UDC 621.3.076.7
DOI: 10.15587/1729-4061.2026.351680

DEVELOPMENT OF A METHOD FOR ENERGY-EFFICIENT CONTROL OF PARALLEL PUMP UNITS USING THE COVARIANCE MATRIX ADAPTATION EVOLUTION STRATEGY

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The object of the study is a pumping station with four parallel-connected centrifugal pump units driven by asynchronous electric motors. The problem to be solved is that modern stations, partially equipped with variable frequency drive (VFDs), allow only maintaining the head without observing allowable modes, failing to ensure reliability and energy efficiency. This leads to rapid wear and efficiency reduction. The solution lies in optimizing energy consumption and keeping operating points within the POR (preferred operating region), to prevent accelerated wear.

The essence of the results obtained lies in the development of a method for energy-efficient control based on the CMA-ES strategy integrated with a model in MATLAB (California, USA). Experiments showed that the balanced strategy reduces energy consumption by 7% while maintaining equipment in the POR zone for 95.8% of the time. Comparative analysis showed that a configuration with two VFDs is a rational compromise, limiting energy overconsumption to 25% relative to systems fully equipped with VFDs.

These results allowed to solve the specified problem due to the introduction of a block performing an analytical express assessment of the required number of units based on affinity laws, using adaptive penalty functions and CMA-ES tuning. This allowed excluding combinatorial enumeration and reducing the search time for the optimal solution to 60–80 seconds, ensuring speed unavailable to standard genetic algorithms.

The conditions under which they can be used on practice involve the application of the developed method as a supervisory control (SCADA) for water supply pumping stations to generate control setpoints with a periodicity of 1–2 minutes without the need for complete equipment replacement

Keywords: parallel pump units, variable frequency drive, energy efficiency, optimization, CMA-ES, constraint handling, MATLAB

Received 09.12.2025
Received in revised form 03.03.2026
Accepted 12.03.2026
Published 29.04.2026

How to Cite: *Bulatbayeva, Y., Kossymbayev, R., Tsypkina, V., Ivanova, V., Bulatbayev, F. (2026). Development of a method for energy-efficient control of parallel pump units using the covariance matrix adaptation evolution strategy. Eastern-European Journal of Enterprise Technologies, 2 (8 (140)), 29–40. https://doi.org/10.15587/1729-4061.2026.351680*

1. Introduction

According to current estimates by the International Energy Agency (IEA) and the 4E Electric Motor Systems Annex program, electric drive systems driving pumps, fans, compressors, and other industrial equipment consume about 50–53% of the world's electricity volume [1]. At the same time, pumping systems use about 6560 TWh per year and possess a technically achievable energy-saving potential of 20–30% when transitioning from local solutions to systemic optimization of operating modes [1, 2]. According to IEA data, approximately a quarter of this consumption can be reduced by economically viable measures, which is equivalent to reducing global electricity demand by 10% [3].

Based on the above sources, it follows that the optimization of the operational parameters of pumping stations can contribute to the implementation of strategies for decarbonization and reduction of electricity consumption by industry [3, 4]. Variable water consumption at pumping stations leads to the fact that pumps must operate in a wide range of flow rates. Such operating modes result in a strong deviation of the pump operating points from the best efficiency point and exit from the zones of optimal efficiency (preferred operating region – POR). This determines the overconsumption of electricity and accelerated wear of the equipment. This problem is particularly acute at pumping stations with a group of parallel units partially equipped with variable frequency drives (VFD), where, in addition to maintaining the head, it is necessary to quickly solve the problem of choosing the optimal operating mode [5].

In practice, modern manufacturers of frequency converters and programmable logic controllers offer built-in software macros for multi-pump control [6, 7]. These standard industry solutions successfully solve the primary problem of precise head stabilization using PID controllers and cascade staging logic based on predefined frequency or pressure thresholds. However, they rely on fixed setpoints and do not dynamically track the actual position of the operating point relative to the specific efficiency map of the pumps. Consequently, while solving the basic automation task, they do not guarantee the operation of units strictly within the POR zone, which leaves a significant margin for energy optimization. At the same time, the introduction of control methods based on optimization algorithms can allow increasing energy efficiency and preserving the reliability of existing systems without the need for equipment replacement.

In practice, the value of such solutions lies in the possibility of reducing operating costs and increasing the reliability of pumping stations by maintaining pump operating points within the POR. Therefore, study devoted to the development of methods for energy-efficient control of parallel pump units using optimization algorithms adapted for real-time operation is relevant.

2. Literature review and problem statement

Studies show that accounting for mode efficiency and correct control of the composition of the pump group allows reducing energy consumption. In particular, for group control, savings of about 8–10% are shown with the timely shutdown of a regulated unit with low efficiency [5]. The disadvantage of the proposed method is the use of passport characteristics of pump units to calculate unit efficiency, as this reduces the accuracy of the method when working with worn-out pump units. In paper [8], the control of pumping stations taking into account current water consumption is considered, and the potential for energy saving when adapting the mode to the load is demonstrated.

Methodological works on pumps with a variable frequency drive form a calculation basis for analyzing modes and emphasize that in parallel operation, not only the characteristics of pumps are important, but also the sequence of switching units on and off; the influence of the switching order on the group efficiency is noted [9, 10]. However, these studies are more often focused on calculation and analysis during the development of a feasibility study for the application of a controlled electric drive, rather than on finding an energy-efficient solution for application at existing pumping stations.

There are approaches aimed at selecting the optimal number of operating pumps and constructing switching boundaries. For identical pumps in parallel, algorithms for selecting the number of units and the area (Q, H) where it is advisable to change the configuration are proposed [11]. The strength is transparency and ease of implementation, but assumptions about the identity of pump units and the stationarity of the mode, as well as the number of switchings, remain limitations.

To account for nonlinearity and mixed variable types, optimization algorithms are widely used. In paper [12], optimization of a parallel pump system based on a genetic algorithm showed the possibility of increasing energy efficiency. In the following study [13], experimental verification of genetic optimization for a complex pumping station with parallel pump units was carried out, which increases the evidence of the approach. At the same time, computational and implementation barriers to the application of complex procedures in real time are emphasized [14].

In paper [15], the formulation was expanded beyond single-criterion energy saving; a trade-off between energy efficiency and reliability through maintaining the mode in POR and combined regulation was considered. In another work [16], a multi-objective model for parallel pump installations proposes adapting priorities between energy efficiency and reliability indicators. However, the choice of weights and the interpretation of reliability indicators in studies remain sensitive and require justification.

Another direction is related to improving algorithms and handling constraints. For a pumping station with VFD, an energy-saving strategy based on an improved differential evolution algorithm with field testing was proposed [17], which confirms the practical potential but also emphasizes the role of approximating characteristics and correct formulation of constraints.

Combining optimization algorithms with simulated annealing is used to increase the globality of the search and increase the share of feasible solutions under strict constraints [18].

To overcome the limitations of standard genetic algorithms associated with premature convergence and low sensitivity to control parameter correlation, the covariance matrix adaptation evolution strategy (CMA-ES) is of particular interest [19].

