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ПОВЫШЕНИЕ ЭНЕРГОЭФФЕКТИВНОСТИ НАСОСНЫХ АГРЕГАТОВ НА ГОРНОДОБЫВАЮЩИХ ПРЕДПРИЯТИЯХ: АНАЛИЗ, ДИАГНОСТИКА И ПУТИ ОПТИМИЗАЦИИ

Р.В. Клюев

Московский политехнический университет, Москва, Россия, e-mail: kluev-roman@rambler.ru

Аннотация: Рассмотрена проблема повышения энергоэффективности насосных установок, которые являются одними из основных потребителей электроэнергии. Представлен комплексный анализ причин низкой эффективности, включающий детальный разбор гидравлических, объемных и механических потерь в насосах. Особое внимание уделено влиянию технического состояния и режимов эксплуатации оборудования на его совокупный коэффициент полезного действия. На примере реального насосного парка электролитного цеха продемонстрирован подход к выбору электродвигателей с учетом фактических условий работы, таких как повышенное гидравлическое сопротивление из-за солевых отложений. Центральное место в исследовании занимают результаты энергетического обследования, выявившего серьезные проблемы с качеством электроэнергии: несимметрию токов в фазах (разница до 7%, ток в нейтрали 2,04 А) и значительный уровень высших гармонических искажений (до 7% для 11-й и 13-й гармоник), что приводит к дополнительным потерям и сокращению срока службы оборудования. На основе проведенного анализа предложен комплекс технических и организационных мероприятий для оптимизации энергопотребления. Ключевыми из них являются внедрение частотно-регулируемых приводов для насосов с переменной нагрузкой, компенсация реактивной мощности, каскадное управление группой насосов, а также снижение гидравлических потерь в трубопроводных сетях и борьба с утечками. Реализация предложенных мер позволяет существенно снизить эксплуатационные расходы и повысить надежность работы критически важного оборудования горных предприятий. Насосные установки горнодобывающих предприятий обладают существенным резервом для повышения энергоэффективности, что подтверждается анализом всех видов потерь и результатами энергообследования.

Ключевые слова: энергоэффективность, насосные агрегаты, горнодобывающее предприятие, энергетическое обследование, частотно-регулируемый привод, гидравлические потери, коэффициент полезного действия, качество электроэнергии, несимметрия нагрузки, высшие гармоники.

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Improving the energy efficiency of pumping units in mining enterprises: analysis, diagnostics, and optimization paths

R.V. Klyuev

Moscow Polytechnic University, Moscow, Russia, e-mail: kluev-roman@rambler.ru

Abstract: This article addresses the critical issue of improving the energy efficiency of pumping units, which are among the primary consumers of electricity, in the mining industry. The paper presents a comprehensive analysis of the causes of low efficiency, including a detailed examination of hydraulic, volumetric, and mechanical losses in pumps. Particular attention is paid to the impact of the technical condition and operating modes of the equipment on its overall efficiency. Using a real-world example of an electrolytic shop pumping fleet, an approach to selecting electric motors is demonstrated, taking into account actual operating conditions, such as increased hydraulic resistance due to salt deposits. The study focuses on the results of an energy audit, which revealed serious power quality issues: current asymmetry in phases (up to 7% difference, neutral current 2.04 A) and a significant level of higher harmonic distortion (up to 7% for the 11th and 13th harmonics), which leads to additional losses and a reduced equipment service life. Based on the analysis, a set of technical and organizational measures was proposed to optimize energy consumption. Key measures include the implementation of variable-frequency drives for variable-load pumps, reactive power compensation, cascade control of pump groups, and the reduction of hydraulic losses in pipeline networks and leak control. Implementation of these measures significantly reduces operating costs and improves the reliability of critical mining equipment. Pumping units at mining facilities have significant potential for improved energy efficiency, as confirmed by an analysis of all types of losses and the results of energy audits.

Key words: energy efficiency, pumping units, mining enterprise, energy survey, variable frequency drive, hydraulic losses, efficiency, power quality, load unbalance, higher harmonics.

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Introduction

In mining enterprises, it is necessary to conduct a comprehensive analysis of the operation of pumping units [1, 2] and identify reserves for improving energy efficiency in order to develop a number of technical and organizational measures [3, 4]. The main purpose of their implementation is to optimize the operating modes of the equipment, reduce operating costs and extend its service life.

