UDC 532.542.1:681.518
DOI https://doi.org/10.32782/EIS/2026-109-34

COMBINED METHOD FOR DETECTING LEAKS IN THE PIPELINE

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The article deals with the problem of improving the quality of water supply, which is the main element of the urban system. Water distribution is usually carried out through underground pipes. Monitoring underground water pipelines is more complex than monitoring water pipelines located on the ground. This can lead to a permanent loss if there is a disturbance in the pipeline, such as a leak. Water leakage is not only a waste of water resources, but also incurs large social and economic costs. This article provides a comprehensive overview of possible water leakage control approaches and specifically discusses the benefits of each.

It is concluded that water leakage can be further reduced by improving the leak detection capability through a combination of intelligent modeling and equipment monitoring, optimization of the pipe maintenance strategy, and the development of an instantaneous pressure control system. In the work, the system of automatic pressure regulation in the main pipeline was investigated in order to find unaccounted leaks of the working fluid. To achieve the specified goal, the control system as a whole, the peculiarities of pressure regulation and its fluctuations in the pipeline were analyzed. The structure of the system of automatic pressure regulation in the pipeline is provided, a block-functional model of the pressure regulation system is built using a piezoelectric pressure sensor, which can be used to detect leaks in the network.

Key words: *pipeline, leak detection, pipeline monitoring, pressure regulation, automatic control.*

Суботін Олег, Койфман Олексій, Сімкін Олександр. Комбінований метод виявлення витоків у трубопроводі

У статті розглядається проблема покращення якості водопостачання, яке є основним елементом міської системи. Розподіл води зазвичай здійснюється підземними трубами. Моніторинг підземних трубопроводів води є складнішим, ніж моніторинг водопроводів, розташованих на землі. Якщо в трубопроводі виникне порушення, то це може призвести до безповоротних втрат. Витік води не тільки трата водних ресурсів, але й великі соціальні та економічні витрати.

У цій статті наведено огляд можливих підходів до контролю витоків води та окремо розглянуто переваги кожного з них. Зроблено висновок, що витік води можна ще більше зменшити, покращивши можливості виявлення витоків за допомогою поєднання моделювання та моніторингу обладнання, оптимізації стратегії обслуговування трубопроводів та розробки системи миттєвого контролю тиску. У роботі досліджено систему автоматичного регулювання тиску в головному трубопроводі з метою виявлення неврахованих витоків робочої рідини. Для досягнення поставленої мети проаналізовано систему керування в цілому, особливості регулювання тиску та його коливання в трубопроводі. Наведено структуру системи автоматичного регулювання тиску в трубопроводі, побудовано функціональну модель системи регулювання тиску з використанням п'єзоелектричного датчика тиску, який може бути використаний для виявлення витоків у мережі.

Ключові слова: *трубопровід, виявлення витоків, моніторинг трубопроводів, регулювання тиску, автоматичне керування.*

Introduction. One of the features of the operation of pumping stations for intake and pumping of water is the fundamentally uncertain mode of their operation, which is associated with daily and seasonal changes in water consumption by both industrial enterprises and the population. This uncertainty often prevents the design stage from choosing a working machine that optimally satisfies the system's operating mode. Also, in the process of operation, the operating modes of the installation change significantly [1].

Traditional methods of regulating the supply of pumping units are aimed at technological tasks and practically do not take into account the energy aspects of water transport. With such regulation, from 5 to 15%, and in some cases up to 20–30% of the consumed electricity, is spent irrationally due to: energy losses in the throttle body; creation of excess pressure in the pipeline network; leaks and unproductive consumption of water in the network and at the consumer [2].

With the wide demand for water supply, the problem of pipeline leak detection is becoming more prominent [3]. The leak occurs as a result of aging, deterioration of pipelines or from excessive pressure. Traditional methods of leak detection mainly rely on periodic inspections by maintenance personnel, which require intensive human involvement, but periodic inspections do not provide real-time monitoring of the pipeline. Accordingly, the leak will be detected with a delay, which will lead to large economic losses and environmental pollution. Thus, the development and implementation of an organizational leakage control policy is one of the possible ways to reduce the leakage rate. In addition to the leakage control policy, it is necessary to develop a model for automatic pressure regulation in the pipeline. Since sudden pressure drops are the main cause of aquifer system breakdowns.