Analysis of the literary data shows that the developed control methods aim to ensure optimal load distribution and maintain pumps within the POR, yet they have significant drawbacks. At the same time, the application of modern optimization algorithms makes it possible to eliminate the shortcomings of the aforementioned methods and find the best energy-efficient solutions; however, such algorithms are limited by high computational complexity and the difficulty of accounting for technological constraints in real-time.

All this allows to conclude that it is expedient to conduct research devoted to finding a balance between energy efficiency, equipment reliability, and algorithm speed.

Thus, the unresolved scientific and practical problem can be formulated as the development and investigation of methods for controlling a parallel group of pump units using optimization algorithms with an objective function in the form of minimizing total power at a given head and strict constraints on the allowable operating region, while ensuring a high share of feasible solutions and acceptable computation time.

3. The aim and objectives of the study

The aim of the study is the development of a method for energy-efficient control of parallel pump units based on the CMA-ES evolutionary strategy. This will enable the implementation of optimal control in real-time, ensuring minimum energy consumption while maintaining the equipment within the preferred operating region (POR).

To achieve the aim, the following objectives were set:

– to develop a simulation model of a pumping station in the MATLAB&Simulink environment;

– to formalize an objective function that takes into account the accuracy of head stabilization, the retention of pumps within the POR, and energy consumption;

– to develop an accelerated algorithm based on the CMA-ES evolutionary strategy;

– to investigate the influence of the objective function weight coefficients on the energy efficiency and reliability of the system;

– to conduct a comparative analysis of the method's efficiency for various pumping station configurations and to estimate the computational complexity of the algorithm.

4. Materials and methods

The object of the study is a pumping station with four parallel-connected centrifugal pump units driven by asynchronous electric motors. The variable frequency drives controlling the motors operate in a scalar control mode (V/f) with a quadratic voltage-to-frequency characteristic. For centrifugal pumps with a parabolic load torque characteristic, the main requirements for the electric drive are met by the scalar control type, which ensures smooth flow regulation without the need for complex vector control. The pumping station is designed to maintain pressure head at a dictating point of the main pipeline located at a distance of 2 km from the pumping station.

The main study hypothesis is that the introduction of an analytical block for the preliminary assessment of the required number of pumps, combined with the CMA-ES evolutionary strategy using adaptive penalty functions, will ensure convergence to a minimum of energy consumption within a time acceptable for real-time process control or monitoring, while strictly observing constraints regarding the POR zone.

The following assumptions were adopted in the work:

1. The physical properties of the pumped fluid, such as density (998 kg/m^3), kinematic viscosity (1 mm^2/s), and temperature (20°C), are assumed to be constant.

2. The hydraulic resistance of the pipeline network is considered constant over time, with the exception of the variable load element.

To reduce the computational burden, the following simplifications were introduced:

1. Steady-state hydraulic and electromechanical modes are considered; transient switching processes and motor acceleration dynamics are not taken into account due to the difference in process time constants, as the inertia of the hydraulic system significantly exceeds the electrical one.

2. The head-flow characteristics of the pumps are approximated by second-degree polynomials.

Modeling and optimization of the pumping station operating modes were performed in the MATLAB&Simulink software environment using the Simscape Fluids physical modeling library. The optimization algorithm was implemented using the standard open-source MATLAB script for CMA-ES provided by its developer, which was then adapted by the authors for the specific multi-objective function. The choice of this environment is due to the possibility of integrating the hydraulic model (Simulink) and optimization algorithms (MATLAB), which allows implementing control with complex logic in a single information space.

To verify the proposed approach, a program of experimental studies was compiled, including the simulation of water consumption in the range of 30–100% of the nominal capacity.

Comparison of control efficiency was carried out for three equipment operation scenarios:

1) configuration A: all 4 pumps are equipped with VFDs;

2) configuration B: 2 pumps with VFDs, 2 pumps with throttling;

3) configuration C: 1 pump with VFD, 3 pumps with throttling.

5. Results of research on the energy efficiency of the control method for parallel pump units based on the covariance matrix adaptation evolution strategy

5. 1. Development of a simulation model of the pumping station

Each D630-90 pump ($Q = 630$ m^3/h, $H = 90$ m, $P = 250$ kW) is implemented using the "Centrifugal Pump" block. The head-flow characteristic based on passport data is defined as a table of values for power, head, and efficiency dependencies on the flow rate. Subsequently, the block determines a second-degree polynomial, which ensures the calculation of the pump head as a function of the flow rate. The system model is presented in Fig. 1.

Subsystems 1–4 contain pump units with pressure pipelines. Subsystem 1 is shown in Fig. 2. Subsystems 2–4 are structurally identical to Subsystem 1.

Since the passport characteristics were obtained by the manufacturer in laboratory conditions, the model provides for the possibility of making adjustments to the characteristics simulating parameter degradation during wear, such as a decrease in efficiency in the operating flow zone. The pump unit wear coefficient was introduced when calculating power according to the methodology proposed in the study [20].

Main and pressure pipelines are modeled by "Hydraulic Pipeline" blocks specifying length (4 km), internal diameter (400 mm for pressure and 600 mm for main pipelines), and internal surface roughness parameters (15 μm).

To account for the hydraulic resistance of the fittings and prevent backflow when stopping individual units, "Check valve" blocks are installed on the pressure lines of each pump.

The fluid type (water) is defined by the "Hydraulic Fluid" block specifying density (998 kg/m^3), viscosity (1 mm^2/s), and temperature (20°C), which ensures the correct calculation of hydraulic losses and energy indicators in the model.

The system static head H_s (30 m) is set via the "Pressure Relief Valve" element. The variable water consumer load is simulated by a controllable "Gate Valve", which allows reproducing consumption in the range of 30–100% of the maximum capacity. The valve has an equal-percentage flow characteristic with an average flow coefficient of 0.65.

Flow rate and head values are recorded by the "Hydraulic Flow Rate Sensor" and "Hydraulic Pressure Sensor" blocks. The blocks are ideal and have no error.

All parameters are transmitted to the MATLAB workspace and back via the "To Workspace" and "From Workspace" blocks.

