Improving the energy efficiency of pump station electric drives through optimal intelligent control

Elmurod Yuldashev[1, a)], Islombek Abdullabekov[2], Raxmatillo Karimov[1, 2], Elbek Ganiyev[1], Iroda Husanova[1], Diyorjon Nuritdinov[1]

[1] *Almalyk State Technical Institute, Almalyk, Uzbekistan*
[2] *Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*

[a)] *Corresponding author: rahmatillo05.03.1982@gmail.com*

Abstract. This paper is devoted to developing an integrated functional architecture for controlling electric drives in pump stations under energy-saving and stable operating modes, and to substantiating its technical effectiveness. The proposed scheme combines, within a single control loop, flexible adjustment of motor speed in accordance with process demands using a frequency converter, limitation of reactive power flow and improvement of the power factor through a capacitor bank, as well as continuous diagnosis of power-quality parameters based on a phase meter. Coordinated control of valves and actuating mechanisms is implemented via the AUMA module, while local control units independently perform the protection and signaling functions of each subsystem, ensuring the modular reliability of the overall system. Based on real-time data, the central control computer carries out monitoring, operating-mode selection, and optimization tasks, helping maintain the pump unit's operating point near the optimal region. As a result, conditions are created for reducing hydraulic, volumetric, cavitation, electrical, and transient losses, decreasing network loading, and extending equipment service life. The proposed approach is characterized as a practical solution aimed at improving the energy efficiency of dewatering and process pumping systems in mining and industrial environments.

INTRODUCTION

Dewatering of deep underground horizons, maintaining dry drifts and stopes, and conveying water for technological processes are critical prerequisites for the uninterrupted operation of the mining industry. In deep mines, water inflow is typically non-stationary: it varies over time due to seasonal and hydrogeological factors, changes in fracture permeability, and the progressive development of mining works. At the same time, the depth and productivity of boreholes and sumps are often heterogeneous, while long-distance pipelines experience continuously evolving hydraulic resistance caused by scaling, corrosion, sediment deposition, and changes in flow regime. Under such complex and dynamic conditions, pumping stations become one of the dominant consumers of electrical power in a mining enterprise [1-3].

Available industrial evidence indicates that pumping systems may account for a significant share of mine electricity consumption, in some cases reaching several tens of percent of total power demand. This high energy burden is intensified by the widespread use of conventional control strategies in which pump units operate at constant speed regardless of actual process requirements. When demand fluctuates and head or flow requirements decrease, fixed-speed operation leads to a systematic mismatch between the supplied hydraulic energy and the required technological load. Consequently, throttling losses increase, the operating point deviates from the best efficiency region, and the overall specific energy consumption rises. In practice, this inefficiency can translate into an additional 20–30% energy use beyond the real-time necessity, particularly in networks where flow regulation is performed by valves rather than speed control [4-9].

These challenges make the transition to intelligent, adaptive pump control not only desirable but strategically necessary for modern mining. Optimal control based on real-time monitoring of inflow, pressure, and energy indicators enables the pump operating point to be continuously aligned with the evolving hydraulic demand. Such approaches can reduce hydraulic and transient losses, mitigate cavitation risk during unstable inflow periods, and lower mechanical stress on equipment. Moreover, the integration of variable frequency drives with power-factor correction and diagnostic modules provides a pathway to improving both the electrical and hydraulic performance of the station as an integrated system. Therefore, the development of intelligent, optimization-based control frameworks for deep-mine pumping infrastructure represents a high-impact engineering direction aimed at reducing energy costs, enhancing operational reliability, and extending the service life of critical dewatering assets [10-16].

EXPERIMENTAL RESEARCH

The energy efficiency of pump units is determined by their internal hydraulic, mechanical, volumetric, and electrical losses. The largest share of losses is observed in hydraulic processes: flow separation in the impeller region, increased turbulence, and friction in pipelines cause part of the pressure to be converted into heat. Internal geometric mismatches and deviations of the flow direction further intensify this process. Mechanical losses are associated with friction in bearings, gland seals, and around the shaft, which increases the torque required from the motor. Volumetric losses, in turn, reduce the pump's actual delivery due to backflow and leakage. A critical drop in pressure leads to cavitation, accelerating impeller wear. Electrical losses arise from the motor's thermal and magnetic characteristics. Frequent speed changes also cause additional energy consumption in dynamic (transient) regimes. The combined effect of these factors typically limits the overall pump efficiency to the range of 55-75%. Figure 1 presents a loss diagram of the pump system [17-23].