Analysis of known solutions. Different methods are used to study the flow and their localization. There are two main methods for detecting leaks: a hardware method and a method based on the development of virtual models.

Hardware methods of detecting and locating leaks are based on observing the pipeline using appropriate equipment. These methods are distinguished by excellent sensitivity and are very accurate in searching for a place of localization. But they are very expensive and installing the equipment is a difficult task.

Methods of detecting leaks based on the development of virtual models are based on monitoring the internal parameters of the pipeline (pressure, temperature, flow).

Most of these methods have been studied and analyzed in detail. Below is a brief analysis of the main ones [3].

Method of acoustic detection. Acoustic sensors that are installed outside the pipe detect the level of internal noise. When a leak occurs, a low-frequency acoustic signal is detected and investigated [3]. The disadvantage is the need for sensor contact with the pipeline surface [4].

Optical method. The principle of operation consists in the fact that during a rush, the liquid comes into contact with the cable. Investigating changes in the temperature of the cable, it is possible to detect the location of the leak [5].

Method using measuring cables. The time delay between the input pulse and the reflected pulse is used for leak localization [6]. The disadvantage of these methods is the need to lay the cable along the pipe [4].

Steam sampling method. The method involves installing a tube along the entire length of the pipeline. Localization of the leakage is carried out by calculating the ratio of the final peak to the arrival of the leakage peak [6]. The method has a difficult implementation, as it is necessary to lay another pipe in the trench [4].

Soil monitoring. By analyzing the soil above the pipeline, it would be possible to estimate the presence of a leak and its location [7]. It is difficult to implement, so it is used very rarely [5].

Method of mass balance. A leak can be identified if the difference between the flow measurements changes by more than a defined threshold [3]. The disadvantage of this method is that the location of the leak is unknown. Therefore, needed to combination with the other methods [4].

Simulation in real time. This method is based on pipe flow models that are constructed using the equations of conservation of mass, conservation of momentum, and conservation of energy. Billman and Isermann [4] used this approach for leak detection and localization.

The method of negative wave analysis. The negative pressure wave received by the two sensors can identify a pipeline leak and determine the location of the leak [8]. A signal processing technique is small wavelet transform. Zhao J. [9] used this transformation for leak detection.

Statistical method. Uses advanced statistical techniques to analyze pipeline flow, pressure, and temperature measurements. Method can be applied to various pipeline systems [3]. It is also suitable for real-time applications [10].

The disadvantages of all these methods are the following factors: small and slowly growing leaks are difficult to find, with a small number of sensors.

The hardware method is accurate but expensive, and the model-building method is cheap but not as reliable. It is economically unprofitable to use only one of them for finding leaks. Thus, the use of only one method does not guarantee a high probability of detecting leaks and achieving maximum economic benefit.

To increase the technical and economic parameters of the leak control system, a combination of the acoustic method and the real-time modeling method should be used. The combined method involves measuring the pressure in the pipeline using pressure sensors, controlling the noise in the pipeline and correlating the obtained data with the results of modeling in real time [11,12].

Today, pressure control systems are widely used, which rely on pressure measurement sensors, with the possibility of automatic data transmission. Electromechanical pressure sensors are mainly installed in modern water supply systems. The principle of operation of these sensors is based on the fact that a membrane is installed inside its body, which deforms and reports data about deformations to the automatic pressure control system [13]. Due to the inertia of the mechanism, the bandwidth of these sensors does not exceed tens of hertz. To measure high-frequency dynamic processes in the pipeline, a piezoelectric pressure sensor is usually used [14].