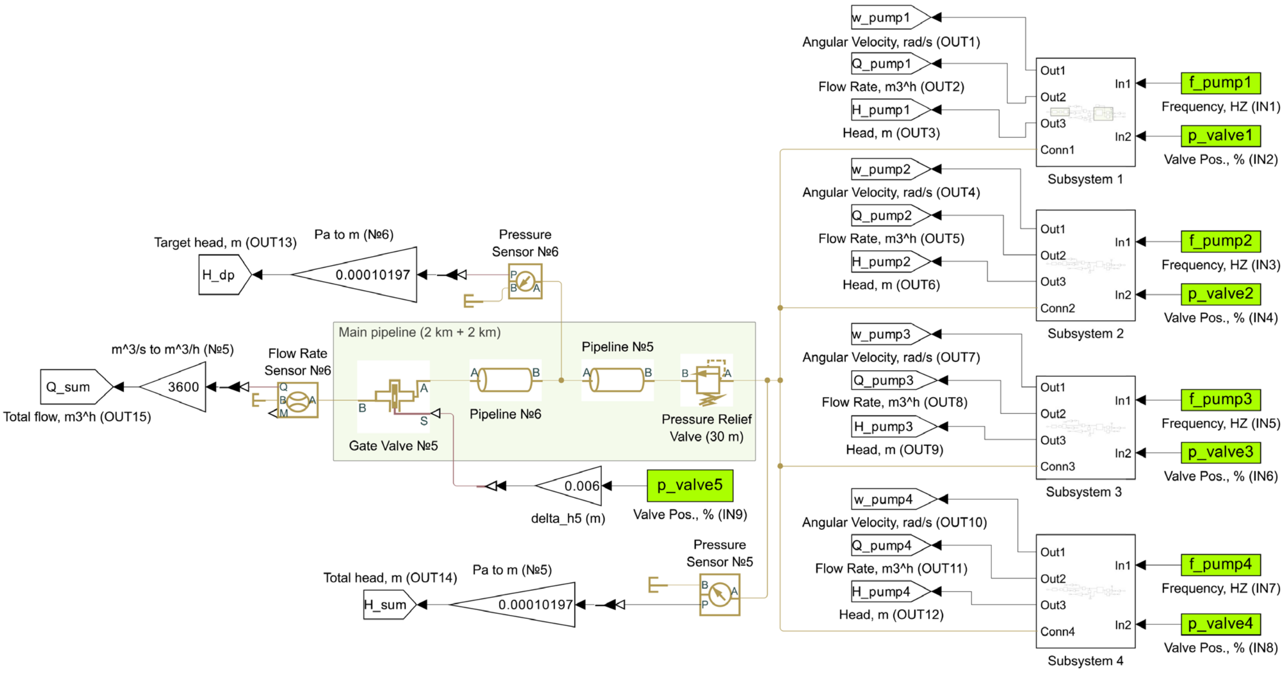

Fig. 1. System model with four parallel pump units

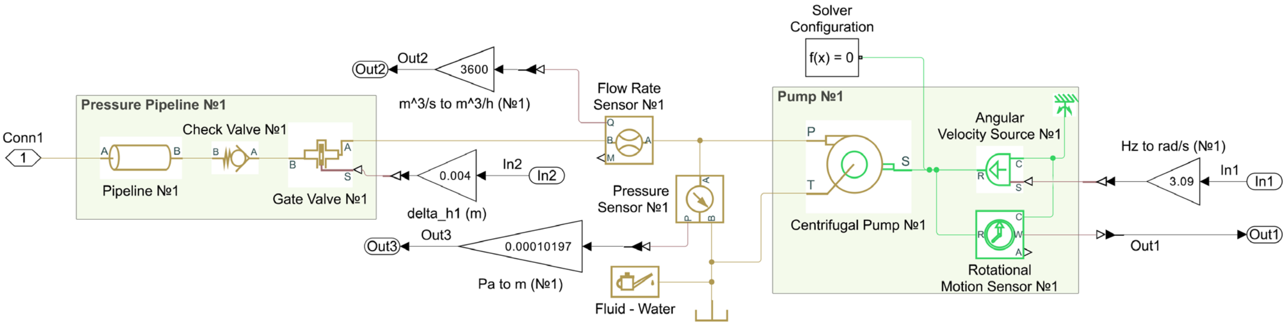

Fig. 2. Subsystem 1 with a pump unit and a pressure pipeline

5. 2. Formalization of the objective function and constraint system

The problem is formulated as a search for the optimal control vector minimizing the objective function. The control vector includes

$$\vec{x}=\left[f_1,\ldots,f_4,V_1,\ldots,V_4\right]^T, \tag{1}$$

where f_i – the stator current frequency of the i-th pump, V_i – the opening degree of the control valve.

The search limits for current frequencies and valve positions are defined as

$$f_{\min}\le f_i\le f_{\max}, \tag{2}$$

$$V_{\min}\le V_i\le V_{\max}, \tag{3}$$

where $f_{\min}$ = 30 Hz, $f_{\max}$ = 50 Hz, $V_{\min}$ = 0%, $V_{\max}$ = 100%.

The boundary frequency $f_{\min}$, below which there is no useful work, was determined by the formula

$$f_{\min}=f_{\max}\sqrt{\frac{H_s}{H_f}}=50\sqrt{\frac{30}{99}}=27.52\approx 30\,\text{Hz}, \tag{4}$$

where H_s – the system static head, H_f – the pump head at zero flow rate according to passport characteristics.

The objective function has the form of a weighted sum of normalized components

$$J=\omega_H J_H+\omega_D J_{ZD}+\omega_C J_{ZC}+\omega_P J_P, \tag{5}$$

where J_H – the penalty for head deviation, J_{ZD} – the penalty for exiting the POR zone, J_{ZC} – the penalty for the number of pumps outside the POR zone, J_P – the power penalty, ω – the weight of each component.

The penalty for head deviation J_H is determined as

$$J_H=\frac{\left|H_{fact}-H_{target}\right|}{H_{target}}, \tag{6}$$

where H_{fact} – the actual head at the dictating point, H_{target} – the target head at the dictating point.

The operating region boundaries are calculated for each active pump depending on the current speed according to pump affinity laws by the formula:

$$Q_{\max}=1.1Q_{nom}\frac{\omega_n}{\omega_{nom}}, \tag{7}$$

$$Q_{\min} = 0.7 Q_{nom} \frac{\omega_n}{\omega_{nom}}, \tag{8}$$

where $Q_{\max}$ – the upper POR boundary, $Q_{\min}$ – the lower POR boundary.

The individual penalty J_i for each active pump is determined by the expression

$$J_i = \frac{\left| Q_i - Q_{\min/\max} \right|}{Q_{\min/\max}}. \tag{9}$$

The total penalty for exiting the zone J_{ZD} represents the average value of penalties of all active pumps

$$J_{ZD} = \frac{\sum J_i}{N_{active}}, \tag{10}$$

where N_{active} – the number of active pumps.

The penalty for the number of pumps J_{ZC} outside the POR zone

$$J_{ZC} = \frac{N_{out}}{N_{active}}, \tag{11}$$

where N_{out} – the number of pumps outside POR.

The power penalty J_P is determined as the ratio of the total power consumption of active pumps to the maximum system power

$$J_P = \frac{P_\Sigma}{P_{\max}}, \tag{12}$$

where P_Σ – the total power consumption of active pumps, $P_{\max}$ – the maximum power of active pumps.

Pump efficiency η_n is calculated based on a dependency that takes into account the deviation of flow rate and speed from nominal values by the formula

$$\eta_n = \eta_{nom} - \left(\frac{Q}{Q_{nom}} - \frac{\omega}{\omega_{nom}} \right)^2 \eta_{nom} \frac{\omega}{\omega_{nom}}, \tag{13}$$

and the power consumed by the pump unit is determined as

$$P_n = \frac{\rho Q H g}{\eta_n \eta_{em} \eta_{fc} k}, \tag{14}$$

where η_n – the actual pump efficiency, η_{nom} – the nominal pump efficiency, η_{em} – the electric motor efficiency, η_{fc} – the efficiency for the mode with VFD (in the absence of VFD $\eta_{fc} = 1$), Q – the actual flow rate, m^3/s, k – the pump unit wear coefficient ($k = 1$ – new, $k < 1$ – worn), Q_{nom} – the nominal flow rate, m^3/s, H – the actual pump head, m, ω – the actual angular speed, rad/s, ω_{nom} – the nominal angular speed, rad/s, ρ – the fluid density, kg/m^3, g – the acceleration of gravity, m/s^2.

