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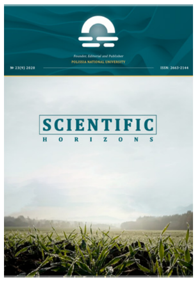

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Improving the Efficiency of Distributed Water Supply Systems by Means of an Adjustable Electric Drive

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Abstract. The water supply of the pumping station must meet the needs of the consumer which change during the day. Therefore, its performance needs to be adjusted. Any deviation of the pump unit's performance from the nominal value leads to additional energy costs. Under such conditions, great importance is paid to optimising the operation of electric drives of the water supply pumping station. To regulate the performance of a pumping station, it is often resorted to changing the number of operating pumping units, the engines of which are started directly from the electrical network. Medium-and high-power engines are subject to technical restrictions for a direct start, which are supplemented by the need to maintain pauses between starts. Therefore, when ensuring the desired value of pumping station performance, it is very important to consider the features of starting pump engines. Control systems are widely used in the field of electric drive and water supply. It is in these areas that the efficiency of the control system depends on the amount of electricity that will be consumed by the technological process or the reliability of its operation. It is known that pumps account for about half of all energy produced. Therefore, the issue of effective control systems is particularly relevant in the field of water supply. The purpose of this study is to increase the reliability and efficiency of the water supply system by considering the distribution properties of the pipeline network when controlling electric pump drives, which will allow coordinating the operation of the pumping station, the pipeline network, and the consumer. To achieve this purpose, the study was conducted to assess the impact of the distribution and length of the pipeline network. The system of water supply and distribution is analysed, what criteria affect the correct performance of work and what problems may arise during operation for a long period of time are investigated. Ways to optimise the operation of pumping stations to increase their energy efficiency and cost-effectiveness of installations are investigated. The main reasons for the expediency of using an adjustable electric drive to control pumping units are considered

Keywords: water supply, water supply system, electric pump station drives, mathematical models of electric drive, pumps

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INTRODUCTION

The design of automatic control devices has been studied by many scientists [1-4]. Among them, the works of I.A. Vishnegorodsky should be highlighted, who became the founder of the theory of automatic devices in the 19th century [5; 6]. The scientist determined that the machine and the regulator form a single dynamic system that has certain stability indicators (he developed the theory of control stability) and the most important patterns of regulation based on the feedback principle [7-9]. Nowadays, there is a rapid development and active use of microprocessor technology in water supply systems. It allows linking all information flows between all elements of the water supply system. Up-to-date information about the progress of the technological process is sent to the operator very quickly. Similarly, the operator can influence the technological process by sending control signals. In such systems, the state of technological objects is measured, monitored, and regulated [9; 10].

Automation in water supply processes has allowed increasing productivity by 20 times and reduce operating costs by 10 times. There are many difficulties in water supply processes. The main problems related to water supply can be formulated in two phrases: there is an abundance of water where it is not needed so much, and there is no water where it is needed. One of the serious problems on the way to full automation of the water supply process was the distribution of these systems in space and time. Therefore, the thesis proposes to develop the ideas of well-known scientists on effective management of distributed systems, and implement them on water supply systems. Notably, the efficiency of water supply systems is mainly determined by the energy and hydraulic aspect. The paper will focus specifically on energy.

The purpose of the study is to increase the reliability and efficiency of the water supply system by considering the distribution properties of the pipeline network when controlling electric pump drives, which will allow coordinating the operation of the pumping station, the pipeline network, and the consumer. The goal is achieved by solving the following tasks: to analyse literature sources on the subject of paper; to identify the main parameters of the water supply system, on which the reliability and efficiency of its operation depend; to assess the impact of the length and distribution of the pipeline network of the water supply system on the efficiency of electric drives of the pumping station; to offer solutions to improve the operation of water supply systems precisely by considering their distribution; to model the operation of the water supply system in different modes. The object of research is the process of controlling electric drives of a pumping station. The subject of the research is mathematical models of electric drives, pumps, and water supply systems.