Piezoelectric pressure sensor is necessary for dynamic pressure measurement. The high-frequency sensor has the ability to measure rapid changes in pressure, and is also capable of measuring quasi-static pressure. The sensor has the ability to detect the fast frequency response in the pipeline system. The signal and frequency response of the pipeline system is the state of the pipeline. Theoretically, pressure transients occur when there is a sudden change in water flow by closing or opening valves in a pipeline network. Wave propagation will occur along the pipeline, and its characteristic will be used as a way to detect pipeline leakage along the channel network. Piezoelectric sensors installed in pipe outlets have shown improved sensitivity to vibrations and pressures occurring in pipe outlets, especially in bends with small curvature coefficients. Compared with the response to pressure changes of electromechanical sensors, piezoelectric sensors showed excellent performance characteristics [15].

Wireless sensor networks (WSN) have recently been developing at a rapid pace and have become one of the main areas of research in the field of wireless technologies. This rapid development contributes to the development of miniaturization of electronics, increased productivity, and energy efficiency. The development of new wireless communication technologies and the drop in their prices have made it possible to use the latest technologies for wireless sensor network devices [13; 16].

Taking into account analyze the advantages and disadvantages of existing methods, proposed a combined method of detecting leaks.

Low-power wide-area network (LPWAN) technology is expected to be used to transmit sensor data from end nodes to base stations – LoRa®. This technology is designed to provide low-power broadband connectivity with low data rates. These features meet the requirements for battery-powered sensors. LoRaWAN provides data rates from 0.3 kbps to 50 kbps, which are considered acceptable for real-time sensor data transmission in IoT, Machine-to-Machine (M2M), smart city and industrial devices [16].

For this, LoRa technology will be used with the installation of piezoelectric pressure sensors in water wells. With the help of this sensor, pressure surges and vibration in the pipe will be monitored.

Purpose of the study. The purpose of the work is to search for possible leaks to reduce fluid losses during its transportation and distribution to consumers by modernizing and researching the automated pressure control system in the pipeline.

Improvement of the pressure regulation system in the main pipeline will optimize the operation of the system, increase the technical and economic indicators and increase the service life of the system equipment.

Materials and research methods. The existing urban technological scheme of the water pumping station was studied (Fig. 1). The water pumping station supplies fresh water for technological installations and fire-fighting needs from local water supply sources. It operates continuously throughout the year and consumes about 760 000 m^3/year of water. The consumers of the pumping station are the sewage pumping station and the booster pumping station [17].

Water intake is carried out using НД-200×36 series booster pumps with drive asynchronous motors (M1, M2) of the ВАО-81-2У2 series with a capacity of 40 kW. The suction pipeline of the НД pumps has a filter *1*, which prevents the pump from contamination. At the outlet, the НД pumps have valves *2* (40×100) with which the water intake is regulated and the technical pressure gauge *6* at the outlet shows the pressure under which water is pumped. This system with the booster pumps forms a booster pumping unit. Further along the pipeline through the filter *3* and the valves at the intake *5* (150×40), water enters the ЦНС-105×245, which is driven by an asynchronous motor (M3, M4) of the ВАО-315м-2У2-5 series with a capacity of 160 kW. From the ЦНС, water enters the pumping well, and from there through valve *8* to consumers *7*. A valve *12* (150×210) is installed in the pumping well to consumers. The technical pressure gauge *4* at the intake shows the pressure under which water enters the ЦНС. The СВУ-200 meters show the amount of water supplied to the consumer. The pressure gauge *9* on the collector shows the pressure in the pipeline under which water is pumped. The check valve *10* and valve *11* prevents the backflow of water.

The investigation of the automatic control system (SART) is carried out in normal and emergency modes of operation.

To ensure the necessary operational mode of operation, main pumping stations (MPS) include serially connected pumps, MPS with high consumption of electrical energy. The central problem of pumping water is maintaining the pressure established by regulatory requirements. Recently, a practice has developed in which pressure regulation and water supply in the pipeline is carried out due to changes in the rotation speed of the engine pump.