5. 3. Development of an accelerated algorithm based on the covariance matrix adaptation evolution strategy

To solve the problem of energy-efficient control of pump units, an algorithm based on the CMA-ES evolutionary strategy was developed. The choice is due to its ability to work effectively with multi-objective functions and avoid local minima, as well as the absence of the need to calculate the gradient.

The algorithm interacts with the Simulink dynamic model to search for optimal VFD frequencies and control valve positions. The algorithm in the form of a block diagram is presented in Fig. 3.

To accelerate the algorithm, the following modifications were introduced, allowing finding an energy-efficient solution sufficient for industrial application significantly faster than a full enumeration of CMA-ES generations:

1. To exclude combinatorial enumeration of discrete states (on/off), the number of required pumps N_{req} is determined analytically by the method of a single test run of all pumps before starting the optimization:

$$Q_{req} \approx Q_\Sigma \sqrt{\frac{H_{target}}{H_{\max}}}, \tag{15}$$

$$N_{req} \approx \frac{Q_{req}}{0.9 Q_{nom}}, \tag{16}$$

where Q_Σ – the total flow rate of all pump units, $H_{\max}$ – the head obtained when starting all pumps.

In a real system, the unit quantity determination block N_{req} can receive data from the station's common flow meter without starting the units. Within the framework of modeling, the lack of a consumption value is compensated by preliminary identification of the network characteristics.

2. The optimization process is interrupted if technological conditions are met, the head is within the allowable corridor of ± 5%, and constraints on the operating region are observed, while the objective function value has ceased to improve for 20 iterations.

The configuration parameters of the CMA-ES evolutionary strategy are presented in Table 1.

The population size was increased from 8 to 24 individuals, which allowed better exploration of a wide range. The number of iterations is limited to 50, as experiments have shown that the solution stabilizes by the 40-50th iteration. The calculation limit is set to 1200, which guarantees algorithm convergence. An initial step of 1/3 of the range of allowable variable values allows covering the entire search space at the initial iterations.

Relaxing the accuracy by changing the TolFun parameter to 0.01 is sufficient for an engineering task, since the measurement noise of the instruments exceeds this value. Stopping the search using the TolX parameter if frequency changes are less than 0.1 Hz or valve position changes are less than 0.1%, which corresponds to the discreteness of actuators, allows reducing optimization time by cutting off iterations early.

Below are the graphs obtained during mode optimization for 100% load.

The graph in Fig. 4 demonstrates the process of minimizing the pen alty function. It is seen that at the initial stage, up to approximately evaluation 400, a coarse search with a large step occurs. This is caused by the enumeration of active pump combinations. Sharp jumps correspond to moments when the population falls into the region of inadmissible solutions, which leads to an increase in penalties. After evaluation 400, the algorithm moves to the stage of fine-tuning frequencies, and the function value stabilizes.

Fig. 5 presents the head graph at the dictating point. The black dashed line indicates the required head setpoint of 30 m. At the initial moment of time, random initialization of parameters can lead to head deviations of up to 10–15%. Due to the high weight coefficient of the head error in the objective function, the algorithm forcibly returns the head to the allowable technological corridor of ± 5% by evaluation 400. The remaining iterations are spent on minimizing energy consumption within this corridor without violating head constraints.

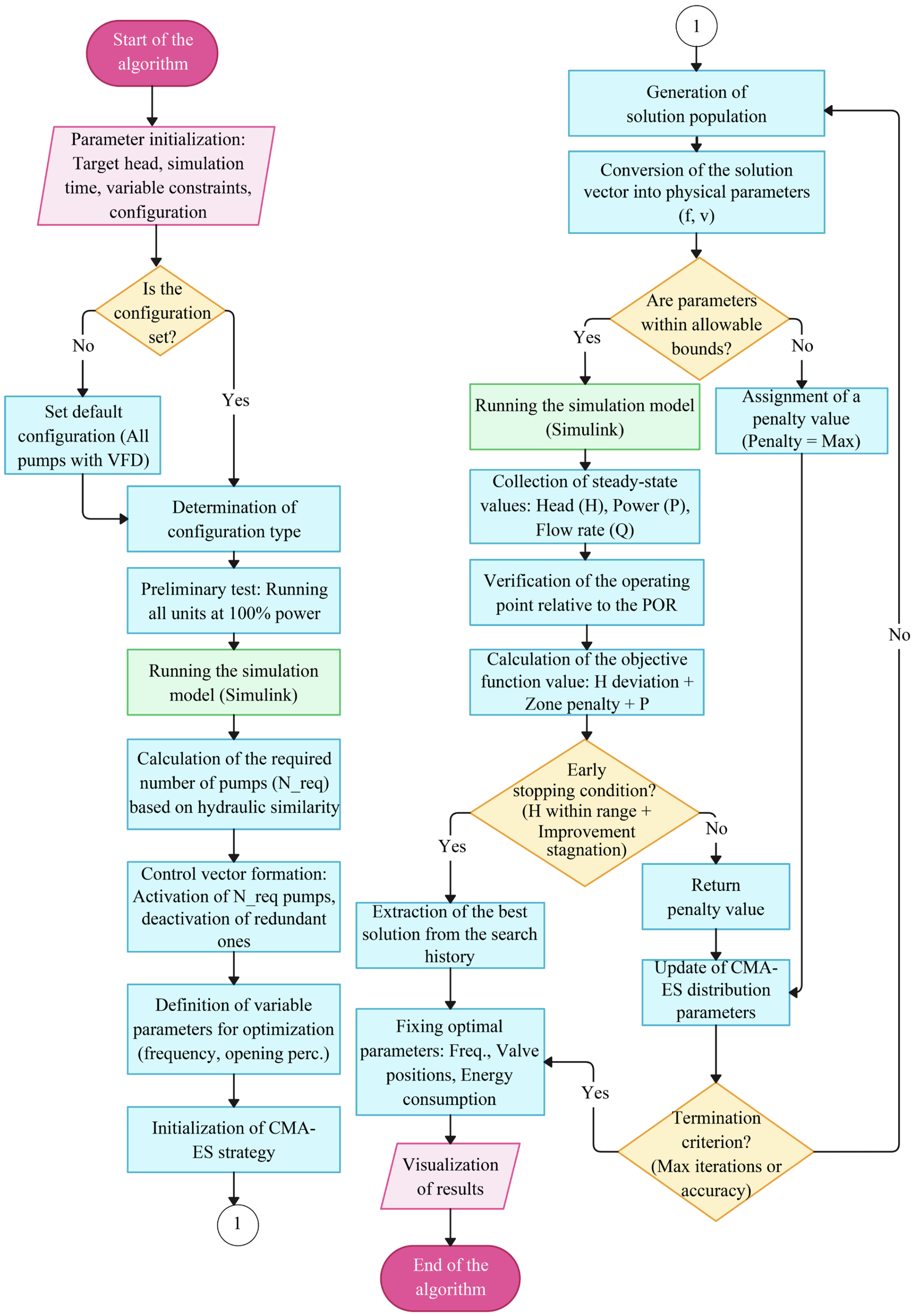

Fig. 3. Block diagram of the optimization system algorithm

Table 1

Configuration parameters

No.	Parameter	Value
1	Population size	24
2	Max. number of iterations	50
3	Max. evaluations	1200
4	Initial step	$(U_B - L_B) / 3$
5	Function tolerance (TolFun)	1e-2
6	Step tolerance (TolX)	1e-1

The graph in Fig. 6 shows how the algorithm iterates through pump frequencies. A correlation can be noticed between the decrease in the objective function value in Fig. 3 and the search for frequencies with a large step up to evaluation 400.

