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Stabilization of Pressure in a Common Pipeline through Frequency-Based Control of Pumping Units

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Abstract. Parallel pumping systems are widely used in industrial water supply but remain major consumers of electrical energy. This study investigates energy-efficient control and optimization strategies for pumps operating in parallel on a common pressure pipeline. Intelligent optimization methods, including machine learning–based approaches, are analyzed to minimize energy consumption, stabilize pressure, and reduce losses. The results demonstrate that intelligent control significantly improves system efficiency and operational reliability under varying load conditions.

INTRODUCTION

Due to climate change and the adverse consequences of environmental degradation, increasing attention is being paid worldwide to the efficient use of electrical energy. In industrial sectors, particularly in electric drive systems of industrial enterprises, ensuring energy efficiency has become a crucial task. Pumping units represent one of the major energy consumers in these sectors, accounting for approximately 20–30% of total electricity consumption [1]. Therefore, significant potential still exists for energy savings through effective control and optimization of pumping units. Although multi-pump systems operating in parallel on a common pressure pipeline are widely used in practice, their energy efficiency is often not sufficiently considered. This efficiency can be substantially improved through the application of advanced control algorithms and optimisation methods [1][3]. Recent studies have employed intelligent approaches such as the gravitational search algorithm, artificial neural networks, NSGA-II, and machine learning techniques for parallel pumping systems. These methods have been shown to minimise the energy consumption of pumping units, enhance overall efficiency, ensure stable delivery pressure, and reduce entropy generation or energy losses [1–4]. Furthermore, the application of intelligent control and optimisation strategies to pumping units operating in parallel on a common pressure pipeline has demonstrated a significant increase in energy-saving potential [3][4]. In this context, intelligent optimisation and control strategies play a vital role in improving the energy efficiency and operational reliability of parallel pumping systems, necessitating a detailed analysis of the interactions between various control parameters and operating conditions [4].

EXPERIMENTAL RESEARCH

The development of a block diagram for the control system of a pumping station operating on a common pressure pipeline is aimed at ensuring the stability of the required water pressure in the pipeline. The water supply schedule of a pumping station connected to a common pressure pipeline is characterised by a variable load, since the volume of water delivered to consumers varies significantly at different times of the day. Under such conditions, maintaining stable water pressure in the common pressure pipeline while controlling the pumping station in energy- and resource-efficient operating modes is currently considered one of the priority tasks. As a solution to this problem, a control approach is proposed in which, under variable water consumption rates, the required water pressure in the common pressure pipeline is maintained by sequentially starting parallel-operating pump units connected to the pipeline.

Accordingly, the pumping station control system based on this principle is applied to the water supply system, providing stable pressure regulation while improving the overall energy efficiency and operational reliability of the pumping station.

Figure 1 presents the block diagram of the control system for a pumping station operating on a common pressure pipeline, designed to ensure the stability of the required water pressure in the pipeline. The block diagram illustrates four pump units operating on the common pressure pipeline, along with the electric motors driving them. Each pump unit is connected to the common pressure pipeline via communication pipelines. Each communication pipeline is equipped with a check valve, a pressure shut-off valve, and a pressure sensor. In addition, valve-type shut-off devices are installed on the suction pipelines of each pump unit. A pressure sensor is also installed on the common pressure pipeline. The block diagram of the control system consists of the following elements.