The key direction is the introduction of modern frequency-controlled electric drives (FCED) on pumps operating in variable load mode [5]. This allows flexible control of the unit's performance without resorting to throttle valves, which provides a direct energy-saving effect. The second important measure is the compensation of reactive power using automatic capacitor units (ACU). This reduces the load on the supply networks, reduces electricity losses and avoids fines from energy supply organizations [6, 7]. To combat harmonic distortion detected during measurements, it is proposed to install filter compensating devices or active filters. For FCED, savings are determined by reducing the consumption of active electricity. For the ACU, savings from reducing reactive energy consumption are taken into account, as well as a possible reduction in fees for the maximum declared capacity [8]. Additional factors include lower repair and maintenance costs due to more gentle operating modes of the equipment.

Regular energy inspections of pumping units are becoming particularly relevant. Considering that hydro-transport and drainage systems are often the largest consumers of electricity at an enterprise, even a slight increase in their efficiency results in significant financial savings. The examination reveals not only obvious defects, but also hidden reserves, such as suboptimal operating modes, non-compliance of pump characteristics with real hydraulic network conditions or excessive pressure losses. Thus, diagnostics goes beyond simple maintenance of working capacity and becomes a tool for strategic cost management.

In mining enterprises, it is necessary to conduct a comprehensive analysis of the operation of pumping units and identify reserves for improving energy efficiency in order to develop a number of technical and organizational measures. The main purpose of their implementation is to optimize the operating modes of the equipment, reduce operating costs and increase reliability [9, 10].

Loss analysis and methods for improving the energy efficiency of pumping units

During the research, a theoretical analysis of the types of losses in pumping units (hydraulic, volumetric, mechanical) and their impact on overall efficiency was carried out. The rated power of electric motors for pumps of various types (HGN-200/32, HGN-500/32) is calculated according to a standard formula, taking into account the reserve factor. A full-scale energy inspection of five pumping units was carried out using integrated monitoring devices (PKK-57) and an electricity consumption analyzer (AR5). The measurement method has obtained data on voltages, currents, asymmetry, and harmonic distortion [11, 12]. A comparative analysis made it possible to compare various methods of regulating pump performance (throttling, cascade control, frequency control) with an assessment of their energy efficiency [13, 14].

Hydraulic losses, which account for a significant proportion of total energy consumption, consist of two main components. Firstly, it is the loss of friction of the liquid against the walls of the flow parts — the channels of the impeller, the guide device and the spiral outlet. Secondly, these are losses associated with turbulence and eddy formations: the conversion of kinetic energy into potential energy, as well as hydraulic resistance during turns, curves and in step-by-step transitions. The power of hydraulic losses has a cubic dependence on the pump flow rate.

This highlights the critical importance of choosing the right operating point. To combat these losses, 21st century technologies propose the use of coatings based on epoxy composites and polymers with low roughness, which are applied to the inner surfaces of the housing and impeller, significantly reducing the coefficient of friction.

Volume losses or leaks occur due to the flow of liquid through structural gaps, for example, between the impeller and the chamber sealing rings. The reduction of these losses is achieved through the use of high-precision machining equipment and the use of wear-resistant sealing materials such as tungsten carbide or ceramics, which preserve the geometry of the gaps for a long time.

Mechanical losses include the friction of the wheel discs against the fluid (disc friction), as well as losses in stuffing box seals and bearing assemblies. A promising direction is the transition from stuffing box seals to mechanical end seals, as well as the use of rolling bearings with ceramic elements and new generation lubricants that minimize rotational resistance.

Thus, the modern strategy of increasing the efficiency of pumping units is complex and requires taking into account all types of losses. It includes not only the choice of an energy-efficient model at the design stage, but also the use of advanced building materials for the hydraulic path, the introduction of precision equipment to minimize gaps, as well as the use of reliable mechanical components. This multi-level approach allows mining companies to achieve significant reductions in operating costs and meet high environmental standards.

The total efficiency of the pumping unit is an integral indicator that directly depends on the magnitude of the losses considered — hydraulic, volumetric and mechanical. Its value is determined both by the technical condition of the equipment itself (the degree of wear on the seals, the roughness of the flow channels), and by its operating mode, in particular, the compliance of the operating point with the nominal parameters.

For centrifugal pumps, which are most common in industry, the efficiency value varies depending on the pressure created: low pressure units demonstrate efficiency in the range of 0.4—0.7; medium pressure — 0.6—0.8; high pressure — 0.6—0.8. At the same time, modern models developed using advanced technologies and materials can achieve efficiency values, approaching 0.9 and above, which is a new industry standard.