As can be seen from the graph in Fig. 7, when iterating through valve positions, the algorithm makes no distinction between setpoints of 55% (V_4) and 65% (V_5). This is due to the nature of the equal-percentage valve characteristic; in this range, the regulating capacity is reduced, and a change in the cross-section has practically no effect on the final flow rate.

The selected settings and stopping criteria allowed reducing the calculation time for one operating point to 60–80 seconds on average on a standard PC (CPU AMD Ryzen 5 5600G, 3.90 GHz, RAM 16.0 GB).

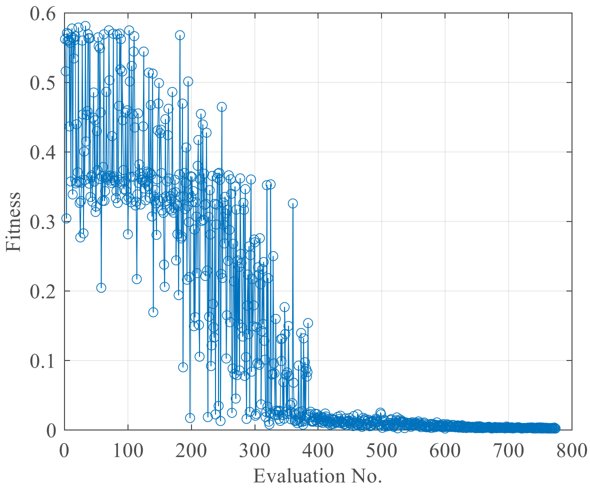

Fig. 4. Dynamics of the objective function

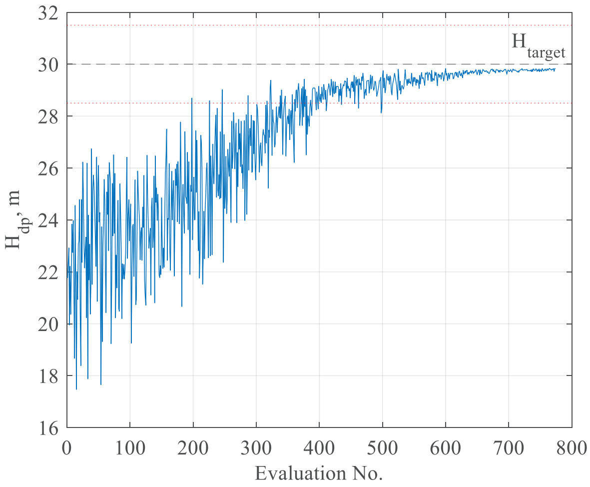

Fig. 5. Head stabilization at the dictating point

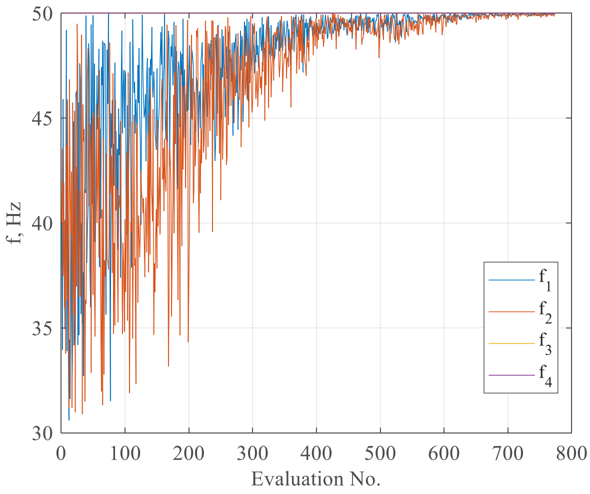

Fig. 6. Evolution of pump frequencies

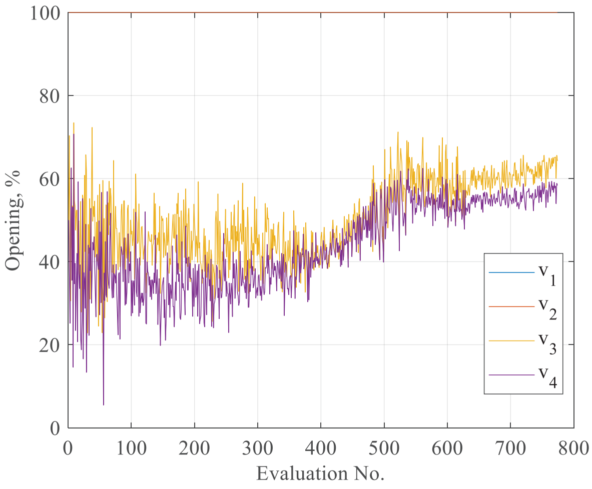

Fig. 7. Evolution of valve positions

5. 4. Investigation of the influence of objective function weight coefficients

To assess the efficiency of the developed algorithm under conditions of limited controllability, an experiment was conducted based on Configuration B. This scheme includes two units with VFDs and two units which flow rate is regulated by changing the valve position on the pressure line and which is a typical solution applied at pumping stations. The results are presented in Table 2.

