



# Parallel nasoslarning intellektual energiya tejamkor boshqaruv tizimi

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**Dolzarbli:** bugungi kunda suv ta'minoti va oqova suv tizimlarida qo'llaniladigan nasos stansiyalari elektr energiyasining asosiy iste'molchilaridan biri hisoblanadi. Ayniqsa, parallel ishlaydigan nasos agregatlarining nomutanosib boshqaruvi energiya sarfining ortishi va ekspluatatsiya xarajatlarining ko'payishiga olib kelmoqda. An'anaviy boshqaruv usul-lari ushbu muammolarni bartaraf eta olmayotgan sharoitda, zamonaviy intellektual boshqaruv tizimlarini joriy etish dolzarb masalaga aylangan. Zamonaviy boshqaruv usullaridan biri bu PLC kontrollerlar bilan integratsiyalashgan sun'iy neyron tarmoqlar (ANN)dan foydalanish bo'lib, ular nasos tizimlarining ish rejimini doimiy kuzatib borish, o'zgaruvchan yuklamalarga moslashish va optimal boshqaruv strategiyasini shakllantirish orqali energiya samara-dorligini sezilarli darajada oshirish imkonini yaratadi.

**Maqsad:** parallel ishlaydigan nasos qurilmalarining elektr yuritma tizimini modellashtirish va ularni boshqarish samaradorligini oshirish uchun optimallashtirilgan intellektual boshqaruv tizimini ishlab chiqish.

**Usullari:** tadqiqotda markazdan qochma nasos, asinxron dvigatel va chastota o'zgartirgichlarning matematik modellari tuzildi. Boshqaruv tizimi MATLAB/Simulink muhitida modellashtirildi va neyron tarmoq asosidagi moslashuvchan algo-ritmlar yordamida sozlandi.

**Natijalar:** individual chastota boshqaruvi yordamida energiya sarfi o'rtacha 25–35% gacha kamaytirildi. Bosimning barqarorligi va nasoslarning optimal ish nuqtasida ishlashi ta'minlandi. Gidravlik zarb va kavitatsiya holatlarining oldi olindi. Model real sharoitga yaqin ishlashga mos va amaliy qo'llashga tayyor deb baholandi.

**Kalit so'zlar:** parallel nasoslar, elektr yuritma, energiya samaradorligi, chastota o'zgartirgich, intellektual boshqaruv, neyron tarmoq, MATLAB/Simulink.

## Интеллектуальная энергосберегающая система управления параллельными насосами

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**Актуальность:** в настоящее время насосные станции, используемые в системах водоснабжения и канализации, являются одними из основных потребителей электроэнергии. Особенно это касается параллельно работающих насосных агрегатов, неэффективное управление которыми приводит к увеличению энергопотребления и эксплуатационных затрат. В условиях, когда традиционные методы управления не справляются с возникающими проблемами, внедрение современных интеллектуальных систем управления становится актуальной задачей. Одним из современных методов управления является использование искусственных нейронных сетей (ANN), интегрированных с ПЛК-контроллерами. Такие системы позволяют постоянно отслеживать рабочие режимы насосных установок, адаптироваться к изменяющимся нагрузкам и формировать оптимальные управляющие сигналы, что существенно повышает их энергетическую эффективность.

**Цель:** разработать оптимизированную интеллектуальную систему управления для моделирования электрического привода параллельно работающих насосных установок и повышения эффективности их управления.

**Методы:** в исследовании построены математические модели центробежного насоса, асинхронного двигателя и преобразователя частоты. Система управления была смоделирована в среде MATLAB/Simulink и настроена с использованием адаптивных алгоритмов на основе нейронных сетей.

**Результаты:** применение индивидуального частотного регулирования позволило снизить потребление энергии в среднем на 25–35%. Обеспечена стабильность давления и работа насосов в оптимальной рабочей точке. Предотвращены явления гидравлического удара и кавитации. Модель оценена как близкая к реальным условиям и готовая к практическому применению.

**Ключевые слова:** параллельные насосы, электропривод, энергоэффективность, преобразователь частоты, интеллектуальное управление, нейронная сеть, MATLAB/Simulink.