In the comparative calculations of energy consumption in frequency-regulated MPS, either constant modes of operation or their start-up modes are considered, and it is not taken into account that, if the pump is in the circuit of automatic regulation of the SAPR, then in the transient modes of this circuit, the electric drive will consume energy to overcome inertial resistance, associated with large flywheel moments on the motor shaft. If the quality of regulation is poor (large fluctuations and significant of overregulation), these losses can be significant [18].

An attractive solution to the problem of pressure regulation (Pp, MPa) is the use of a combined SART, which would include both frequency regulation of the MPS and positional regulation (ΔX, %) with a valve. In such a scheme, the throttle executive device could take on the dynamic resistance of the high-frequency component of pressure disturbances in the pipeline, and the frequency-regulated drive of the MPS – the low-frequency component.

However, in the established practice of throttle regulation, low-speed drives are used, and taking into account the fact that the electromechanical time constant of the MNA drive turns out to be much smaller compared to the throttle device, an additional, faster-acting executive device should be used for the proposed combined SAPR regulation. Such a device can be a throttle valve of a bypass pipeline (TVBP). At the same time, the inertia of the pump supply control circuit (Q, m^3) should be increased to ensure a smooth change in pump speed and thereby reduce the inertial resistance of the flywheel components of the MPS [19]. This can be achieved by using a low-pass filter in the control circuit of the pump unit. An aperiodic link is used as a filter.

Structural diagram of SAPR shown in Fig. 2. Here, the control circuits PID1, PID2 and PID3 correspond to the frequency-controlled drives (FCD) of the pump supply, the main and bypass valve of the pipeline and the pressure sensor.

The parameters of these regulation circuits are selected so that with a high-frequency disturbance, the pressure stabilization circuit by

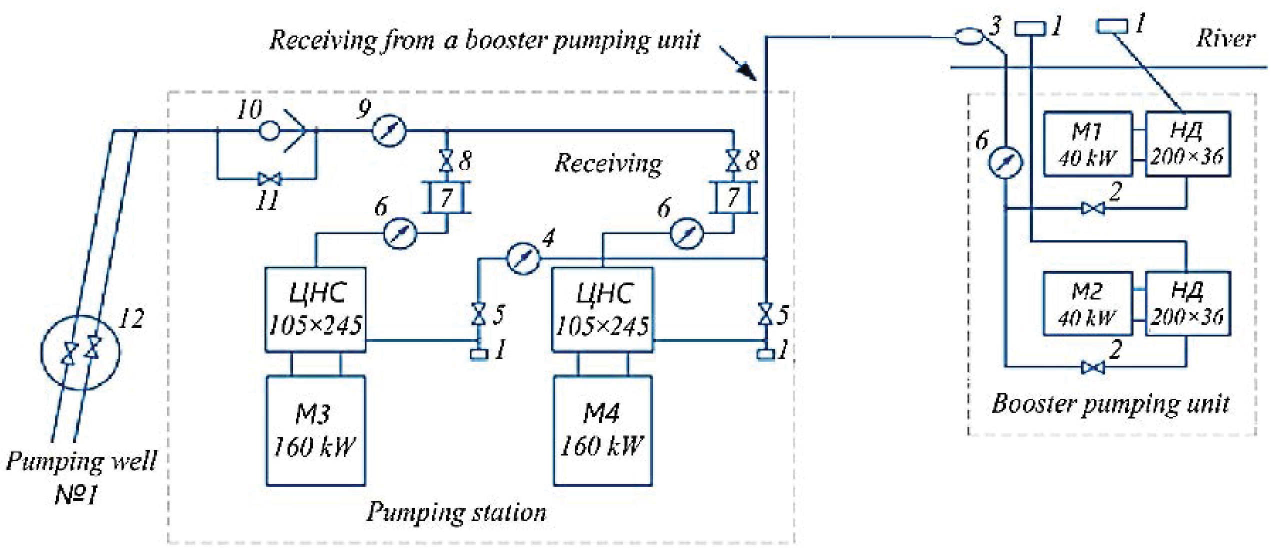

Fig. 1. Technological scheme of the pumping station

the bypass valve takes over the initial resistance to the disturbance, and the regulation circuit by the pump slowly changes the supply, returning in a stable mode the possible movement of the main valve to the opening state, and the bypass valve to the closing state. This is ensured by the use of automatic circuits for restoring the shutter closing percentage, corresponding to the bypass and main shutter opening percentage settings (0.1% and 0.9%).