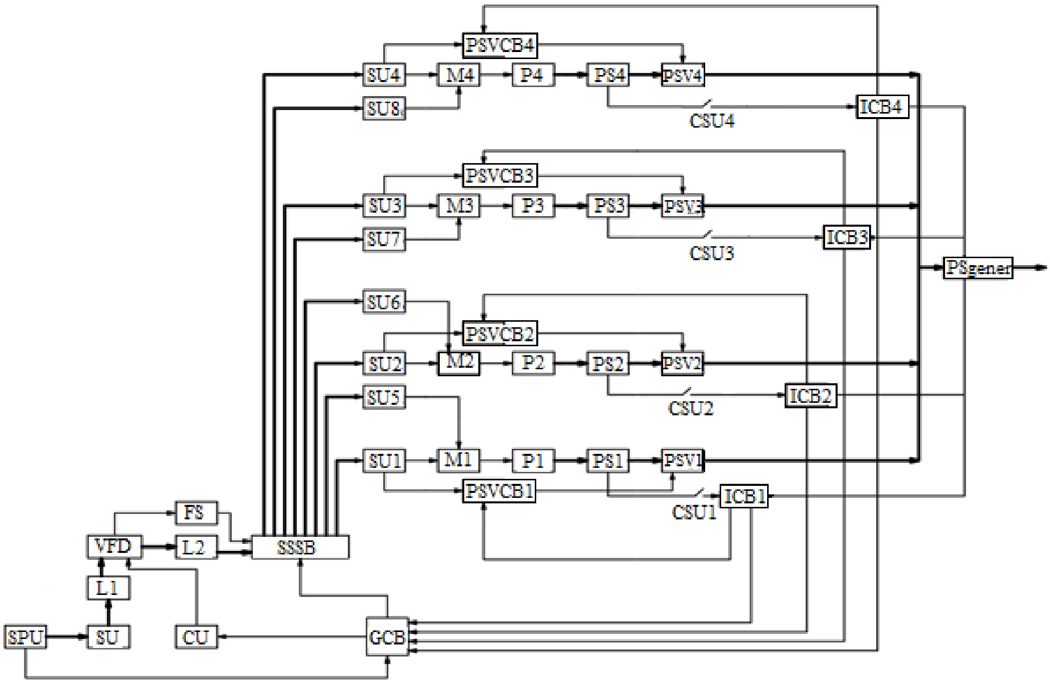

FIGURE 1. Block diagram of the control system of a pumping station operating on a common pressure pipeline, designed to ensure the stability of the required water pressure in the pipeline.

VFD – variable frequency drive;
L1 ÷ L2 – reactors providing protection against high commutation currents;
SSSB – start-up sequence selection block;
M1 ÷ M4 – induction motors;
P1 ÷ P4 – pumps;
PSV1 ÷ PSV4 – pressure shut-off valves in the communication pipelines;
PS1 ÷ PS4 – pressure sensors;
SPU – setpoint unit;
CU – control unit;
FS – frequency sensor;
SU1 ÷ SU8 – starting devices;
PSVCB1 ÷ PSVCB4 – control blocks of the pressure shut-off valves;
ICB1 ÷ ICB4 – intermediate comparison blocks;
GCB – global comparison block;
CSU1 ÷ CSU4 – control contacts of the starting devices.

The sequential start-up of the control system for a pumping station operating on a common pressure pipeline, designed to maintain the required water pressure in the pipeline, is carried out as follows. Prior to start-up, all shut-off valves are initially in the closed position. The setpoint value of the required water pressure is entered into the command device. At this stage, the variable frequency drive is connected to the power network through the start-up device and the L1 reactor, which provides protection against high commutation currents. The variable frequency drive adjusts the voltage and frequency values, while the L2 reactor and the start-up sequence selection block (SSSB) prepare pump M1 for operation with the assistance of the start-up device SU1. The power contacts of SU1 connect motor M1 to the output terminals of the variable frequency drive, while the control contacts send a signal to the control block of the pressure shut-off valve PSVCB1. Consequently, M1 drives pump P1, creating water flow in the communication pipeline. When the communication pipeline is filled with water and pressure is established, the pressure sensor PS1 in the communication pipeline transmits a signal via the intermediate comparison block ICB1 to the pressure valve control block PSVCB1. PSVCB1 issues a command to open the pressure shut-off valve PSV1. As a result, the water pumped by P1 is delivered from the common pressure pipeline to consumers. The water pressure generated by pump P1 is measured by the overall pressure sensor PS_total and transmitted to the global comparison block (GCB). The GCB compares the measured pipeline pressure with the setpoint pressure entered in the command device and, through the control unit (CU), authorizes the variable frequency drive to increase the voltage and frequency up to 50 Hz. If, upon reaching 50 Hz, the pressure in the common pressure pipeline remains below the required setpoint, the GCB sends a signal to the start-up sequence selection block (SSSB). SSSB disconnects M1 from the variable frequency drive network via SU1 and connects it to the power supply network through SU5. Following this procedure, the second and third pump units are started sequentially according to the required water pressure.