# Intelligent energy-efficient control system for parallel pumps

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**Relevance:** today, pump stations used in water supply and wastewater systems are among the main consumers of electrical energy. In particular, the unbalanced operation of parallel pump units leads to increased energy consumption and higher operational costs. In situations where traditional control methods fail to address these challenges, the implementation of modern intelligent control systems becomes a pressing issue. One of the modern control methods is the use of artificial neural networks (ANN) integrated with PLC controllers. These systems enable continuous monitoring of pump station operating modes, adaptation to varying loads, and the formation of optimal control strategies, significantly enhancing energy efficiency.

**Aim:** to develop an optimized intelligent control system for modeling the electric drive of parallel pumping units and improving the efficiency of their control.

**Methods:** the study constructed mathematical models of a centrifugal pump, an induction motor, and a frequency converter. The control system was simulated in MATLAB/Simulink and tuned using neural network-based adaptive algorithms.

**Results:** the use of individual frequency control reduced energy consumption by an average of 25–35%. Pressure stability and operation of pumps at their optimal operating point were ensured. Hydraulic shock and cavitation phenomena were prevented. The model was evaluated as being close to real operating conditions and ready for practical implementation.

**Keywords:** parallel pumps, electric drive, energy efficiency, frequency converter, intelligent control, neural network, MATLAB/Simulink.

## 1. Introduction

Pumping stations employed in water supply and wastewater discharge systems are among the largest industrial consumers of electrical energy. According to global experience, such systems can account for as much as 25–30% of total electricity consumption in certain cases [1]. In particular, groups of pumps operating in parallel consume substantial amounts of energy during water lifting and transmission processes, which underscores the need to enhance system efficiency [2]. Typically, these systems are based on centrifugal pumps, whose operating regimes vary significantly throughout the day [3].

Studies indicate that the energy efficiency of pumping systems can be improved in the following ways: (1) employing modern and energy-efficient equipment; (2) reducing cavitation and hydraulic shocks in the system; and (3) minimizing energy losses through the optimization of control and monitoring algorithms [4].

In recent years, variable frequency drives (VFDs) have been widely adopted as an effective energy-saving solution. According to statistical data, these devices can reduce electricity consumption by up to 30–40% [5]. The application of fuzzy logic and artificial neural networks (ANNs) has shown high effectiveness in systems with complex or variable operating conditions [6,13].

Factors influencing the performance of control systems include the geometry of the pipeline, frictional forces, flow turbulence, and the physicochemical composition of water. Conventional PID controllers often fail to deliver satisfactory performance under such complex conditions, especially in the presence of parameter uncertainty [7]. As a result, there is a growing demand for intelligent control systems capable of real-time adaptation and robust operation [8].

In this study, mathematical models were developed for the key components of pump units and stations—the pump, electric motor, frequency converter, measurement instruments, and control blocks. These models are based on structural and parametric synthesis approaches and aim to support the design and optimization of energy-efficient control systems [9]. Adjustable-frequency drives (AFDs) are considered one of the most effective methods for achieving significant energy savings in pumping systems, with correct calculation methods being essential to justify their implementation [10]. Optimal vector control strategies have also been successfully applied to induction motor drives in pumping and ventilation systems, providing improved dynamic performance and efficiency [11].

Recent studies emphasize that increasing the operational reliability of electric drives directly contributes to the overall efficiency and durability of industrial systems [12]. Furthermore, predictive control approaches based on artificial neural networks (ANNs) demonstrate high potential for optimizing pump electric drives under varying operating conditions [13].



## 2. Methods and materials

This research focuses on enhancing the efficiency of a group of pump units integrated into technological complexes, connected in parallel, series, or combined configurations. The system was modeled based on a group control approach for the electric drives of the pumps. The selection of the connection scheme primarily depends on the following factors, which were incorporated into the mathematical formulation of the system: configuration of the hydraulic scheme, technical and operational conditions, and technological requirements.

A methodological approach was applied to optimize the control system, based on the following key principles:

Definition of an energy efficiency evaluation criterion – A generalized objective function was developed to assess system performance. This criterion was formulated considering the output power of the system, electrical energy consumption, and pressure stability.