As an example, consider the pumping fleet of an electrolyte workshop. Pumps of the HGN-200/32 type for working with neutral liquids and high-performance pumps of the HGN-500/32 type serving the cooling tower system are used here for technological operations of supplying solutions. An analysis of the efficiency of such a diverse fleet makes it possible to identify bottlenecks and plan modernization measures aimed at replacing outdated equipment with energy-efficient ones, which entails a significant reduction in operating costs.

The choice of the rated power of an electric motor is a critically important stage in the design of a pumping unit [15, 16]. This calculation is performed using a formula that takes into account both the hydraulic parameters of the pump and the losses in the system itself.

$$P = \frac{kQH\gamma}{3600 \cdot 102\eta_p\eta_t} \text{ kW}, \qquad (1)$$

where Q — pump capacity (feed), m^3/h; k — power reserve factor, which ensures reliable operation of the engine without overloads; H — the total pressure developed by the pump, taking into account the geodetic height and all pressure losses in the pipeline, m; η_p — the efficiency of the pump itself, expressed in fractions of a unit, %; η_t — transmission efficiency (for example, belt drive or clutch), %; γ — the density of the pumped liquid, kg/m^3.

Special attention is paid to the stock ratio (k). Its value is regulated depending on the pump supply: for units with a capacity of up to 100 m^3/h, it is accepted in the range of 1.2—1.3, and for more powerful installations (Q > 100 m^3/h) — from 1.1 to 1.5. The introduction of this coefficient is a standard engineering practice that makes it possible to compensate for possible fluctuations in the technological regime and prevent overheating of the engine.

Based on calculations of the required power for pumping units installed in the workshop, the appropriate electric motors were selected. At the same time, key attention was paid not only to the nominal parameters, but also to the actual operating conditions, which have a significant impact on energy consumption.

The calculated power value for pumps of the HGN-200/32 type showed the need to use a medium-power engine. However, a significant increase in hydraulic resistance in the pipeline system caused by the intensive deposition of salts on the inner walls of the pipes has become a critical factor. This phenomenon leads to an increase in the required pressure and, as a result, to an increased load on the electric motor. In this regard, an asynchronous motor of type 5A225M4 with a rated power of 55 kW and a rotational speed of 1470 rpm was chosen. This decision is also confirmed by the existing practice in the workshop, where engines of this model are successfully operated on similar pumps. P = 41 kW.

The calculation for pumps of the HGN-500/32 type showed the need to use a powerful engine. Based on the data obtained, a 90 kW 5A250M4 type engine with a synchronous rotation speed of 1,500 rpm was selected. This model fully complies with the calculated hydraulic parameters and ensures reliable operation of the pump without overloads P = 86 kW.

Conducting an energy inspection of pumps at mining enterprises

Conducting an energy survey is critically important for mining enterprises, which are traditionally classified as energy-intensive. A significant share of the costs in the cost of production of such enterprises is accounted for by electricity, and the main consumers are powerful electric motors of pumps, fans, compressors and lifting machines. Systematic monitoring and analysis of their operation makes it possible to identify not only direct losses associated with suboptimal operating modes or equipment wear, but also hidden reserves for improving energy efficiency [17, 18]. Special attention should be paid to the quality of electricity. The presence of a large number of converter equipment, frequency drives and other nonlinear consumers leads to higher harmonics in the network. These harmonics cause overheating of the windings of electric motors and power transformers, reduce their efficiency and service life, and can also cause false alarms of protection and automation systems. Thus, the assessment of the quality of electricity is an integral part of a comprehensive energy survey aimed not only at saving money, but also at improving the reliability and continuity of the entire technological cycle [19, 20].

As part of the survey, the operating parameters of five pumping units (neutral and acidic media, as well as cooling towers) with a rated power of 55 to 90 kW at a rotational speed of 1,500 rpm were analyzed. The PKK-57 integrated monitoring device and the AR5 power consumption