The model of the dynamic system of automatic pressure regulation was developed on the basis of experience [15; 19].

To assess the effectiveness of the proposed research, a block-functional model of SAPR was developed and investigated in MATLAB Simulink (Fig. 3).

The SAPR model has the following contours (from up to down): the pump supply control circuit; the circuit for adjusting the position of the main latch; the circuit for adjusting the position of the bypass valve; imitation of disturbing influence.

Model studies showed that main three contours in a steady state make a proportional (symmetric) contribution to the formation of the pressure in the pipe. Therefore, to implement the conceived idea, it was decided to add asymmetry to the operation of the control circuits. The following decisions were made in the SAPR model:

– the dynamics of SAPR is described at the output of the system;

– control circuits are implemented using PID controllers of the MATLAB package;

– the rate limiter is set by the Rate Limiter;

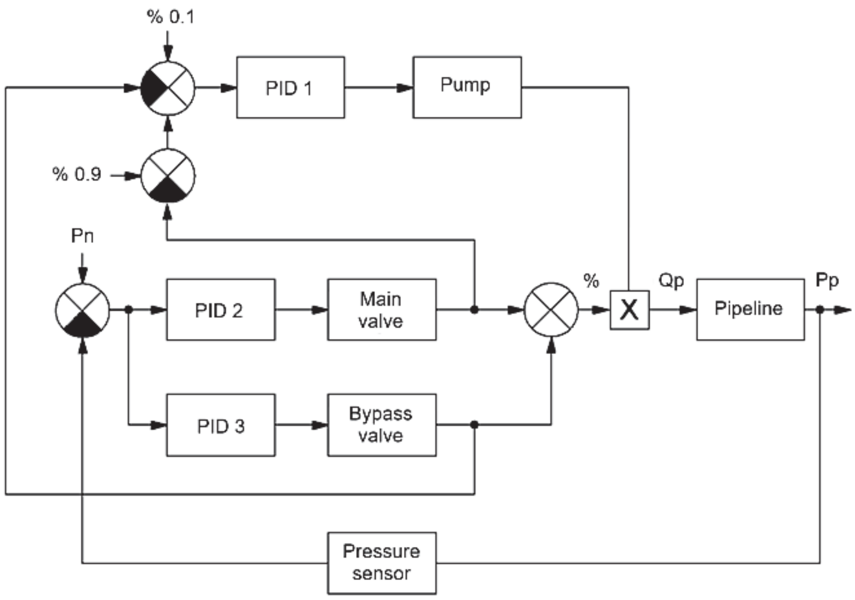

Fig. 2. Structural diagram of SAPR

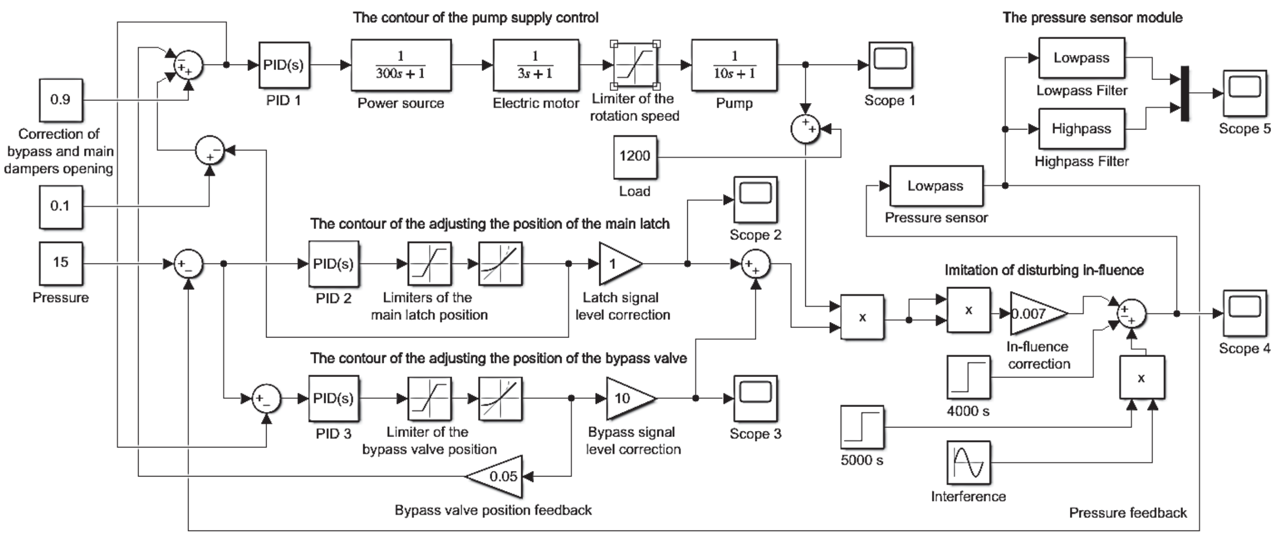

Fig. 3. Block-functional model of SAPR

– PID – gate regulators are a combination of integrating links that describe the change in the position of the gate and proportionally differentiate the control algorithms of the control unit of their drive, used in the study of different operating modes of the system;

– the limitation of the water supply of the pump is set by the upper limit of the rotation speed of its drive near the operating point;

– the limits of the positions of the flap drives are set by the drive's moment limiters;

– the asymmetry of the throttle control circuits of the actuators is ensured by a signal of incomplete opening of the main valve in the bypass valve circuit;