Maintaining stable pressure under uncertain flow conditions – In scenarios with variable flow rates in the pipeline, a real-time stabilization model based on a PID controller was developed to maintain static and dynamic pressure levels. The model was tested in the MATLAB/Simulink environment.

Enhancing reliability under cavitation and hydraulic shock conditions – To improve system durability, operating conditions in cavitation zones were simulated, and adjustable configurations resistant to hydraulic shocks were developed. Specific hydraulic resistance functions were utilized in these simulations.

Self-adaptive control system – The control system was designed to continuously retune its parameters in real time using adaptive algorithms based on an artificial neural network. The neural regulator processes incoming data and adjusts the electric drive parameters toward optimal values.

The main technical components employed in this study include a centrifugal pump, a frequency converter, an induction motor, flow and pressure sensors, a programmable logic controller (PLC), and neural regulation units. The system models were constructed using structural block diagrams, and mathematical modeling and simulation were conducted using the MATLAB/Simulink platform.

**Mathematical models of the electric drive systems for pump units.** The variation in the rotational speed of the pump impeller results in corresponding changes in all operational parameters of the pump. The pump characteristics can be recalculated for a given operating speed  $\omega_i$  using similarity laws:

$$p_i = k_p \omega_i^2 \quad (1)$$

$$Q_i = k_Q \omega_i \quad (2)$$

$$M_i = k_M \omega_i^2 \quad (3)$$

$$P_i = k_p \omega_i^3 \quad (4)$$

here,  $p_i, Q_i, M_i, P_i, \omega_i$  - represent the current values of the pump's rotational speed, pressure, flow rate, static resistance torque, and power consumption.

To simplify the execution of calculations and analytical procedures, the article expresses the relationship between pressure and head using the following equation:

$$p_i = H_i \rho g \quad (5)$$

here,  $p_i$  — pressure, Pa;  $H_i$  — pressure head (head), m;  $\rho$  — fluid density, kg/m<sup>3</sup>;  $g=9.8$  m/s<sup>2</sup> — gravitational acceleration.

**The head characteristic of a pump operating at a variable rotational speed.** When the impeller's rotational speed varies, the pump's head characteristic is represented by a quadratic parabolic equation:

$$p_i = p_0 \left( \frac{\omega_i}{\omega_{nom}} \right) - R_{pump} Q_i^2 \quad (6)$$

here:  $p_0$  — pressure developed by the pump at zero flow rate;  $R_{pump} = \frac{p_0 - p_{nom}}{Q_{nom}^2}$  — hydraulic resistance of the pump. This value is determined according to nominal data, i.e., corresponding nominal pressure and nominal flow rate.  $p_{nom}$  - nominal pressure;  $Q_{nom}$  - nominal flow rate; These parameters are used to determine:  $Q_i$  — actual (real) flow rate of the pump;  $\omega_i$  — current angular frequency of the pump shaft;  $\omega_{nom}$  — nominal angular frequency.



The zero-flow pressure  $p_0$  determined at the nominal rotational speed  $\omega_{nom}$  is used to calculate the zero-flow pressure at any arbitrary rotational speed.

$$p_{0i} = \frac{P_0}{\omega_{nom}^2} \omega_i^2 \text{ va } p_{0i} = k_{p0} \omega_i^2 \quad (7)$$

The network (mainline) characteristic, in the presence of resistance, is determined using the following equation:

$$p_c = p_{II} + R_c Q_c^2 \quad (8)$$

here:  $p_c$  — current pressure in the network (system);  $p_r$  — resistance pressure, which is related to the difference in geodetic level between the highest point of the fluid column and the installation location of the pump;  $R_c = \frac{P_{nom} - p_r}{Q_{nom}^2}$  — hydraulic resistance of the pipeline;  $Q_c$  — actual flow rate in the pipeline. Using similarity laws, when pumps operate under resistance pressure, it is important to account for not only the rotational speed but also the ratio of the resistance pressure  $p_r/p_0$  in determining the working parameters of centrifugal pumps.