MATERIALS AND METHODS

The paper uses methods of probability theory, mathematical statistics (statistical linearisation, processing of experimental results, testing statistical hypotheses), operations research (mathematical programming, graph theory), automatic control theory, theory of ordinary differential equations, theory of experiment planning, modelling on a computer.

Due to an increase in water consumption, it is necessary to develop new methods for designing and managing water supply systems. Such methods should have the following functions: to reduce unproductive resource losses as much as possible by analysing the operating modes of water delivery systems and increase the efficiency of decision-making during their operation and development; to increase the durability and survivability of water delivery systems by optimising them using simulation modelling; to test options for possible solutions for managing the water delivery system during its operation using simulation parametric and structural modelling; to quickly identify the current state of the water delivery system depending on the position of shut-off and control devices, etc., graphically interpret and visualise on the monitor screen (static identification), identify changes in the current state of the water delivery depending on changes in the position of one or a group of regulating units (dynamic identification); reduce losses from accidents in the water distribution network due to more rapid localisation of the emergency zone, as well as reasonable interaction with dispatchers of operation services of other engineering systems of the city (for example, with heat supply and hot water supply systems, power supply).

The most important role in the rational use of water resources in the region is played by the water delivery system, which is directly related to the operation of pumping stations, reservoirs, and the city's water supply network. Water networks belong to the class of continuously evolving systems, the development of which is carried out both in time and space. The main functional purpose of the water delivery system is to provide consumers with the target product – water of the required quantity and quality and under a given pressure with minimal head losses on the networks. Water consumption is, as a rule, a non-stationary stochastic process containing determined monotonically increasing trends and periodic components, the parameters of which change over time [11].

Often, when analysing water supply systems, there is not enough information about their condition. This leads to a decrease in the efficiency of the water supply and distribution management system. There are different approaches to improving the performance indicator. The conventional technical approach is based on minimising cost factors with some simplified restrictions.

Thus, it is usually considered optimal to increase the efficiency of the pumping station system, the efficiency of modes on water networks or water disinfection, which ensures the safety of water supply to the population. In the practice of operation, insufficient attention is paid to the hydrodynamic characteristics of the water delivery system. Therewith, they play an important role in evaluating a balanced integrated approach to rational management of the water supply system.

Modern water supply management systems cannot be considered effective if they do not have information technology. As a rule, it takes about 10 years to implement information systems in water supply companies. Usually, those who implement an automated process control system can only partially discuss the results of implementing automated control systems in blocks. It is known that in modern water supply systems, the following rules must be observed: it is necessary to ensure a sufficient flow of water with the necessary head and satisfactory water quality. The criteria for the quality of water network operation in practice are compliance with two conditions: the pressure at each water supply point must be between the minimum and maximum permissible values of 20 and 60 m H_2O. Accordingly, the head fluctuation in the network should not exceed 45-50% of the maximum allowable head. Controlling the flow rate in its pipelines is extremely important since the impact pressure during a water hammer changes directly in proportion to the nominal value of the average speed in the pipe. It is this indicator that allows distributing water flows in pipelines and equalise water consumption in different sections of the pipeline.

RESULTS AND DISCUSSION

Development of a block diagram of the water flow system in water supply networks

The main purpose of the operation of the water supply system is to provide consumers with uninterrupted water supply in exact accordance with their current needs. Therewith, this goal should be achieved with the highest possible efficiency. There are many sources and ways to improve the efficiency of the water supply system. Most of them can be unambiguously attributed to one of three groups: ways to improve the efficiency of water supply sources; ways to improve the efficiency of pipeline networks; ways to improve the efficiency of water supply systems [12].

Improving the efficiency of flow control systems will be achieved by reducing the total number of measuring instruments and control bodies of the control system and improving the efficiency of flow control. These points will improve the efficiency of pipeline networks and water supply systems. To achieve this purpose, it is necessary to formulate the concept of efficiency of flow control systems, determine what it depends on, and investigate how it can be achieved using mathematical modelling [13].