– disturbances in the form of stepped (0–3 MPa) for 4000 s and sawtooth (0–2 MPa) for 5000 s functions are formed in the section of the time interval for the established mode of SAPR operation.

The pump control loop settings correspond to the parameters of the devices used in the basic pipeline flow diagram, and the available booster units are used to scale the parameters of the other loops.

The pressure sensor is used to read the high and low frequency signals. This sensor performs two functions at the same time. It simultaneously measures the pressure in the system and reads data on the amount of fluctuation in the pipeline system. In the diagram, it is depicted as a low-pass filter. The range of frequencies in which it works are indicated according to its passport data.

In the normal and emergency modes of operation the pressure in the pipeline remains un-changed. But in emergency operation mode a disturbing effect is added. To take into account possible operating modes of the pipeline and the ability to evaluate them, SAPR modeling is performed in normal and emergency operating modes with pressure control at high and low frequencies of the pressure sensor.

The results of the simulation of the pump supply control circuit are shown in Fig. 4. For clarity, a graph of the transient process for a pressure sensor when operating at low frequencies is provided.

The graph shows that when the pump unit is turned on in the system, the amount of supply gradually increases, and then the graph reaches the set value (Fig. 4, *a*). The results of the simulation of the pressure state in the pipeline are shown in Fig. 4, *b*.

The results of the simulation of the contours of the bypass and main valves position adjustment are shown in Fig. 5.

The graph shows the dynamics of bypass valve operation (Fig. 5, *a*). The role of this valve is that it raises or lowers the inlet pressure in the system to a given level and keeps it constant at the outlet.

