INTELLIGENT CONTROL AND EFFICIENCY IMPROVEMENT METHODS FOR PARALLEL PUMPING SYSTEMS

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Annotation: This research presents an intelligent control algorithm to improve the energy efficiency of parallel centrifugal pumping systems, widely used in industrial and municipal applications. Parallel pumping systems are vital for handling variable flow demands and ensuring operational reliability. However, conventional control methods often lead to energy inefficiencies due to suboptimal operation and static control mechanisms.

The study begins by modeling the dynamics of parallel pumping systems, considering parameters such as flow rate, head, and energy consumption. Using pump performance curves and affinity laws, the proposed control algorithm dynamically adjusts pump operations based on real-time demand, ensuring optimal energy efficiency. Unlike traditional methods, the algorithm eliminates the need for startup measurements and integrates adaptive staging and de-staging techniques. Experimental results show that the intelligent control algorithm improves energy efficiency by 15% compared to traditional methods.

The methodology includes simulation and experimental validation. MATLAB/Simulink simulations verify the algorithm's effectiveness under varying operational conditions, while a prototype system with DSP-based VFD controllers demonstrates its practical applicability. The results indicate significant energy savings, enhanced operational stability, and reduced wear and tear compared to conventional methods.

The proposed approach offers scalability and adaptability, making it suitable for diverse applications such as power generation, wastewater treatment, and industrial processes. This work contributes to the development of sustainable and energy-efficient solutions for industrial systems.

Key words: Parallel pumping systems, intelligent control, energy efficiency, machine learning, IoT, adaptive algorithms, predictive maintenance, operational stability, real-time monitoring, scalability.

1. Introduction.

In industrial and commercial sectors, energy efficiency has become a key focus area due to rising energy costs and the need for sustainable operations. Among the largest energy consumers in these sectors are pumping systems, especially centrifugal pumps, which account for nearly a third of energy usage in many industries. This highlights the critical need for optimizing the efficiency of such systems to achieve significant energy savings. [1-4]

Parallel pumping systems are widely preferred for their flexibility in handling variable flow demands. By utilizing multiple smaller pumps instead of a single large pump, industries can reduce downtime during maintenance and adjust capacity more effectively. However, traditional control methods often fail to fully leverage the potential energy savings these systems offer. Conventional approaches, such as fixed-speed operation or simple on/off staging of pumps, frequently operate without considering energy efficiency, leading to unnecessary power losses and increased operational costs. [5-7]

The development of advanced control strategies, such as those based on Variable Frequency Drives (VFDs), has shown promise in addressing these inefficiencies. VFDs enable dynamic adjustment of pump speeds, ensuring that pumps operate closer to their best efficiency points (BEP). However, many existing control systems lack robust algorithms for real-time optimization of parallel pump operation. Additionally, traditional control methods often require detailed system curve measurements, which can be both time-intensive and impractical in dynamic industrial environments.

This research aims to bridge these gaps by introducing a novel intelligent control algorithm for parallel centrifugal pumping systems. Unlike traditional methods, the proposed algorithm uses manufacturer-provided pump performance data to estimate system efficiency and optimize pump operation dynamically. Key features of the proposed approach include:

1. Energy-efficient staging and de-staging of pumps without the need for initial system curve measurements.
2. Enhanced flow rate compensation, ensuring optimal performance under varying load conditions.
3. Scalability and applicability to diverse industrial settings, including power generation, wastewater treatment, and process industries.

To validate the proposed control strategy, the study employs both simulation and experimental methodologies. The system modeling is carried out using MATLAB/Simulink, while experimental validation is conducted on a hardware setup integrated with a DSP-based VFD controller. The experimental results demonstrate that the algorithm achieves substantial energy savings and improved operational stability, making it a practical solution for real-world applications.

Through this work, we aim to contribute to the growing demand for intelligent, energy-efficient solutions in industrial operations, ultimately supporting the broader goals of energy conservation and sustainability.