The water supply system as an object of control in the process of its functioning interacts simultaneously with two systems: the external environment and the water supply control system. The external environment, acting on it, leads to a violation of its hydraulic and thermal conditions, which accordingly affects the quality of customer provision. The main task of the water supply control system is to compensate the influence of the external environment to maintain the necessary hydraulic and thermal conditions, while the task of the flow distribution control system as an integral part of the control system is to ensure optimal distribution of water between consumers, which is achieved by controlling the flow distribution in the pipeline network.

The mechanism of interaction between the water supply system and the external environment is quite complex, which is explained by the large number and complex nature of external disturbances due to their physical nature, so it is not possible to create a simple mathematical model of the relationship between the water supply system and the external environment. Well-known mathematical models are partial in nature and in most cases turn out to be too complex for their direct application in the mathematical model of the flow control system. In this regard, the authors will continue to assume that external disturbances are not directly controlled and their impact can only be judged by changes in the parameters of the water supply system.

Let us divide the vector of parameters of the water supply system R into parameters of elements D and parameters of the state (mode) Z. The parameters of elements D include those parameters of the water supply system that are not affected by external disturbances and remain almost unchanged throughout the entire time of operation, or change very slowly (coefficients of hydraulic and thermal resistance of pipelines, flow characteristics of pumps, parameters of control bodies, etc.). Let us assume that the parameters of the elements are known, respectively, they will be included in mathematical models as constants, so in further mathematical calculations, the authors will not select the vector of parameters of the elements D separately. The parameters of the Z state (flow rates, heads, temperatures of the coolant, variable coefficients of hydraulic and thermal resistance of consumers), on the contrary, constantly change under the influence of external disturbances, and they determine the state of flow distribution. In the future, when referring to flow distribution, the authors will keep in mind the parameters of the Z state.

The flow control system is a complex system that consists of four subsystems (Fig. 1): collecting and transmitting information, processing information, developing control influence, and implementing control influence.

