due to active rectifiers.
Based on the analysis of energy processes and experimental studies performed, the main relationships between the consumed and recovered energy during the operation of a mining excavator and the voltage at its input and losses in the supply line are determined.

Improving the quality of electrical energy at the input of the excavator is achieved by regulating the flow of reactive energy using high-speed compensating devices. In this case, the network losses with a decrease in the load power factor increase inversely with its square. The contradiction between the level of voltage fluctuations and losses in the supply network is the reason for the use of special complex control algorithms for compensating devices.

The results of the study and the proposed methods for increasing the energy efficiency of electric excavators are implemented in control systems offered by the "Joint Power" Company. Further development of the issues of the use of compensating devices considered lays the foundation for the technical improvement of the power supply systems of quarries.

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