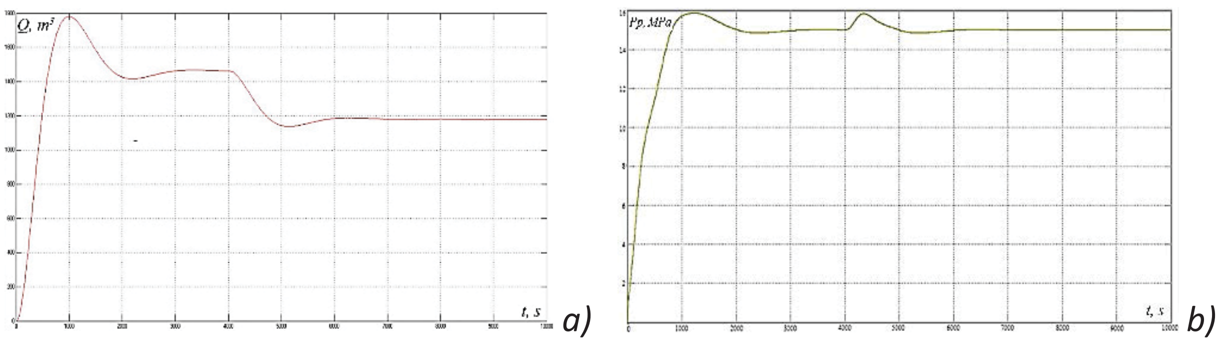

Fig. 4. Processes in the pump control circuit (*a*) and pressure state in the pipeline (*b*)

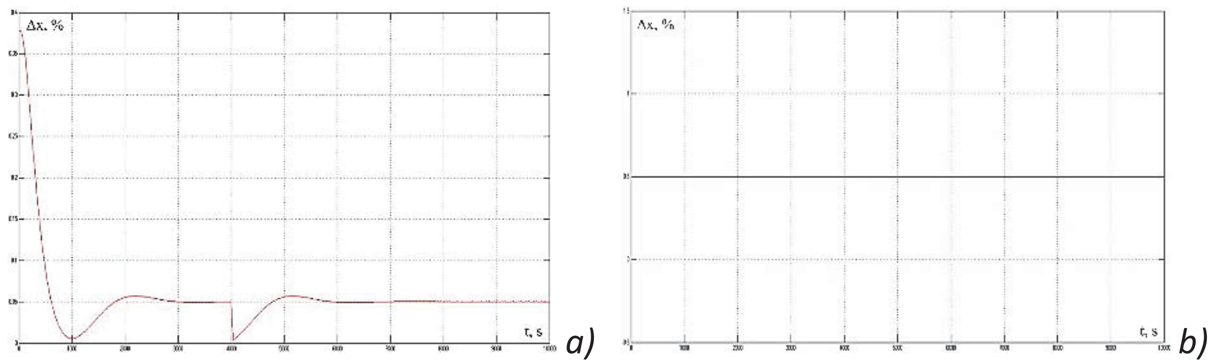

Fig. 5. Processes for the bypass: *a*) and main *b*) valve position control circuits

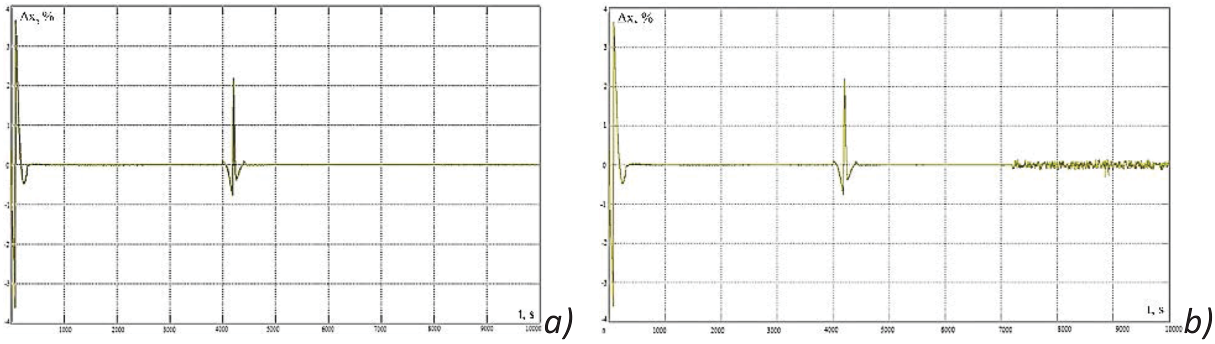

Fig. 6. Processes for a pressure sensor when working at high frequencies in the normal: *a*) and emergency *b*) modes of operation

The circuit for adjusting the position of the main latch keeps its set position unchanged (Fig. 5, *b*).