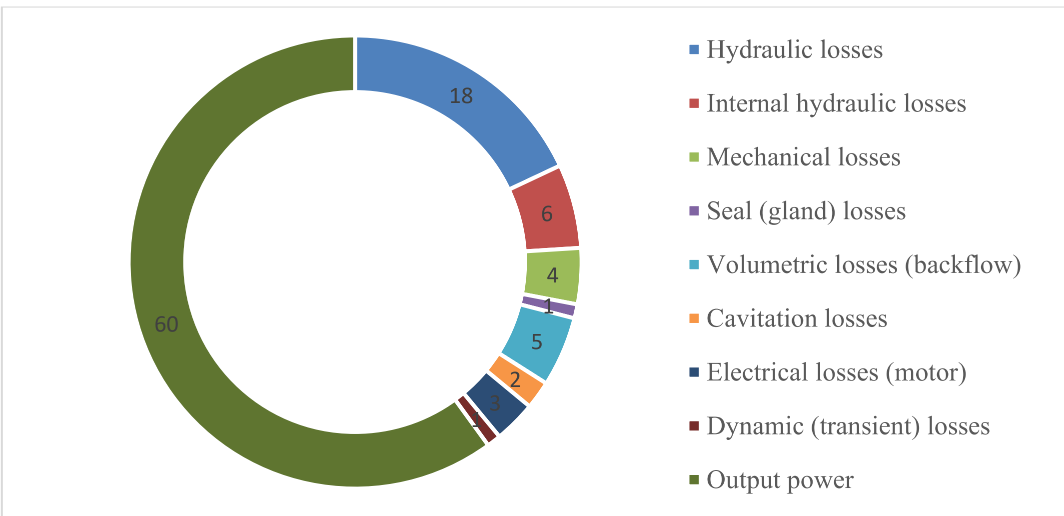

FIGURE 1. Distribution of losses in the pump system

Linear variation of a pump's rotational speed has a direct impact on the hydraulic, mechanical, and energy performance of the system. When the speed is reduced, the flow rate decreases proportionally, while the head decreases in proportion to the square of the speed. As a result, power consumption drops sharply according to the cubic law, leading to a significant improvement in energy efficiency. The reduction in flow velocity also decreases friction losses in the pipeline network and contributes to the stabilization of hydraulic processes. Speed optimization affects volumetric losses as well: because the pressure differential is reduced, backflow decreases and the pump's actual delivery increases. Mechanical losses are reduced due to lower loading of bearings and seals, which extends the service life of the unit. A decrease in rotational speed also reduces the probability of cavitation, since suction-side pressure variations become less pronounced and critical conditions at the impeller inlet are less likely to occur. The mathematical expressions describing the reduction of losses achieved through linear motor-speed control are presented below in Eqs. (1), (2), and (3) [24-30].

$$h_f(n) = (\lambda \frac{L}{D} + \sum \zeta_i) \frac{v^2(n)}{2g} \tag{1}$$

$$Q(n) = Q_0(\frac{n}{n_0}) - k(\Delta p(n)) \tag{2}$$

$$P(n) = \frac{\rho g Q(n) H(n)}{\eta_h(n) \eta_m(n) \eta_v(n)} \tag{3}$$

Linear control of the motor speed also leads to the optimization of electrical energy consumption. Thermal and magnetic losses in the rotor–stator pair decrease, thereby improving the overall efficiency of the motor. The smooth nature of the control process eliminates excessive energy use during transient regimes, which enhances the overall stability of the system. In general, linear pump-speed control significantly reduces hydraulic losses, optimally decreases mechanical and volumetric losses, and improves system performance by lowering electrical energy consumption. For this reason, adaptive speed control is considered one of the most effective energy-saving strategies in modern pump stations [31-36].

RESEARCH RESULTS

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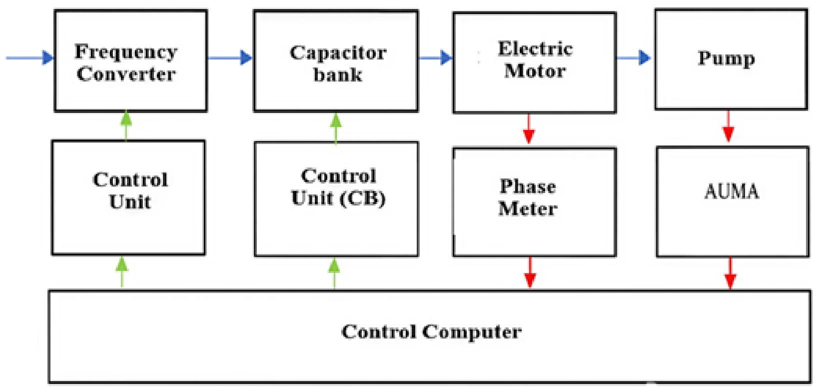