When solving the pump and pipeline equations jointly with respect to the actual flow rate  $Q_i$ , and if the pump flow rate depends on changes in its angular frequency, the following expression under resistance pressure conditions is used:

$$Q_i = Q_{nom} \sqrt{\frac{(\omega_i / \omega_{nom}) - (p_r / p_0)}{1 - (p_r / p_0)}} \quad (9)$$

The presented equations define the statics of hydraulic processes. When describing the dynamic behavior of fluid flow within the hydraulic section of a pump unit, the fluid is considered an incompressible medium with density  $\rho$ , occupying a volume within a hypothetical pipe of constant cross-sectional area  $S$  and length  $L$ .

In this case, an increase or decrease in flow rate is characterized by a corresponding increase or decrease in fluid frequency, which occurs under the influence of pressure forces and hydraulic resistance in the hydraulic section of the pump unit.

The frequency variation in the hydraulic part of the pump unit is expressed as follows:

$$\frac{dQ_i}{dt} = \frac{s}{\rho L} [p_1 + p_0 - p_c - (R_{\Sigma} Q_i^2)] \quad (10)$$

here:  $p_1$  — pressure in the suction pipe of the pump,  $R_{\Sigma}$  — total hydraulic resistance of the pump and pipeline system,  $S$  — cross-sectional area of the pipe,  $L$  — length of the pipe,  $\rho$  — fluid density.

The hydraulic (useful) power of the pump and the power consumed by the pump are determined by the following expressions:

$$P_{hyd} = p_i Q_i ; P_t = \frac{P_i Q_i}{\eta_i} \quad (11)$$

here:  $\eta_i$  - current pump efficiency

The variation of the pump's efficiency ( $\eta$ ) as a function of angular frequency is determined using the Moody formula, adapted specifically for pumps, in the following form:

$$\eta_i = 1 - \frac{1 - \eta_{nom}}{(\omega_i / \omega_{nom})^{0.36}} \text{ or } \eta_i = k_{\eta} \omega_i^{0.36} \quad (12)$$

here:  $\eta_{nom}$  — current efficiency of the pump.

The torque of the pump is determined by the following expression:

$$M_p = \frac{P_t}{\omega_i} = \frac{p_i Q_i}{\omega_i \eta_i} \quad (13)$$

**Models of electric drives with frequency-controlled induction motors.** The “frequency converter – induction motor” (FC–IM) system operates using vector control. The dynamic model of the electric drive based on sensorless vector control is formulated in the d–q coordinate system by analyzing the varying state variables and aligning them with the direction of the rotor flux.

The following equations describe the behavior of the stator current components  $i_{id}$  and  $i_{iq}$ , the rotor flux linkages  $\psi_2$  va  $\psi_2$  and the rotor EMF frequency  $\omega_p$ :



$$\dot{i}_{1d} = \frac{1/R_1}{\sigma T_1 p} (u_{1d} - R_1 \dot{i}_{1d} + \omega_{0\text{st}} \sigma TR_1 i_{1q} - k_2 p \psi_2) \quad (14)$$

$$\dot{i}_{1q} = \frac{1/R_1}{\sigma T_1 p} (u_{1q} - R_1 \dot{i}_{1q} + \omega_{0\text{st}} \sigma TR_1 i_{1q} - k_2 \omega_{0\text{st}} \psi_2) \quad (15)$$

$$\psi_2 = \frac{1}{T_2 p} (L_m \dot{i}_{1d} - \psi_2) \quad \omega_p = \frac{k_2 R_2 \dot{i}_{1q}}{\psi_2} \quad (16)$$

The formula for electromagnetic torque and the equation for angular frequencies:

$$M_D = \frac{3}{2} p_p k_2 \psi_2 \dot{i}_{1q} \quad \omega_{\text{del}} = \omega p_p + \omega_p \quad (17)$$

The fundamental mechanical equation:

$$p_\omega = \frac{M_D - M_N - M_c}{J} \quad (18)$$

here,  $M_n$ ,  $M_c$ ,  $J$  — represent the motor torque, resistive (load) torque, and the moment of inertia of the pump unit (PU) drive system, respectively.