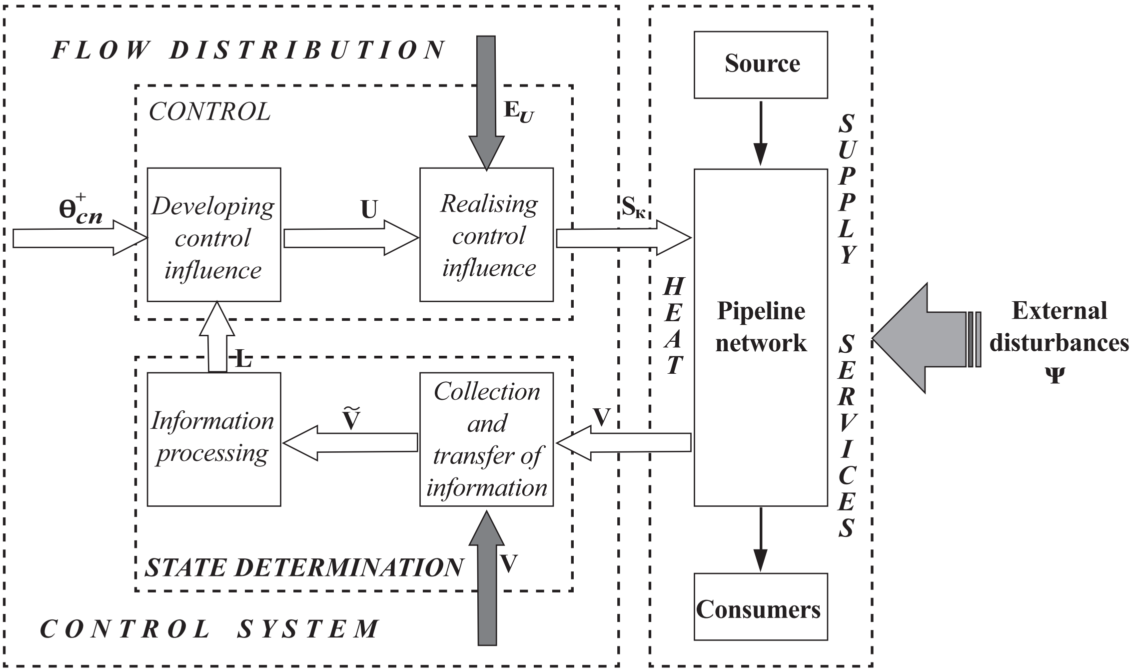

***Figure 1**. Block diagram of the flow control system*

The presented scheme is closely intertwined with the system of automation and control of water supply systems [14]. The automated process control system of a pumping station is a comprehensive solution to the problem of managing the water supply of pumping stations of industrial enterprises, as well as public utilities based on the introduction of advanced energy-saving technologies. The implementation of automated control systems can be carried out both at newly designed pumping stations and at existing ones, considering existing equipment. The essence of the solution is to manage the water flow.

Purpose of the system: automatic maintenance of the set water pressure in the outlet water supply; remote control of the operation of pumps and valves; visualisation of the technological process at the operator's workplace; collection and processing of statistical data on the volume of rolled water and the status of pumping units; ensuring the optimal mode of water supply to the outlet water supply; improving the reliability of pumping station equipment; extending the life of electric motors of pumps; reducing energy costs.

The system is a three-level hardware and software complex, namely: the level of control of technological units (pressure and water flow sensors, adjustable and unregulated electric drive of pumps and valves); the level of control of the technological process (programmable logic controller); the level of operational and administrative control (operator's workstation based on a personal computer).

In urban water supply systems, water supply failures often occur. There is a pressure drop or the pipe becomes clogged, which makes the flow weaker. In addition, considering the current trend towards urbanisation, expansion of cities and the growth of the population in cities, the issue of increasing the capacity of water supply and increasing the capacity of pumping stations becomes relevant. For remote consumers, the issue of ensuring a sufficient level of pressure in the pipeline is acute. Commonly, the pressure on the outskirts of a locality is less than the required values. Therefore, for the water supply of such places, water supply stations are used in addition to the centralised water supply system. The pumping station consists of pumping units and communications. The appearance of the engine room of the pumping station is shown in Figure 2.

It is such a station that stabilises the pressure and its indicators become constant. And most importantly, an uninterrupted supply of the necessary amount of water for any needs is achieved. A modern pumping station should operate in a fully automated mode and does not require specialised regular maintenance. It can be used for the following areas: fire water supply; industrial; private. Modern pump automation systems allow implementing closed systems for stabilising water pressure in the pipeline. For this purpose, the centrifugal pump is equipped with an adjustable alternating current electric drive. Changing the speed of rotation of the latter is performed by the frequency method, that is, by changing the frequency to the supply voltage of the drive motor. To maintain the pressure, a regulator and feedback with a pressure sensor are used.

Let us build a block diagram of the water supply system using a pumping station and feedback on the water pressure in the pipeline (Fig. 3).