The parallel operation of the pump units on the common pressure pipeline, as well as the number of pumps, is used to determine their operational efficiency coefficient, ensuring optimal energy performance of the pumping station.

Operation of a single pump unit (PU) of model D12500-24 in the pressure network (Q = 3.69 m^3/s, H = 21.5 m, η_{PU} = 0.78, T = 3636 h).

Two identical pump units of model D12500-24 operating in a common pressure network (Q = 2.43 m^3/s, H = 27.75 m, η_{PU} = 0.74, T = 48 h).

Two dissimilar pump units operating in a common pressure network (Q_1 = 2.72 m^3/s, H_1 = 26.1 m, η_{PU_1} = 0.77, T_1 = 36 h; Q_2 = 1.75 m^3/s, H_2 = 26.1 m, η_{PU_2} = 0.76, T_2 = 36 h).

Operation of a single pump unit of model D6300-27 with a driven electric motor type SD2-85-57-8 in the pressure network (Q = 2.26 m^3/s, H = 15.5 m, η_{PU} = 0.61, T = 5064 h).

The efficiency values of the driven electric motors under the considered operating modes are determined according to the following relation:

$$\eta_{M.n.i} = \frac{1}{1+\left(\frac{1}{\eta_{M.n.i.r}}-1\right)*\frac{(K_{n.i}+\frac{a_{con}}{K_{n.i}})}{(1+a_{con})}}. \tag{1}$$

The weighted average efficiency values of the pumps, $\eta_{P.i}^{avr}$, operating in their respective pressure networks, are calculated as follows:

$$\eta_{P1}^{avr} = \frac{\eta_{P1.1}*Q_{1.1}*H_{1.1}*T_{1.1}+\eta_{P2.1}*Q_{2.1}*H_{2.1}*T_{2.1}}{Q_{1.1}*H_{1.1}*T_{1.1}+Q_{2.1}*H_{2.1}*T_{2.1}} \tag{2}$$

$$\eta_{P2}^{avr} = \frac{\eta_{P1.2}*Q_{1.2}*H_{1.2}*T_{1.2}+\eta_{P2.2}*Q_{2.2}*H_{2.2}*T_{2.2}+\eta_{P3.2}*Q_{3.2}*H_{3.2}*T_{3.2}}{Q_{1.2}*H_{1.2}*T_{1.2}+Q_{2.2}*H_{2.2}*T_{2.2}+Q_{3.2}*H_{3.2}*T_{3.2}} \tag{3}$$

The weighted average efficiency values of the driving electric motors, $\eta_{M.i}^{avr}$, of pump units operating in a common pressure network are determined as follows:

$$\eta_{M.1}^{avr} = \frac{\eta_{M1.1}*\frac{Q_{1.1}*H_{1.1}*T_{1.1}}{\eta_{P1.1}}+\eta_{M2.1}*\frac{Q_{2.1}*H_{2.1}*T_{2.1}}{\eta_{P2.1}}}{\frac{Q_{1.1}*H_{1.1}*T_{1.1}}{\eta_{P1.1}}+\frac{Q_{2.1}*H_{2.1}*T_{2.1}}{\eta_{P2.1}}} \tag{4}$$

$$\eta_{M.2}^{avr} = \frac{\eta_{M1.2}*\frac{Q_{1.2}*H_{1.2}*T_{1.2}}{\eta_{P1.2}}+\eta_{M2.2}*\frac{Q_{2.2}*H_{2.2}*T_{2.2}}{\eta_{P2.2}}+\eta_{M.3.2}\frac{Q_{3.2}*H_{3.2}*T_{3.2}}{\eta_{P3.2}}}{\frac{Q_{1.2}*H_{1.2}*T_{1.2}}{\eta_{P1.2}}+\frac{Q_{2.2}*H_{2.2}*T_{2.2}}{\eta_{P2.2}}+\frac{Q_{3.2}*H_{3.2}*T_{3.2}}{\eta_{P3.2}}} \tag{5}$$

RESEARCH RESULTS

An analysis of the operating parameters of the pump units of models D12500-24 and D6300-27, operating in parallel on the common pressure pipeline, is presented. The results of the study encompass variations in water flow rate (Q), water pressure (H), and efficiency coefficient (η) under different operating conditions.