**The regulators in the control loops are implemented in a conventional manner.** The functional module that links the specified value of flux linkage with the rotational speed command corresponds to the load characteristic of the pump unit (PU) and establishes an energy-efficient operating mode by reducing the reactive component of the stator current.

The vector control system does not account for the interdependencies between the control loops of active and reactive currents.

Since the transient times of electromagnetic processes in the PU are significantly shorter than those of mechanical processes, the mutual coupling in the control loops of rotational speed via back electromotive force (EMF) and flux linkage can be neglected.

As a result, the stator current components  $\dot{i}_{1d}$  and  $\dot{i}_{1q}$  as well as the rotor flux linkage  $\psi_2$  are governed by the following set of equations:

$$\dot{i}_{1d} = \frac{1/R_1}{\sigma T_1 p} (u_{1d} - R_1 \dot{i}_{1d} - k_2 p \psi_2) \quad (19)$$

$$\dot{i}_{1q} = \frac{1/R_1}{\sigma T_1 p} (u_{1q} - R_1 \dot{i}_{1q}) \quad (20)$$

here:  $\dot{i}_{1d}$  — time derivative of the stator current in the d-axis,  $u_{1d}$  — stator voltage component in the d-axis,  $R_1 \dot{i}_{1d}$  — voltage drop across stator resistance,  $k_2 p \psi_2$  — term representing the electromotive force (EMF) induced by rotor flux linkage,  $\sigma T_1$  — stator transient time constant, related to leakage factor and inductances.  $\dot{i}_{1q}$  — time derivative of the stator current in the q-axis;

### 3. Results and discussion

**Experimental investigation of electric drive systems in pumping stations.** As part of this study, the following configurations of parallel operation of electric drive systems (EDS) for pump units (PUs) were examined:

1. Group control of multiple PU electric drives using a single frequency converter (FC) and switching devices that provide connection to the power grid.
2. Individual frequency converter for each PU electric drive.

A functional diagram of an electric drive system consisting of two pump units and one frequency converter, along with its pressure characteristic, is shown in Figure 2. This technological solution enables each pump unit to be controlled via an individual FC and ensures independent operation of each unit within its permissible load range.

The control process is carried out based on the pressure measured at the outlet collector of the pumping station or at a dominant pressure point in the main pipeline system.

Applying an individual frequency converter (FC) for each pump unit ensures a higher degree of energy efficiency, precise load adaptability, and independent control of each unit. This approach is particularly effective in irrigation and urban water supply systems characterized by variable demand.

Experimental results indicate that, under the configuration with individual FCs, the operating modes of the pumping station become more stable, excessive energy consumption is reduced, and the service life of the pumps is extended.

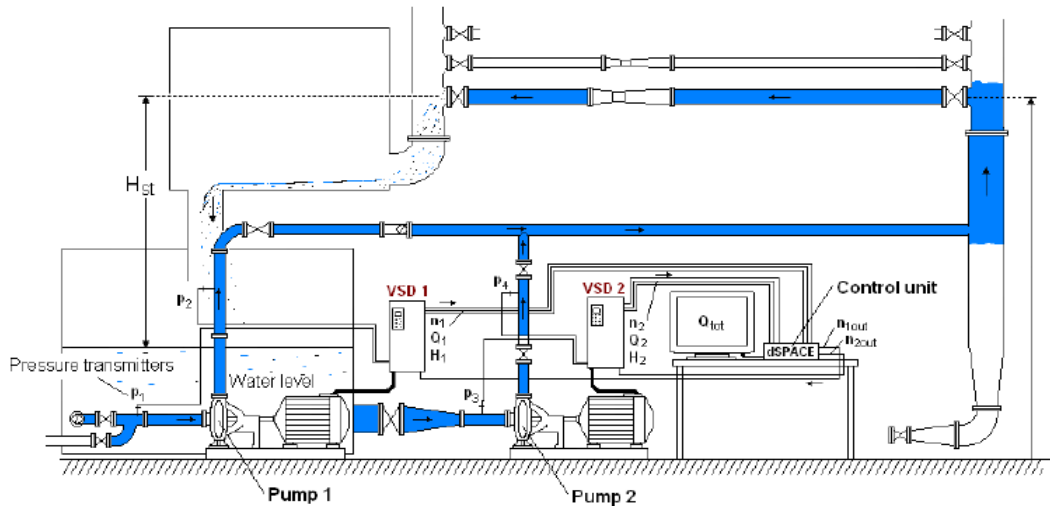


Fig.1. Control strategy for variable speed-driven parallel pumping systems (adapted from Nassiri et al., 2013)