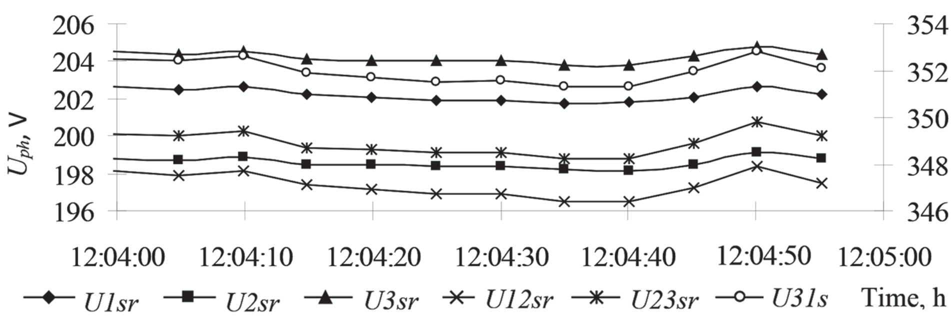

Fig. 1. Dynamics of changes in the values of phase and phase-to-phase voltages
Рис. 1. Динамика изменений величин фазных и междуфазных напряжений

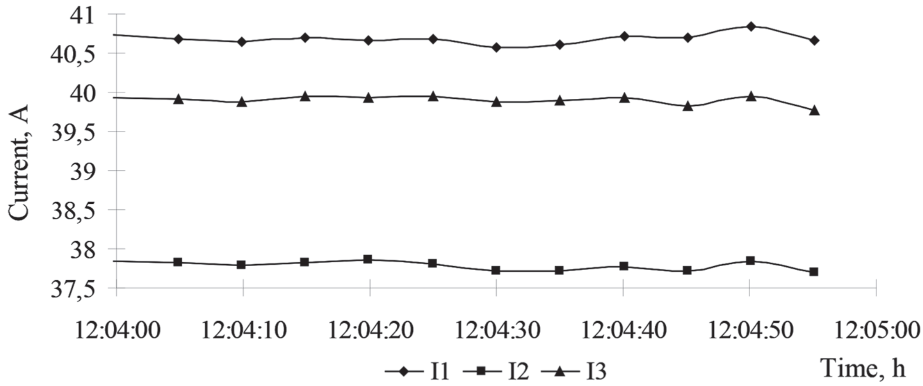

Fig. 2. Dynamics of current changes in phases
Рис. 2. Динамика изменения токов в фазах

analyzer were used for diagnostics. As a result of the measurements, not only the basic electrical characteristics of the units were established, but also significant distortions in the quality of electricity in the supply networks were revealed. These deviations are primarily related to the operation of a nonlinear load, which is widely represented by other technological equipment of the enterprise.

Fig. 1 shows the dynamics of changes in the average values of phase and line voltages over the observation period. The distribution of current loads over individual phases, shown in Fig. 2, clearly demonstrates the presence of significant unevenness.

The analysis of the phase distribution of current loads, shown in Fig. 2, reveals a significant imbalance: the average values are I1sr = 40.68 A, I2sr = 37.78 A, I3sr = 40 A. The resulting asymmetry leads to a current in the neutral conductor of 2.04 A.

The data obtained indicate a redistribution of loads in the three-phase system. The greatest difference is observed between the second and first phases — about 7%, which exceeds the recommended standards.

The analysis of the revealed asymmetry allows us to state that even with a relatively small spread of values (the maximum deviation from the average is about 3%), a significant zero sequence current is observed in the system. This phenomenon indicates that the vector sum of the phase currents is not zero, which is typical for an unbalanced load mode. This issue is becoming particularly relevant in mo-

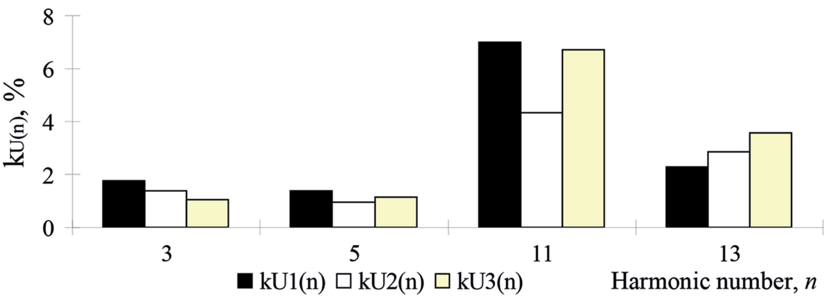

Fig. 3. The level of the n-th harmonic component in the phase voltages
Рис. 3. Уровень n-й гармонической составляющей в напряжениях фаз

dern conditions, where the widespread use of nonlinear consumers (frequency drives, switching power supplies) exacerbates the problem.

To analyze the level of higher harmonics in the network, a histogram of the *n*-th harmonic component of phase voltages was constructed, which is shown in Fig. 3.