TABLE 1. Investigation of the pump units of models D12500-24 and D6300-27 operating in parallel on the common pressure pipeline.

Number of simultaneously operating pumps of model D12500-24	Number of simultaneously operating pumps of model D6300-27	Pump of model D12500-24			Pump of model D6300-27			Σ Q, m^3/s
		Q, m^3/s	N, m	η_r	*Q*, m^3/s	N, m	η_r	
1	-	3,69	21,5	0,78	-	-	-	3,69
-	1	-	-	-	2,26	15,5	0,61	2,26
2	-	2,43	27,75	0,74	-	-	-	4.86
1	1	2,72	26,1	0,77	1,75	26,1	0,76	4,47

According to the data in Table 1, when a single D12500-24 pump unit operates in the common pressure pipeline, the water flow rate is 3.69 m³/s, the water pressure is 21.5 m, and the pump efficiency is 0.78. When a single D6300-27 pump unit operates, the water flow rate is 2.26 m³/s, the water pressure is 15.5 m, and the pump efficiency is 0.61. When two D12500-24 pump units operate simultaneously, the water flow rate reaches 4.86 m³/s, the water pressure is 27.75 m, and the pump efficiency is 0.74. When one D12500-24 and one D6300-27 pump unit operate together in the common pressure pipeline, the water flow rate is 4.47 m³/s, the water pressure is 26.1 m, and the pump efficiency is 0.77.

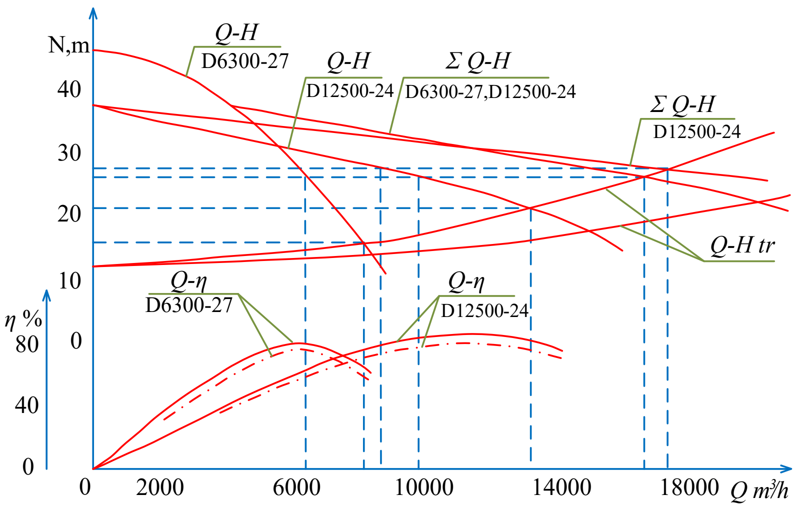

FIGURE 2. Q–H characteristics of water flow rate and pressure for the pump units of models D12500-24 and D6300-27 operating in parallel on the common pressure pipeline.

The Q–H characteristics of water flow rate and pressure presented in Figure 2 demonstrate the capability of the pump units operating in parallel on the common pressure pipeline to maintain the required head. These results indicate that the station can provide a stable water supply even under variable load conditions.

CONCLUSIONS

The block diagram of the control system for a pumping station operating on a common pressure pipeline ensures stable water pressure in the pipeline by gradually starting multiple pump units operating in parallel on the common pressure pipeline using a single variable frequency drive. The system initiates the pumps at limiting start-up currents without causing hydraulic shocks in the pipeline, thereby maintaining stable pressure in the common pressure network. An automatic control system capable of sustaining the required water pressure in the common pressure pipeline has been developed. The application of this system provides reliable pressure management not only in rural and agricultural pumping systems but also in municipal water supply networks, hot water supply, and centralized heating systems.

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