Table 2

Influence of objective function weight coefficients

Load, %	Target head, m	Power, kW	Active pumps / In POR	Error	f_1, Hz	f_2, Hz	V_3, %	V_4, %
Strategy No. 1: $\omega_H = 0.9$, $\omega_D = 0.1$, $\omega_C = 0.0$, $\omega_P = 0.0$								
30	32.18	135.24	1/1	0.06543	42.84	0.00	0.00	0.00
40	30.07	190.66	2/2	0.002645	41.42	41.42	0.00	0.00
50	30.00	240.33	2/2	0.000132	43.13	41.91	0.00	0.00
60	29.92	372.72	3/1	0.007742	42.20	42.42	15.45	0.00
70	30.06	441.58	3/3	0.001671	43.88	43.91	17.39	0.00
80	29.95	731.78	3/3	0.025976	44.10	44.68	51.80	0.00
90	30.02	762.99	4/1	0.016753	45.84	45.92	24.04	61.01
100	29.80	856.27	4/4	0.005909	49.88	49.84	71.44	74.21
Strategy No. 2: $\omega_H = 0.4$, $\omega_D = 0.4$, $\omega_C = 0.2$, $\omega_P = 0.0$								
30	30.33	127.51	1/1	0.00438	42.17	0.00	0.00	0.00
40	29.94	189.89	2/2	0.104036	41.37	41.39	0.00	0.00
50	29.95	239.40	2/2	0.000672	42.00	42.99	0.00	0.00
60	30.05	378.69	3/2	0.085222	42.76	42.64	12.35	0.00
70	29.96	440.69	3/3	0.000469	43.92	43.80	17.28	0.00
80	30.01	530.19	3/3	7.37E-05	45.98	45.28	22.64	0.00
90	31.78	732.12	4/4	0.023693	47.68	47.76	23.31	29.39
100	28.72	830.50	4/4	0.017208	49.97	49.72	40.27	43.85
Strategy No. 3: $\omega_H = 0.5$, $\omega_D = 0.1$, $\omega_C = 0.0$, $\omega_P = 0.4$								
30	27.92	117.65	1/1	0.270048	41.27	0.00	0.00	0.00
40	28.92	189.75	2/2	0.191777	41.42	41.33	0.00	0.00
50	29.96	237.72	2/2	0.238355	42.47	42.48	0.00	0.00
60	28.87	372.18	3/2	0.258462	41.90	42.66	16.02	0.00
70	29.40	426.79	3/0	0.112111	34.77	42.14	90.86	0.00
80	27.17	504.14	3/0	0.172004	38.66	43.28	99.97	0.00
90	29.99	687.02	4/2	0.361852	48.15	39.69	33.03	30.32
100	28.89	839.96	4/4	0.418521	48.36	49.50	61.64	73.64

The aim of the experiment was to identify the optimal balance between head maintenance, energy consumption, and equipment reliability. By changing the weights, three strategies for setting the objective function weight coefficients were determined and tested:

1) strategy No. 1 – Head stabilization priority;

2) strategy No. 2 – Balanced mode taking into account equipment service life;

3) strategy No. 3 – Power minimization priority.

Summary simulation results with load changes from 30% to 100% are presented in Table 3.

Table 3

Comparative analysis of control strategies

Strategy	Average power, kW	Average head error, %	POR Hit, %
1	466.4	1.11	82.3
2	433.6	1.49	95.8
3	421.9	3.7	64.6

Strategy No. 3 demonstrated the best energy indicator. The introduction of a power weight coefficient allowed reducing the average station energy consumption to 421.9 kW, which is 9.5% more economical compared to Strategy No. 1 with an average power of 466.4 kW. However, Strategy No. 3 has the largest head error of 3.7%.

Strategy No. 2 also showed an energy-saving effect, reducing consumption by 7% to 433.6 kW relative to the baseline scenario. This confirms that optimizing the pump operating mode and keeping them in the zone of maximum efficiency indirectly leads to a reduction in energy costs, even if power is not the main optimization criterion.

A critical disadvantage of hybrid schemes is the risk of pumps operating outside the POR zone due to the rigid characteristics of mains-operated units. When using Strategy No. 1, despite high head accuracy, the zone hit rate was only 82.3%. This means that for almost 20% of the time, the pumps operated with overload or underload.

Strategy No. 3 exacerbated this problem, and in the pursuit of savings, the algorithm often drove the pumps into the zone of low flow rates, reducing the POR hit rate to 64.6%, which is unacceptable for long-term operation.

Strategy No. 2 proved its effectiveness, ensuring a maximum reliability level of 95.8%. The algorithm successfully found combinations in which mains-operated pumps were switched on only at moments when the required flow rate corresponded to their nominal capacity.

To visualize the trade-off between conflicting criteria and compare the number of feasible solutions, an analysis of the set of states generated by the algorithm population during evolution was performed. Although the used CMA-ES strategy minimizes the objective function, the search history allows identifying a set of non-dominated solutions forming an empirical Pareto front.

The distribution graphs of the tested solutions in the criteria space at 70% load are presented in Fig. 8, 9. Strategy No. 3 was not considered for this visualization, since when it is applied, the algorithm tends to find local minima outside the POR zone where pumps do not create useful head, which makes the comparison incorrect.

After analyzing the obtained graphs, it is seen that the Pareto front of solutions is clearly expressed when applying Strategy No. 2. When applying Strategy No. 1, the Pareto front of solutions is also expressed, however, the number of feasible solutions for Strategy No. 2 is significantly larger.

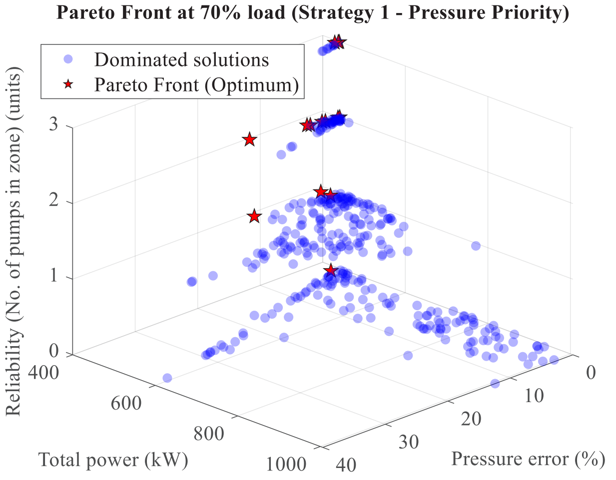

Fig. 8. Distribution of explored solutions in the criteria space at 70% load for Strategy No. 1

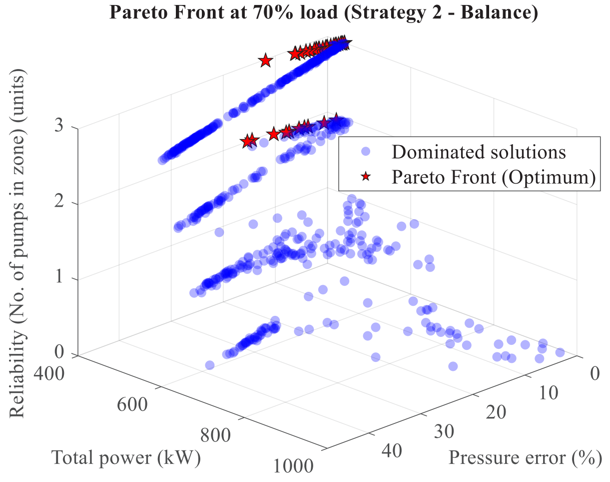

Fig. 9. Distribution of explored solutions in the criteria space at 70% load for Strategy No. 2

The results show that for pumping stations combining variable and fixed-speed units, the application of Strategy No. 2 is the most rational and has a high share of feasible solutions. It eliminates the low operational reliability of hybrid schemes, increasing the zone hit rate to 96%, and simultaneously provides tangible energy savings of 7% while maintaining the regulation error within 1.5%.

5. 5. Comparative analysis of hardware configurations and estimation of computational complexity

To assess the practical applicability of the method at facilities with different degrees of modernization, a comparative analysis of three typical pumping station configurations (Configuration A, B, C) was conducted. Experiments were carried out using Strategy No. 2, as it ensures a compromise between reliability and energy efficiency, which was confirmed during the investigation of control strategies. The results are presented in Table 4.

Summary simulation results by criteria of energy consumption, stabilization quality, and algorithm speed are presented in Table 5.