Figure 2. *Pumping station*

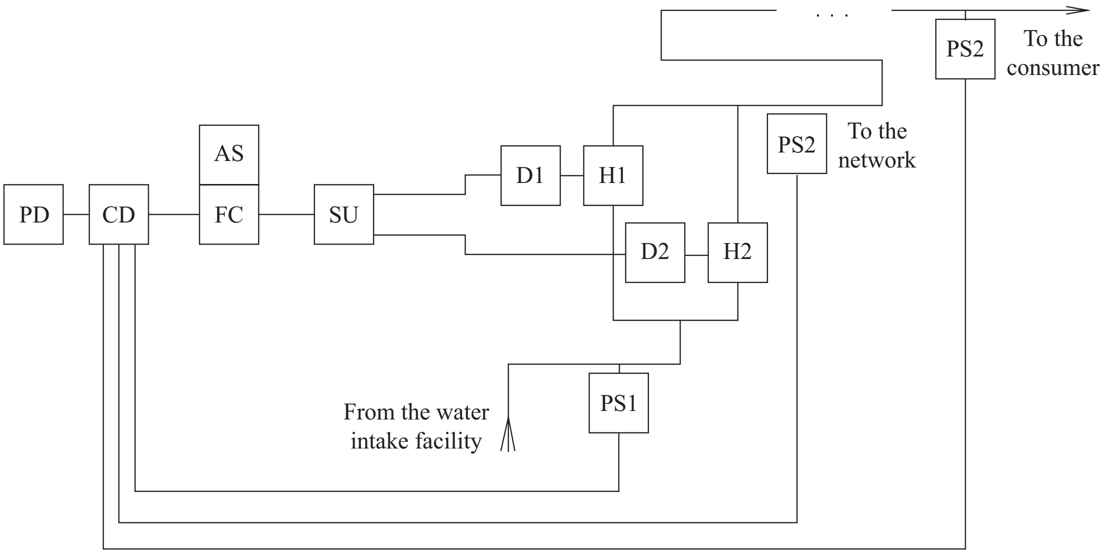

Figure 3. *Block diagram of a distributed water supply system*

Figure 3 shows: D1, D2 – alternating current drive motors; H1, H2 – centrifugal pumps; PS1, PS2; PS3 – water pressure sensors at the station inlet and outlet after the station and near the end user; PSN – power supply network; AS – automatic switch; PD – pushing device; CD – control device; FC – frequency converter; SU – switching unit;.

The pressure sensor PS1 detects the pressure value in the pressure line of the water tower and converts it into an electrical signal of a certain value. The pumping station should only be switched on when the pressure at the station inlet is less than the required pressure value at the dictating point of the consumer. The PS2 pressure sensor allows monitoring the pressure level near the consumer. It is to this signal that the electric drive of the pump unit will respond. That is, when the water pressure near the consumer is insufficient, the electric drive should work faster and vice versa, at high pressure near the consumer, the pump unit should slow down. The CT3 pressure sensor allows analysing system's response to various control actions. Based on the results of this analysis, it is possible to ensure rational control of electric pump drives. The essence of which is that at the input of the water supply system, for example, there is no need to supply a lot of water since at its exit there is still no direct reaction from the supplied amount of water. At the outlet of the pipeline, the water pressure will change according to a certain law and the established value of the output pressure will be set only after passing the transition process. The duration of the transition process will depend on the parameters of the pipeline, its length, material, etc. Therefore, during this time, the pumping station can pump the maximum amount of water, or it can supply a certain permissible value. As a result, there will be an overspend of energy and more intensive use of the pipeline resource than with measured operation of the equipment.

Improving the efficiency of distributed water supply systems

The main condition for water transportation is to ensure its quality, flow rate, and pressure. When transporting water from air conditioning systems in main pipelines, reactions occur between water and the pipeline material. As the water temperature increases, chemical and biological processes in the water increase, and its quality changes the longer the water is in the pipeline system. This also affects the appearance of irregularities (roughness) on the inner surface of the water pipeline.

When designing water pipes, it is considered that the movement of the water flow will be turbulent and only in some cases transition modes may occur in the water pipes. The calculation of steel main water pipes of large diameters is based on the formula proposed by F.A. Shevelev for calculating the coefficient of hydraulic resistance λ for automodel turbulent water flow modes:

$$\lambda = \frac{0.021}{d^{0.3}} \tag{1}$$

where d is the diameter of the water supply system, m.

During long-term operation of water pipelines, the capacity of metal pipelines is considerably reduced due to internal corrosion and inlay. During operation, the hydraulic resistances of pipelines increase by 2-7 times or more compared to the initial values. They depend on the diameter and material of the pipes, the quality indicators of the transported water, the operating conditions and the service life of the pipeline. The most complex and time-consuming operation when calculating the hydraulic resistances of existing water supply lines is to determine the flow rate of water passing through the pipeline. The volumetric method is quite accurate:

$$Q = \frac{W}{t} \tag{2}$$

where W is the tank volume, m^3; t – time it takes for the tank to fill or empty, s.