The analysis of the histogram in Fig. 3 reveals the nature of the distortion of the sinusoidal phase voltage. It is established that the shape of the curve is distorted due to higher harmonic components, among which the most significant are the 3rd, 5th, 7th, 11th and 13th harmonics. The level of these harmonics varies from 0.93 to 7%, with the 11th and 13th harmonic components making the greatest contribution to non-sinusoidality.

The presence of such a spectrum of harmonics, especially of low and high orders, is typical for electrical installations with powerful nonlinear equipment such as frequency converters, rectifiers and devices with switching power sources. The high level of the 11th and 13th harmonics, which are not typical for standard six-pulse converters, may indicate their origin from more complex twelve-pulse systems or be a consequence of resonant phenomena in the network. Based on the analysis, it can be stated:

- the quality of the mains voltage does not meet the requirements of the standards, since the non-sinusoidal coefficient, judging by the harmonic level, exceeds the permissible limits;
- the predominance of higher harmonics (11th and 13th) creates an increased load on the insulation of cables and windings of electric motors, which accelerates their aging and increases the risk of breakdown;
- to reduce the level of harmonic distortion, it is necessary to use passive or active filters configured to suppress the most significant harmonic components. It is also advisable to audit the operation of the main nonlinear equipment to identify the main sources of distortion.

Optimization of pumping unit operating modes as an energy saving factor

The energy efficiency of pumping units is largely determined by their loading level. The lowest specific energy consumption, that is, the number of kilowatt-hours spent pumping one cubic meter of solution, is achieved when the pump is operating in a mode as close as possible to its optimal rated supply.

The actual performance of the unit is determined not by its rating characteristics, but by the operating point, which is formed as a result of the interaction of the pressure characteristics of the pump itself and the hydraulic resistance of the pipeline system, fittings and apparatuses. Therefore, in order to achieve maximum performance and, as a result, minimum specific flow, careful engineering comparison of pump parameters with calculated and actual characteristics of the pipeline network is required.

In cases where there is a significant discrepancy — for example, the pump develops excessive pressure, which has to be damped by throttling, or its performance is insufficient for technological needs — the most rational solution is to replace the pumping unit with a model whose characteristics optimally match the hydraulic regime of a particular system. This allows not only to reduce direct energy costs, but also to reduce equipment wear and increase the stability of the technological process.

Reduction of hydraulic losses in pipeline systems as a reserve for increasing energy efficiency

One of the significant reasons for the increased energy consumption of pumping units is the excessive pressure losses in the pipeline network.

This is caused by factors such as a suboptimal route configuration with sharp turns, faulty or worn shut-off valves, and clogged suction devices. The elimination of these disadvantages makes it possible to significantly reduce the hydraulic resistance of the system and, as a result, reduce the energy consumption for pumping solutions.

Pressure losses in the pipeline consist of friction losses along the length and losses in local resistance.

Friction losses on straight sections are calculated using the formula:

$$\Delta H = \frac{0{,}083 \lambda L Q^2}{d^5}, \qquad (2)$$

where λ — coefficient of hydraulic friction (for water it is usually in the range of 0.02—0.03); L — the length of the pipeline segment in question, m; d — the inner diameter of the pipe, m; Q — actual consumption of the transported medium, m^3/s.

The calculation of pressure losses on local hydraulic resistances is performed using the following expression:

$$\Delta H = \frac{0{,}083 f Q^2}{d^4}, \qquad (3)$$

where f — the total value of the coefficients of local hydraulic resistances, the values of which for various elements are: gate valve — 0.5; elbow with a smooth 90° curve — 0.3; check valve — 5.0.

Reducing the resistance of the system directly affects the required pump pressure. Since the power of the electric motor is proportional to the pressure, reducing hydraulic losses reduces energy consumption, which is quantified by the formula of specific energy consumption.

In practice, a set of measures is used for this:

- optimization of the route configuration with minimizing the number of turns and replacing knees at sharp angles with smooth bends;
- dismantling of excess fittings and replacement of fittings with a high coefficient of resistance (for example, valves with more modern ball valves) with more efficient analogues;
- regular cleaning of pipelines and suction filters from salt and mechanical deposits.

The implementation of these measures makes it possible to significantly reduce the total pressure that the pump must create and switch it to a more efficient mode of operation with lower specific energy consumption, which ultimately leads to significant annual savings.