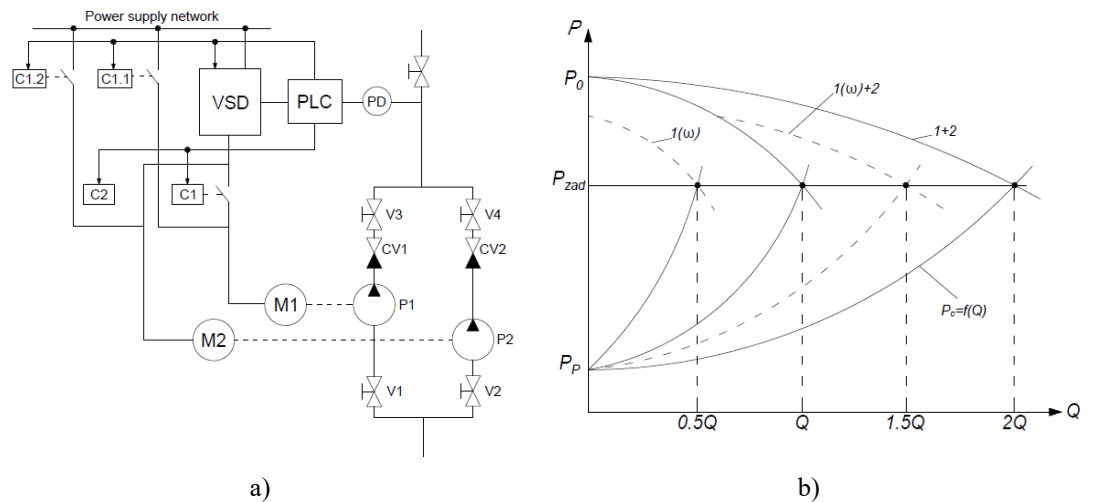


Fig.2. a) Functional control scheme of a pumping station with parallel-operating pump units (PUs) regulated by a single frequency converter (FC); b) Pressure-flow characteristics of two parallel-operated pump units.

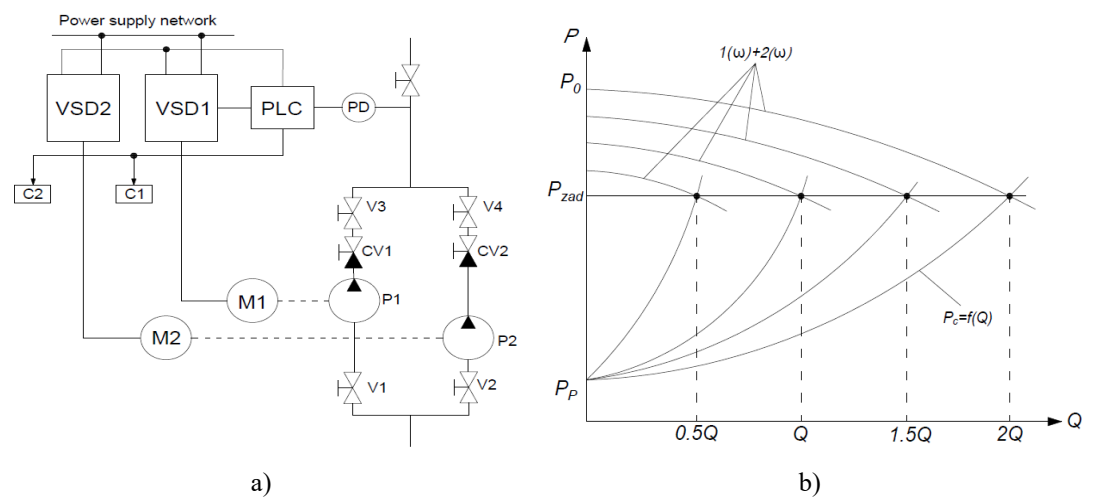


Fig.3. a) Functional control scheme of two parallel pump units (PUs), each driven by a dedicated frequency converter (FC) and connected to the power grid through switching devices; b) Pressure-flow characteristics of two parallel-operated PUs.