The results of the simulation of the state of the pressure sensor for the normal and for the emergency modes of operation at high frequencies are shown in Fig. 6.

The pressure sensor at low frequencies shows the pressure in the main pipeline. At high frequencies, this sensor shows what fluctuations and over what period of time they occurred during the main pipeline operation. Two spikes on the transient graph at high frequencies indicate fluctuations during system start-up and when the bypass valve position changes.

If you compare the graphs of the pressure sensor when working in two modes, you can see that they differ in the final time period. This means that the pressure sensor detected vibrational oscillations in the system at high frequencies. Which in turn can say that a crack has appeared on the pipe in this section of the pipeline, which can lead to water leakage.

With the help of this sensor, we measure the pressure in the main pipeline and detect vibrations that can lead to the destruction of the integrity of the main line. By adjusting the pump supply and opening / closing the valves, we can get rid of these vibrations.

The results of the simulation of the control circuit of the pump supply, the position of the main and bypass valve changes according to the disturbing influence. Thet is why this cannot be shown on the graphs of the model, because this SAPR system is designed to detect vibrational oscillations, not to control the system.

The significance of the model was checked by checking this system according to Fisher's F-criterion, which takes into account possible assumptions in the description of the model structure, measurement errors, the absence of significant variables in the model or their aggregation. For example, the total consumption function is considered as an attempt to generalize the set of decisions of individual consumers about costs, and this is only an approximation of individual relationships with different parameters. Therefore, at the specification stage, paired linear regression took into account the dependence of the change in the output value (ΔY) on the input (ΔX), the parameters of which were estimated by the least squares method. The statistical significance of the equation was checked using the coefficient of determination and Fisher's criterion. It was found that in the studied situation the average approximation error is 0.21 and the coefficient of determination is 0.9776, i.e. the estimate of the regression equation corresponds to a statistically reliable one [20].

Conclusions. It is known that at present few owners of pumping stations develop systems for monitoring unexpected leaks. A combined method of monitoring the pressure state and finding negative vibrations in the pipeline has been proposed. But this requires upgrading the pressure control system in the main pipeline by introducing two control circuits with valves and using a pressure sensor that can simultaneously measure pressure and respond to the presence of vibration oscillations.

As for the pressure sensor, in comparison with electromechanical ones, piezoelectric sensors installed in pipe branches showed improved sensitivity to vibrations and pressure, especially in bends with small curvature coefficients.

Thus, in the proposed SAPR scheme, the circuit for regulating the position of the valve of the bypass pipeline will ensure the suppression of high-frequency dynamics of disturbances in the main pipeline, which will ensure the release of the pump supply control circuit from direct dynamic resistance to high-frequency pressure disturbances in the pipeline. At the same time, the task of the pump supply control circuit will be to counter the low-frequency disturbance components. It is also important to solve the problem of maximum opening of the main pipeline outlet valve by this circuit in stable or quasi-steady water pumping modes.

The system of automatic pressure regulation in the main pipeline was investigated in order to find unaccounted leaks of the working fluid. The control system as a whole, the peculiarities of pressure regulation and its fluctuations in the pipeline were analyzed. The structure of the system of automatic pressure regulation in the pipeline is provided. A block-functional model of the pressure regulation system is built using a piezoelectric pressure sensor to detect leaks. Study of transient processes, it was concluded that the designed system meets the specified requirements.

It is proved that water leakage can be further reduced by improving the leak detection capability through a combination of intelligent modeling and equipment monitoring and the development of an instantaneous pressure control system.

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Дата першого надходження статті до видання: 10.03.2026
Дата прийняття статті до друку після рецензування: 04.04.2026
Дата публікації (оприлюднення) статті: 29.05.2026