Leak control in pipeline systems as a method of reducing operational losses

Leakage of technological solutions through loose joints, worn fittings and damaged sections of pipelines leads to direct and significant losses of electricity. The pumping unit performs the work of pumping the entire volume of liquid, including that part of it that is lost in the network and does not reach the end user, which significantly reduces the overall efficiency of the system.

The following practical methods are used to determine the volume of leaks and the associated energy overruns.

If there are metering devices at the beginning and end of the network section, losses during the reporting period are defined as the difference between the volume of solution, supplied to the network and the volume received by consumers. In extensive networks, the total losses are calculated by summing the data for all individual sites.

For complex systems with a large internal volume, a technique is used in which all consumers are disconnected. The solution is supplied to the network under the control of a high-precision flow meter. In this case, the entire measured volume entering the network is considered a leak loss.

The following formula is used to convert the volume of the lost solution into the amount of overexpenditure of electricity:

$$\Delta E = V_l \cdot W_a,$$

where: V_l — volume of leaks during the period, m^3; W_a — the actual specific power consumption of the pumping station for the supply of solution, kWh/ m^3.

The obtained value clearly demonstrates the amount of electricity that was wasted due to the unsatisfactory technical condition of the pipeline system. Regular monitoring of leaks and their timely elimination are economically feasible measures leading to a significant reduction in the operating costs of the mining enterprise.

Optimization of cooling systems as a reserve for reducing energy consumption of pumping units

A significant reserve for improving the energy efficiency of pumping stations is the rationalization of the cooling systems of technological solutions. The implementation of the following technical measures makes it possible to significantly reduce the load on pumping equipment, in particular, on units servicing cooling towers and circulation circuits.

Key areas of modernization:

- The introduction of adaptive control of the cooling tower. To avoid irrational energy consumption, it is necessary to ensure accurate temperature control. The installation of temperature sensors at the inlet and outlet of the solution into the electrolysis baths allows you to quickly assess the efficiency of heat exchange. Provided that the temperature difference meets the technological regulations, the cooling tower pumps can be completely turned off during the cold season, using only natural atmospheric conditions for cooling. This avoids the operation of powerful pumps idling or in a suboptimal mode.
- Organization of a sequential (cascade) cooling system. Instead of parallel connection of technological devices to the cooling line, it is advisable to set up a system in which the coolant passes sequentially through several installations. This approach makes it possible to maximize its refrigeration potential and significantly reduce the required total consumption of the solution, which directly reduces productivity and, consequently, the power of the pumping units involved.

The integrated implementation of the proposed solutions makes it possible to optimize the hydraulic operating modes of the pumps, reducing their total energy consumption by up to 1.5 times. The economic effect is achieved both by reducing the operating time of the equipment (turning off the cooling tower in winter) and by reducing its productivity (switching to a sequential circuit).

Conclusions

1. Pumping units of mining enterprises have a significant reserve for improving energy efficiency, which is confirmed by the analysis of all types of losses and the results of energy surveys.
2. Diagnostics revealed serious deviations from the standards: phase current asymmetry (up to 7% difference, neutral current 2.04 A) and a high level of higher harmonics (up to 7% for the 11th and 13th harmonics). These factors lead to increased losses, overheating, and reduced life of electric motors.
3. The most effective measures are: the introduction of variable frequency drives (VFDs) for pumps with variable load schedules; the use of cascade control for systems with stable or stepped flow; the installation of compensating and filtering

devices to combat reactive power and harmonics.

4. Significant savings are achieved by optimizing pipeline systems (reducing hydraulic resistance, eliminating leaks) and rationalizing the operation of auxiliary systems such as cooling (adaptive control of cooling towers, cascade circuits), which reduces pump energy consumption by up to 1.5 times.

5. Achieving maximum effect requires not isolated actions, but a systematic approach combining diagnostics, modernization of power equipment, improvement of electricity quality and optimization of hydraulic systems.

This will allow mining companies to significantly reduce the cost of production and increase the reliability of technological chains.

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ИНФОРМАЦИЯ ОБ АВТОРЕ

Клюев Роман Владимирович — д-р техн. наук, доцент,
профессор, Московский политехнический университет,
e-mail: kluev-roman@rambler.ru,
ORCID ID: 0000-0003-3777-7203.

INFORMATION ABOUT THE AUTHOR

R.V. Klyuev, Dr. Sci. (Eng.), Assistant Professor, Professor,
Moscow Polytechnic University, 107023, Moscow, Russia,
e-mail: kluev-roman@rambler.ru,
ORCID ID: 0000-0003-3777-7203.

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