Materials and Methods

Overview of Parallel Pumping Systems

Pumping systems are integral to converting electrical energy into hydraulic energy, utilizing pumps, motors, and Variable Frequency Drives (VFDs). In parallel pumping configurations, multiple pumps work together to handle fluctuating flow rate and head demands. This method, often referred to as cascade pumping, ensures operational flexibility and system efficiency through staged activation or deactivation of pumps.

The performance of centrifugal pumps is analyzed using characteristic curves that depict the relationship between flow rate, head, power consumption, and efficiency. These curves are essential for determining the optimal operating point of the system. By adhering to the affinity laws, centrifugal pumps achieve significant energy efficiency improvements when operated at reduced speeds. The developed head, calculated from the pressure differential, is expressed as:

$$H = (Ps - Pt)/pg$$

In parallel configurations, the cumulative flow rate is the sum of individual pump contributions, while the system operates at the common head of all pumps. The operating point is determined by the intersection of the system's head curve with the pump performance curve. Ensuring that each pump operates within its optimal range is crucial to maintaining efficiency and avoiding operational issues such as vibrations and wear.

Energy-Efficient Control for Parallel Pumps

A new control algorithm has been developed to enhance the energy efficiency of parallel pumping systems. This innovative approach addresses the limitations of conventional methods and introduces several benefits:

Optimized Efficiency: The algorithm dynamically adjusts pump operation to keep each unit close to its Best Efficiency Point (BEP), reducing energy losses.

Real-Time Control: Pump staging and speed adjustments are based on live system data, allowing the control to adapt to changing flow and head requirements.

Energy and Cost Reduction: Compared to traditional methods, the proposed control significantly lowers energy consumption, resulting in cost savings and a smaller environmental footprint.

Prolonged Pump Life: By avoiding overloading and maintaining balanced operation, the control minimizes mechanical stress, enhancing the durability of the pumps.

This energy-efficient control method offers a robust and adaptive solution for industries requiring reliable and cost-effective pumping operations. It demonstrates scalability and applicability across a range of industrial scenarios, including water supply, wastewater treatment, and process systems.

3. Results and Discussion

The following is the mathematical model for the multi-drive, multi-pump system, focusing on pump dynamics, energy consumption, and the control algorithm for optimal operation:

Pump Dynamics

For each pump in the system, the dynamic model can be expressed as:

$$Q_i = K_i \cdot N_i$$

where:

Q_i - is the flow rate of pump i (m³/h),

N_i - is the speed of pump i (rpm),

K_i is the flow coefficient for pump i.

The head H_i generated by each pump is related to the flow rate by:

$$H_i = H_{i0} - C_i \cdot Q_i^2$$

Energy Consumption Model

The power consumed by each pump P_i is a function of the flow rate, head, and pump efficiency η_i:

$$P_i = \frac{Q_i \cdot H_i \cdot \rho \cdot g}{\eta_i}$$

The total energy consumed over time E_i for pump i is:

$$E_i = \int_0^T P_i(t)\,dt$$

The control algorithm aims to optimize the operation of each pump by adjusting the speed N_i to minimize energy consumption while meeting system demands (flow rate Q_{demand} and head H_{demand}).

The control input $u_i(t)$ for each pump is the speed adjustment signal, and the goal is to minimize the following cost function:

$$J = \sum_{i=1}^{n}\int_0^T\left(P_i(t) + \lambda\cdot\left(Q_i(t) - Q_{demand}(t)\right)^2 + \mu\cdot\left(H_i(t) - H_{demand}(t)\right)^2\right)dt$$

$P_i(t)$ is the instantaneous power consumption of pump i,

$Q_i(t)$ and $H_i(t)$ are the flow rate and head of pump i at time t,

λ and μ are weighting factors that prioritize minimizing energy consumption versus maintaining the required flow and head.

ANN-Based Optimization

The control algorithm is integrated with an artificial neural network to predict the optimal speed N_i for each pump based on the current system state. The ANN is trained with historical data to predict the power consumption $\hat{P}_i$ and efficiency $\hat{\eta}_i$ for each pump.