If there are a large number of network sections, such work is very cumbersome. When examining the current water delivery system, it is advisable to test only the characteristic sections of the network, grouping them depending on the material and diameter of pipes, as well as on the conditions and terms of their operation. In hot water supply systems, the operating conditions of pipelines are different. The water temperature there should reach 55-60°C. Under such conditions, deposits on the inner surface of pipelines increase and the live cross-section can considerably decrease. Pipeline calculations should take into account changes in pipe parameters, including overgrowth of pipelines as a result of corrosion and precipitation of suspended calcium carbonate particles from water.

In foreign practice, the Colebrook formula is widely used for calculating water pipes, which determines the value of the hydraulic resistance coefficient depending on the numerical parameter of roughness – equivalent roughness:

$$\frac{1}{\sqrt{\lambda}} = -2\,lg\left[\frac{k}{3.7D} + \frac{2.51}{Re\sqrt{\lambda}}\right] \tag{3}$$

where k is the equivalent roughness; D is the inner diameter of the pipe; Re is the Reynolds number.

Distribution of hydraulic parameters in the water supply and distribution system during normal and emergency operating modes Existing methods for calculating flow distribution allow determining the water pressure at nodes, water flow rates at sites with specified network parameters, node flow rates, and pipe types (diameter and material). Hydraulic linking is based on Kirchhoff's laws, supplemented by dependences for hydraulic head losses on flow rates in the network section. Such models are deterministic and do not consider the uncertainty of the initial data, the main contribution to which is made by the stochastic nature of water consumption. Stochasticity is characterised by an unregulated random process of water intake by consumers, wear and aging processes, as well as accidents associated with equipment failure.

When modelling the hydraulic modes of water supply networks in conditions of emergency shutdowns of individual sections, it is necessary to consider the reduction in water consumption caused by a decrease in heads in a number of consumers. This means that water stops flowing to the upper floors of residential buildings. It can be assumed that under pressure from consumers there is H_i, equal, or greater than necessary $H_{i.req.}$, water consumption Q_i is equal to the standard value of $Q_{i.req.}$, and when the pressure decreases, no water consumption decreases according to the quadratic law:

$$Q_i = \begin{cases} Q_{i.req} at H_i \geq H_{i.req}, \\ Q_{i.req} \cdot \sqrt{H_i/H_{i.req}} at H_{i.crit} \leq H_i \leq H_{i.req} \\ 0 at H_i \leq H_{i.crit}, \end{cases} \tag{4}$$

where $H_{i.crit}$ – critical head corresponding to the complete cessation of water draw-off, which can be assumed to be zero. Thus, the device through which water is taken in the i node at head $H_i \geq H_{i.req}$ operates in control mode, and when the pressure is below this threshold – in throttling mode.

The water supply and distribution system is a renewable object, the operability of which, in the event of a failure, is subject to restoration (in the future, the processes of failures and restoration of only sections of water supply lines will be considered). The process of functioning of the restored element is an alternation of periods: serviceable operation, failure and recovery, and again a period of serviceable operation. The duration of repairs depends on a number of operations, which are determined by various reasons, and are considered random variables. Figure 4 shows the time series of water use in a residential building. The figure shows that water extraction has the form of random periodic fluctuations. At some points in time, it reaches zero values, which corresponds to negative states.