Table 4

Indicators for various configurations

Load, %	Head, m	Power, kW	Time, s	Active pumps / In POR	Error	Regulated parameters			
						f_1, Hz	f_2, Hz	f_3, Hz	f_4, Hz
Configuration A ($\omega_H = 0.4$, $\omega_D = 0.4$, $\omega_C = 0.2$, $\omega_P = 0.0$)									
30	29.94	125.92	6.47	1/1	0.000754015	42.03	0.00	0.00	0.00
40	31.39	198.93	64.60	2/2	0.018536139	41.92	41.87	0.00	0.00
50	29.97	237.90	34.20	2/2	0.000383897	42.64	42.32	0.00	0.00
60	30.21	319.13	50.42	3/3	0.078559828	42.86	42.78	42.41	0.00
70	29.95	393.15	68.72	3/3	0.000679177	44.43	43.86	43.77	0.00
80	30.00	496.57	69.75	3/3	6.62494E-05	45.56	46.32	45.65	0.00
90	29.99	653.97	71.31	4/4	8.0781E-05	46.78	47.15	46.91	47.40
100	29.54	846.86	111.74	4/4	0.006103714	49.74	49.60	49.96	49.70
Configuration B ($\omega_H = 0.4$, $\omega_D = 0.4$, $\omega_C = 0.2$, $\omega_P = 0.0$)									
30	30.33	127.51	9.61	1/1	0.004379579	42.17	0.00	0.00	0.00
40	29.94	189.89	36.46	2/2	0.104035799	41.37	41.39	0.00	0.00
50	29.95	239.40	28.39	2/2	0.000672096	42.00	42.99	0.00	0.00
60	30.05	378.69	105.48	3/2	0.085221742	42.76	42.64	12.35	0.00
70	29.96	440.69	74.82	3/3	0.000469332	43.92	43.80	17.28	0.00
80	30.01	530.19	94.18	3/3	7.37121E-05	45.98	45.28	22.64	0.00
90	31.78	732.12	158.43	4/4	0.023693196	47.68	47.76	23.31	29.39
100	28.72	830.50	89.58	4/4	0.01720813	49.97	49.72	40.27	43.85
Configuration C ($\omega_H = 0.4$, $\omega_D = 0.4$, $\omega_C = 0.2$, $\omega_P = 0.0$)									
30	31.90	134.06	7.28	1/1	0.02534434	42.74	0.00	0.00	0.00
40	29.95	258.46	64.42	2/1	0.130019532	41.48	11.64	0.00	0.00
50	30.01	297.83	68.32	2/2	0.00012971	42.42	15.00	0.00	0.00
60	29.79	430.52	134.95	3/2	0.100476665	41.89	14.62	14.59	0.00
70	30.07	492.08	97.55	3/3	0.000953232	43.93	16.10	16.49	0.00
80	29.98	568.53	77.77	3/3	0.000208504	45.72	23.13	18.36	0.00
90	30.01	731.75	144.28	4/4	0.000147724	46.91	20.41	23.79	20.94
100	29.87	859.53	84.42	4/4	0.001751757	49.98	81.21	87.12	56.49

Table 5

Comparative characteristics of hardware configurations

Configuration	Average power, kW	Energy overconsumption, %	Average head error, %	Average calculation time, s
A	295.3	–	0.97	49.0
B	370.5	25.5%	0.54	61.1
C	447.2	51.5%	2.91	87.2

Energy overconsumption is calculated relative to the reference Configuration A.

Configuration A showed reference efficiency with an average power of 295.3 kW. Frequency regulation allows precisely adjusting the pump head to the network resistance, while valves remain fully open, eliminating hydraulic losses.

Configuration C demonstrated the worst result with +51.5% to consumption. In this scheme, when the capacity of one pump with a VFD is not enough, the algorithm connects mains-operated units. Since their head is fixed, the algorithm is forced to close the pressure valve to stabilize the head. Despite the optimizer finding the ideal valve opening percentage for the current mode, the very principle of throttling converts excess head into heat and energy losses.

Configuration B took an intermediate position with +25.5% and provided the best accuracy in the experiment; the error was 0.54%. The presence of two VFDs allows managing without switching on mains-operated pumps and throttling for most of the load range, which significantly saves resources compared to Configuration C.

Configuration C showed an error of 2.91%. The dynamics of one pump with a VFD and regulated valves turned out to be insufficient for rapid compensation of disturbances during mode changes.

In Configuration A, the algorithm optimizes 4 variables (frequencies), which takes 49 s on average. The wide range of valve regulation in Configuration C with many local minima increases the solution search time to 87.2 s, and even with optimal control of the valve opening degree, throttling regulation in Configuration C loses to Configuration A by more than 50% in energy efficiency.

Configuration B acted as a compromise with a calculation time of 61.1 s, ensuring high accuracy and an acceptable level of losses if full station modernization is impossible.

6. Discussion of results of investigating the energy efficiency and reliability of the proposed control method

The results obtained from the developed simulation model, the objective function, the control algorithm, and the comparative analysis of control strategies allow explaining the mechanism of achieving energy savings and evaluating the advantages of the proposed method in comparison with existing control methods.

Unlike the analytical models used in [5, 8–10], where assumptions reduce accuracy, the implementation using the certified Simscape Fluids library in Simulink allowed taking into account the non-linear characteristics of the hydraulic network and the mutual influence of parallel units (Fig. 1, 2).

The ability to find an optimal balance between criteria is explained by the structure of the formalized objective function (expression (5)) and the direct influence of its individual components. Maintaining the operating points strictly within the POR zone was made possible by introducing a weighted sum of normalized penalty components (Table 2). In particular, increasing the weight of the head deviation penalty (J_H) ensures precise stabilization but reduces operational reliability, while a high power penalty (J_P) artificially drives the system into unacceptable low-flow regions. The balanced application of penalties for exiting the boundaries (J_{ZD}) and for the number of units outside the zone (J_{ZC}) effectively adapts the algorithm to current priorities and prevents equipment wear.

The computational efficiency of the adapted algorithm (Fig. 3) based on CMA-ES, unlike heavy models requiring 1000 generations to find the optimum [14], ensures convergence in 60–80 seconds. The rapid stabilization of the objective function after approximately 400 evaluations (Fig. 4) indicates the high efficiency of the search process. This convergence directly correlates with the algorithm's ability to dynamically adapt the frequencies (Fig. 6) and valve positions (Fig. 7). As a result, accurate head stabilization is ensured strictly within the allowable ± 5% corridor (Fig. 5). This was made possible by the introduction of an analytical block for express assessment, which eliminates combinatorial enumeration.

During the experiments, a dependence between energy consumption and reliability criteria was revealed, which can be explained by the physics of centrifugal pump operation. The success of Strategy No. 2, which ensured a reduction in energy consumption by 7% with a maximum zone hit rate of 96% (Table 3), is explained by the correlation between the POR zone and the area of the pump's maximum hydraulic efficiency. The mechanism of this balance is visually confirmed by the distribution of solutions in the criteria space. Strategy No. 2 (Fig. 9) generates a significantly denser Pareto front of feasible optimal solutions compared to the head-priority Strategy No. 1 (Fig. 8). The CMA-ES algorithm avoided modes with low efficiency, where most of the energy is spent on heat losses rather than on useful hydraulic work. Based on this, it can be concluded that in the long term, maintaining the mode in the high-efficiency zone is a more sustainable energy-saving strategy than direct power minimization.