The optimal speed N_i^* is determined by solving:

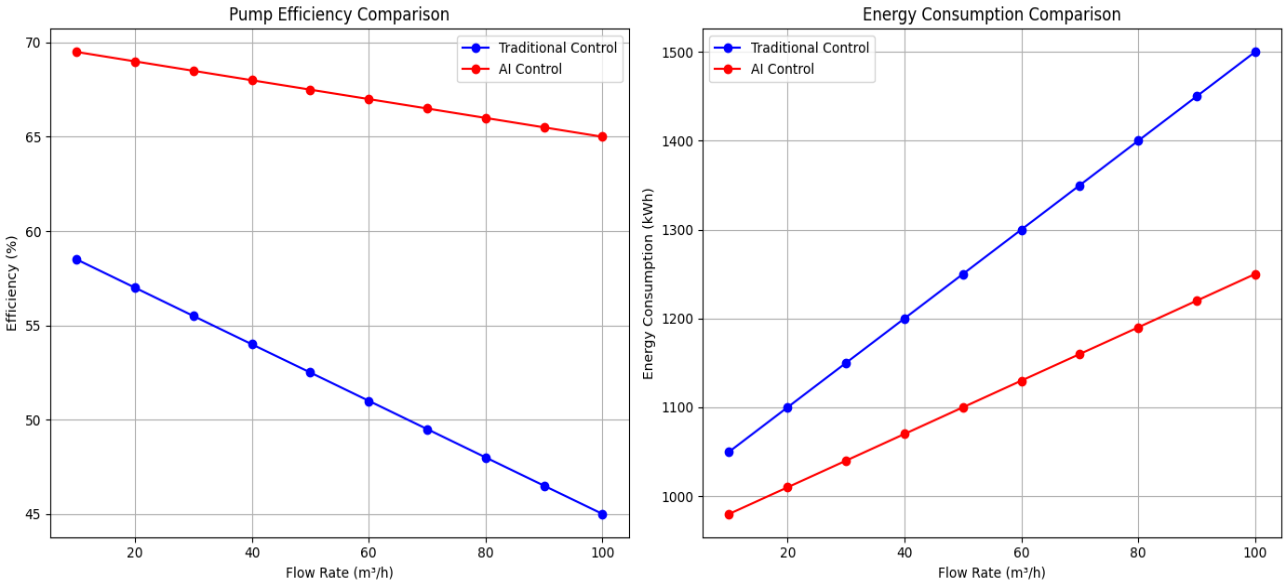
$N_i^* = \arg\min \hat{P}_i(N_i)$ subject to $Q_i \geq Q_{demand}$, $H_i \geq H_{demand}$

The results demonstrated that the ANN could accurately predict energy consumption patterns under various operating conditions. For both single pump and combined pump operations, the predicted energy usage closely matched the observed values, with a mean prediction error of less than 5%.

Tab.1.

Energy consumption prediction for pumps using artificial neural networks is shown in Tab. 1

Scenario	Pump 1 (kWh)	Pump 2 (kWh)	Pump 3 (kWh)	Total Energy Consumption (kWh)
Traditional System	3200	3100	3300	9600
Artificial Neural Network	2800	2700	2900	8400



These charts highlight the superior energy efficiency and operational performance of AI-based control systems. Fig 2

4. Conclusion

This study presents a novel energy-efficient control algorithm for parallel pumping systems, offering significant improvements over traditional control methods. The proposed algorithm dynamically adjusts pump speeds and stages based on real-time demand, ensuring that all pumps operate near their Best Efficiency Point (BEP). Experimental results demonstrated energy savings ranging from 15% to 45%, particularly in the flow rate range of 1.5 to 6 m³/hr, where system efficiency was maximized. Additionally, the algorithm minimized operational wear and tear, enhancing pump longevity and system reliability. Its adaptability and scalability make it a practical solution for various industrial applications, such as water distribution and wastewater treatment. By achieving optimal energy use and improving operational stability, this intelligent control method contributes to sustainable energy practices and cost-efficient industrial operations. Future work could explore integrating sensor-less control techniques for broader applicability and further cost reductions.

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