This control system can regulate the pressure either at the outlet of each individual pump unit or at the discharge collector of the pumping station. a) Functional control diagram of parallel-operating pump units (PUs), each equipped with a separate frequency converter (FC); b) Pressure characteristic of two parallel-operating PUs. The most efficient configuration is Figure 3, as it provides the highest energy efficiency. Parallel-connected pumps are typically of the same type, which ensures balanced load distribution when all pumps operate simultaneously.

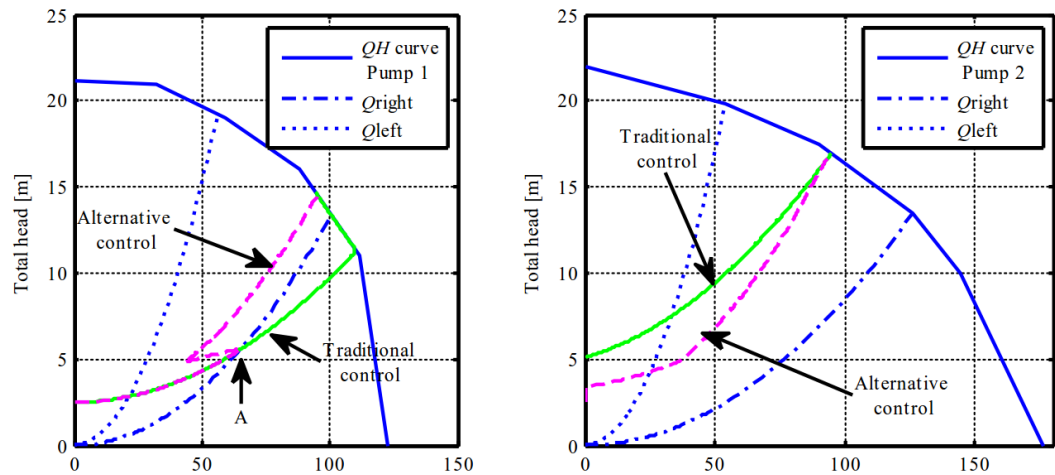


Figure 4. Comparison of conventional and alternative control strategies on the operating performance of parallel pump units: Q–H characteristics of Pump 1 and Pump 2 under different control modes.

Using pumps of different sizes may result in the dominance of the largest pump within the system, forcing the remaining pumps to operate below their minimum nominal flow rates. If pumps of different sizes must be connected in parallel, their performance characteristics (operating curves) should be carefully analyzed to ensure that each pump operates above its minimum required flow rate.

Additionally, switching pumps on and off can help maintain their operating point close to the optimal efficiency point. However, when operating with parallel pumps, it is essential to ensure that the minimum flow requirements of each pump are met.

Thus, high-quality control of pump units can be achieved through individual frequency regulation, as demonstrated in the efficient configuration shown in Figure 3. The above analysis shows that frequency-controlled pump units offer a highly effective and reliable solution to various operational challenges. The energy efficiency evaluation was also performed considering both external and internal disturbances.

#### 4. Conclusion

This study addresses the issue of improving energy efficiency by optimizing the control system of electric drives for parallel-connected pump units. The mathematical model and control system developed during the research enable the pumps to operate in variable modes, adapted to their actual operating conditions. The analysis demonstrated that controlling each pump unit with an individual frequency converter significantly reduces energy consumption. Additionally, the system ensures pressure stability, enables pumps to operate at their optimal working points, and enhances overall reliability. Taking into account variable loads, hydraulic shocks, and cavitation conditions in the control process, stable and adjustable mechanisms were developed. The effectiveness of the proposed approach was validated through experimental testing.

The results of this study provide a solid foundation for the development of energy-efficient control systems that can be implemented in real industrial applications in the future.

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