When applying Strategy No. 3, the algorithm finds local power consumption minima, but this leads to a low reliability indicator of 64% (Table 3). At these points, the active motor power is indeed minimal, but such modes significantly reduce the station's reliability. This confirms that blind optimization by power is unacceptable.

The high efficiency of Configuration B compared to the minimal Configuration C is due to the presence of two VFDs. In the scheme with Configuration C, the algorithm is forced to limit the flow rate when switching on mains-operated pumps by throttling valves, which generates direct energy losses of more than 50% (Table 5).

The obtained results quantitatively agree with research data [5, 8], where the potential for energy saving in group control is declared at the level of 8–10%. However, unlike traditional cascade schemes, the developed method based on CMA-ES allowed realizing this potential (7% savings in Strategy No. 2) while simultaneously guaranteeing the location of operating points in the POR zone (96%). Classical algorithms focused only on maintaining the pressure setpoint do not take into account the pump POR zone. This often leads to prolonged operation of units regulated by VFDs in the low flow zone with an efficiency of less than 40–50% when working together with unregulated ones.

Comparison with methods using genetic algorithms (GA) [12, 13] shows that the selected CMA-ES algorithm often demonstrates an advantage due to the covariance matrix adaptation mechanism, which allows taking into account the strong correlation of control parameters. During parallel operation of pumps, a change in the operating mode of one pump affects the operating points of the others. Standard crossover operators in a genetic algorithm often destroy effective combinations of modes. CMA-ES, in turn, gradually reveals hidden dependencies between variables and adapts the shape of the search ellipsoid towards the minimum of the objective function. This ensures stable convergence of the algorithm even under conditions of poor problem conditioning.

The study results are valid within the accepted assumptions and have the following limitations regarding applicability to real objects:

1. Since the study focuses on steady-state modes, the developed algorithm does not take into account electromechanical and hydraulic transient processes during motor startup.

2. The model does not take into account changes in the physical properties of the fluid during operation. With significant seasonal fluctuations in water temperature, the accuracy of calculating efficiency and power consumption may decrease. In this case, it would be necessary to introduce correction coefficients into the algorithm, which was not considered in this work.

3. Passport characteristics of pumps were used in the simulation. However, in practice, impellers wear out, which degrades their parameters. In the algorithm, this is taken into account only through the wear coefficient when calculating power; due to this, over time, the optimization efficiency may decrease compared to the initial setting.

4. The study did not take into account changes in the hydraulic resistance of the pipeline. During operation, a change in roughness or other pipeline parameters is possible, so periodic calibration will be required to maintain model accuracy on a real object.

5. Simulations were carried out at a constant load, without changing it during the process. Under conditions of real, randomly changing water consumption, the method's efficiency may drop. This is due to calculation delays when searching for a solution.

6. The formulated objective function minimizes only operational criteria (energy consumption and equipment wear). The study does not account for capital expenditures. Since frequency converters for high-power pumps involve significant financial costs, any practical decisions regarding station modernization (such as moving from Configuration C to B) require a separate economic feasibility study to evaluate the payback period against the achieved energy savings.

The disadvantages of the proposed method include the high sensitivity of the algorithm to the tuning of weighting coefficients. As demonstrated in the experiment with Strategy No. 3, shifting the priority towards power minimization leads to the algorithm converging to local minima that are energy-efficient but unacceptable in terms of reliability, as the POR zone hit rate dropped to 64.6% (Table 3). This indicates that the method requires expert tuning of penalty functions for a specific object.

Another disadvantage is the inability to operate in real-time. The CMA-ES requires 60–80 seconds to find a solution. This makes the developed method inapplicable for compensating for rapid disturbances and limits its scope of application to the level of supervisory control (SCADA) with a discrete setpoint update period. This period must exceed the time constant of the hydraulic system itself.

In the future, real-time operation can be achieved by implementing a warm start strategy, where the optimal solution from the previous optimization cycle serves as the initialization point for the next one. Since hydraulic processes possess inertia, the new optimum is likely located close to the previous one, which will reduce the search time during smooth load changes. Furthermore, the possibility of applying parallel computing will be investigated. The computational process can be distributed across multi-core processors or GPUs, which will significantly accelerate the algorithm's convergence.

From an implementation perspective, a barrier is the limited computing power of industrial controllers, which are not designed for the complex operations required by CMA-ES.

This will require the integration of an industrial PC into the control system.

7. Conclusion

1. The study is based on the developed simulation model of the pumping station. Standard mathematical models were abandoned, and the model was implemented in the MATLAB&Simulink environment using the Simscape Fluids physical library. This solution allowed to directly link optimization algorithms with a detailed model of pipelines and valves, as well as correctly take into account the mutual influence of parallel pumps.

2. A multi-criteria objective function has been formulated, which contains penalties for head deviation, exiting POR boundaries, distance to the POR boundary, and power consumption. POR boundaries are dynamically recalculated depending on the current rotation speed according to affinity laws. By changing the weight coefficients in the objective function, the most balanced strategy was identified.

3. A modified control algorithm based on the CMA-ES evolutionary strategy is proposed. In order to accelerate, the algorithm was supplemented with a block for analytical express assessment of the required composition of units, which allowed excluding the need for a full enumeration of discrete combinations and limited the search space. Adaptive convergence criteria via "TolFun" and "TolX" parameters were applied, which allowed reducing the average time to find the optimal solution to 60–80 seconds. This makes it possible to apply the developed method in SCADA loops with a setpoint issuance period of 1–2 minutes, thereby overcoming the computational barrier inherent in genetic algorithms.

4. Strategy No. 2 proved to be the optimal strategy for setting weight coefficients. It ensured a reduction in energy consumption by 7% while maintaining pumps in the POR zone for 95.8% of the operating time. Direct power minimization through the application of Strategy No. 3, although yielding a gain of 9.5%, reduces the POR hit rate to an unacceptable level of 64.6%. This efficiency is explained by the correlation between the POR zone and the maximum efficiency area, which allows avoiding modes with high losses.

5. Comparison of configurations showed that Configuration B with two VFDs is a rational compromise for modernization. Energy overconsumption amounted to 25.5% relative to a system fully equipped with VFDs, with a minimal regulation error of 0.54%. At the same time, it was revealed that Configuration C with one VFD leads to an energy overconsumption of 51.5% and an increase in calculation time to 87.2 s. The low efficiency of the minimal configuration is explained by the wide range of valve regulation and the complex landscape of the optimization function.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

Authors' contributions

Yuliya Bulatbayeva: Conceptualization, Methodology, Writing – original draft; **Rauan Kossymbayev**: Writing – original draft, Investigation, Software, Visualization; **Victoria Tsypkina**: Writing – review & editing, Methodology, Formal analysis; **Vera Ivanova**: Writing – review & editing, Formal analysis, Visualization; **Felix Bulatbayev**: Writing – review & editing, Formal analysis.

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