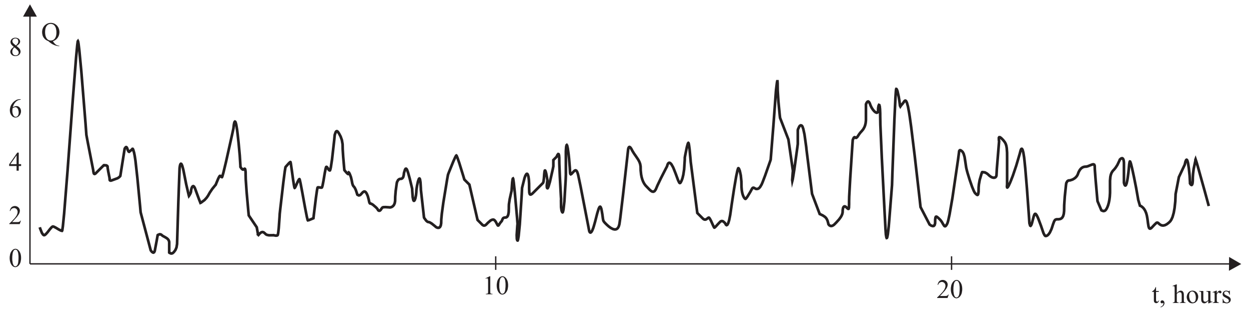

***Figure 4**. Measurements of water use during the day*

The recovery process lasts several hours, during which water consumption is constantly changing in accordance with daily fluctuations and stochasticity of the process. Thus, when disconnecting sections, in some cases, nodes will fail due to a lack of heads in them, in other cases, with a decrease in water consumption, there will be no node failure. To reduce negative phenomena in the post-accident period, the parameters of the water feeder can be controlled, for example, by turning on additional pumps.

As a result, the authors come to the following calculation sequence:

1. At the initial point in time, all sections are considered serviceable. By simulating, arrays of failure and recovery times of each section are formed. The time of the nearest failure is determined, which is converted to the calendar date and hour of the day. They are used to find the number of the water consumption schedule (if there are several of them) and the estimated time. According to another software implementation of the algorithm, the most unfavourable case is selected – the hour with the maximum consumption during the day.
2. A random vector of water consumption is simulated and a hydraulic calculation of the system is performed when the emergency section is disconnected according to the scheme with non-fixed selections. The possibility of switching on additional pumps is determined.
3. The nodes with less than the required pressures are identified and the results are saved in the output file.
4. The transition to the next time of day is conducted and the time after the accident is compared with the recovery time. If the repair continues, the water consumption vector is played out for the new hour and the network is linked. The calculation is repeated until the end of the accident elimination time, after which the site is considered working and a new failure and recovery time is determined for it.
5. The time of the nearest accident is simulated and the calculation until the end of the simulation is repeated.
6. The received data is processed, as a result of which the total failure time for the simulation period and the contribution of accidents of individual sections to the failure of the selected node are determined for each node.

When developing the algorithm, the following assumptions are made: site failures are independent of each other; when simulating nodal costs, changes in the nature of water consumption at the time of the accident associated with the redistribution of water analysis time are not considered; nodal costs obey the normal distribution law.

The process of operational management of the water delivery system in cities is considered as a controlled process of joint operation of pumping stations, water network, reservoir, and their components. The presence of the main components in water consumption processes, such as the harmonic component and random noise, leads to the need to build a two-level control scheme for the current management of the existing network of the water delivery system. This scheme includes planning of water transportation and distribution modes, which allows purposefully tracking harmonic trends by changing the structure and parameters of the existing network; operational management that eliminates unwanted pressure changes at the dictating point of the network. The need for a certain amount of time to implement control actions at the considered control stages requires the use of a discrete control method at each of these stages. Therefore, the control interval is divided into discretion (Quanta), which are determined both by the accuracy of approximation of the corresponding components (harmonic, noise) of water consumption processes and by the time of control implementation at each stage. The discreteness of management allows presenting this process at each stage in the form of a sequential multi-step decision-making procedure. The effectiveness of any system is related to the qualitative and quantitative goals of managing this system. The main qualitative goal of managing the system in question is to implement the technology of water transportation and distribution.

For the quantitative characterisation of achieving the purpose, the management criterion is used, which in this case can acquire only two values: one (if the purpose is achieved, the consumer has water at any highest point) and zero (otherwise, the consumer does not have water). Qualitative goals are strategic and are used at the highest level of the entire system management hierarchy, as they are related to providing water to all consumers. The apparent simplicity of such a control criterion is deceptive since the functional dependence of the criterion on the controlled parameters can be quite complex.