FIGURE 2. Functional control scheme of the pump unit

This text shows the logical outcome of the proposed control scheme. Since the frequency converter adjusts the motor speed to match the load, the pump operating point shifts closer to the optimal region, leading to lower hydraulic, volumetric, and cavitation losses. The capacitor bank improves the power factor and helps reduce network current and electrical losses. The phase meter and the central control computer monitor power-quality indicators, limiting excessive heating and unstable operating conditions caused by phase unbalance and deviations in operating mode. Fig.3 presents the energy efficiency of the pump system under the baseline mode and under the proposed control scheme [42-45].

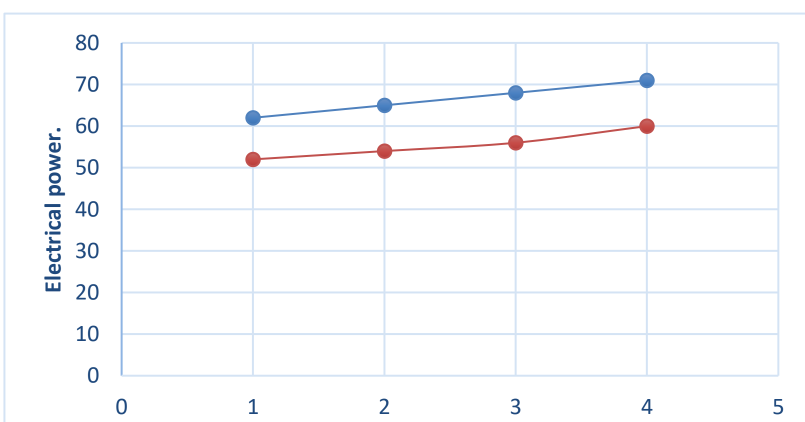

FIGURE 3. Energy efficiency of the pump system in the baseline mode and under the proposed control scheme

The unit and local control blocks synchronize the control of valves and actuating mechanisms, thereby reducing extra losses that typically arise during transient regimes. In general, the diagram indicates that after implementing the new scheme, the main share of losses remains within the hydraulic group, while electrical and dynamic losses represent a relatively smaller fraction. Therefore, the next optimization stage with the greatest additional benefit may involve reducing hydraulic resistance in the pipeline network, bringing the operating point closer to the BEP, and improving suction conditions. Figure 4 presents the loss diagram of the pump system [46-48].

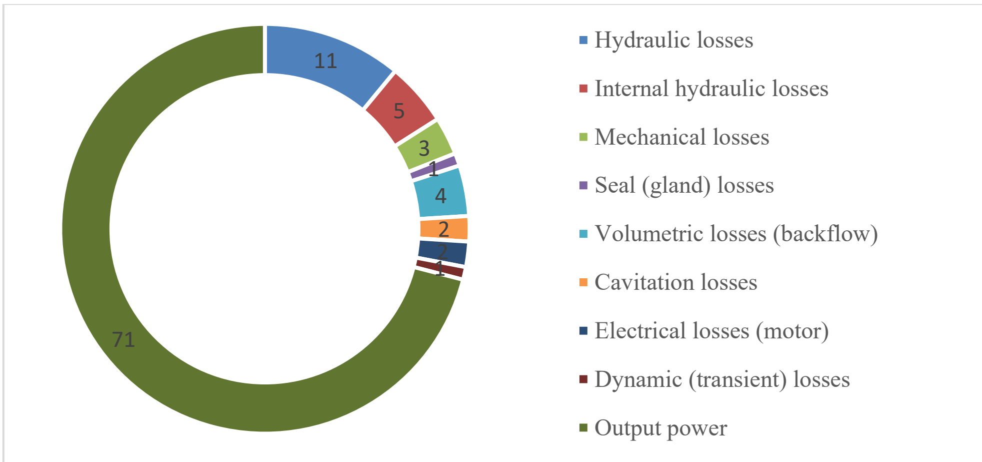

FIGURE 4. Distribution of losses in the pump system

CONCLUSION

Achieving energy and resource savings was made possible by intelligent control of the pump unit speed. Experimental results show that hydraulic losses were reduced by 7%, internal hydraulic losses by 1%, mechanical losses by 1%, volumetric losses by 1%, and electrical losses by 1%. As a result, the overall efficiency of the pump unit increased from 60% to 71% (an improvement of 11 percentage points).

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