Suppose P_j and P_j^+ – current and minimum allowable pressure in the j node, respectively. Then the total excess heads at time t will be equal to:

$$y(t) = \sum_{j \in V} (P_j(t) - P_j^+) = \sum_{j=1}^{v} (P_j(t) - P_j^+) \qquad (5)$$

where V is the set of vertices of the network graph; v – the number of its vertices.

The management criterion is key in understanding many problems that arise in the organisation of rational functioning of water delivery. Under normal conditions of optimal operation of the water delivery system, the current pressure P_j in the j node should always be greater than or equal to P_j^+. Ideally, the pressure of consumers should be the minimum allowable P_j^+, but from the physical essence of the water delivery system, it follows that the pressure at the pumping station should always be higher than in any other node of the water network. On the other hand, it is known that excess of the current pressure over the standard one leads to undesirable consequences: an increase in electricity consumption; increases water leakage in the internal networks of buildings (unproductive water consumption); increases the probability of damage to the water network, which in turn leads to an increase in the probability of damage from an accident, etc. Evaluation of this criterion over a period of time [0, T] allows judging the effective functioning of the water delivery subsystem from the standpoint of fulfiling the latter's main functional purpose. Change in piezometric height, and therefore pressure P_j (The authors will sometimes call it the free head at a point) at each vertex of the graph (node connection diagram) of the water delivery subsystem at a given time interval [0, T] the authors will characterise it with a functional of the form:

$$Z_j = \frac{1}{T} \int_0^T \varphi(P_j(t)\, dt \qquad (6)$$

where $P_j(t)$ – a random process of changing the free pressure value in the j node of the water delivery subsystem;

$$\varphi_j(t) = \varphi(P_j(t)) = \begin{cases} 1, \ at\ P_j(t) \geq P_j^+ \\ 0, \ at\ P_j(t) < P_j^+ \end{cases} \qquad (7)$$

Functionality characterises the relative time during which the water delivery subsystem performs its functional purpose in the j node of the network, that is, the j-consumer is provided with water on all floors of a residential building in any node. If information about the value of the free head in the j node was received at discrete time points t, $t + 1$, then in this case the expression can be approximately replaced by an integral sum:

$$Z_j = \frac{1}{T} \sum_{k=1}^{T} \varphi(P_{jk}) \Delta t_k, \ (j \in V) \qquad (8)$$

where k is the discreteness of the time interval equal to the number t; T is the time interval (usually in practice T=24 hours). The quality of functioning of the water delivery system over the time interval [0, T] in the simplest case can be characterised by a function of the form.

$$Z = \frac{1}{v} \sum_{j \in V} Z_j \qquad (9)$$

where V is the set of nodes; v – number of nodes.

As is evident, the values of these criteria range from 0 to 1. Quantitative management goals are to reduce (or increase) the value of certain criteria that reflect the operating modes of the managed object. As such a criterion, quite often in water supply networks, a function is used trying to find its minimum. Another common criterion for the efficiency of water delivery functioning is energy consumption at time t:

$$y(t) = \sum_{j \in L} \frac{h_j^{(a)}(t) q_j(t)}{102 \eta_j} \qquad (10)$$

where $h_j^{(a)}$, q_j, n_j – head loss, the flow rate at the j pumping station and its efficiency, respectively; L – set of pumping stations. Integral estimation of energy consumption over the time interval [0, T]:

$$Z = \int_0^T y(t) dt \qquad (11)$$

or with a discrete method of capturing information:

$$Z = \sum_0^T y_j \Delta t_j \qquad (12)$$

The authors will focus on a number of other criteria for the functioning of water delivery that have become widespread in practice. Maximum excess pressure at time t (it is dictated from the conditions of the number of storeys of buildings and the prevention of free head in the distribution network pipelines of more than 60 m of water column):

$$Z(t) = \max_{j \in N} P_j(t) \qquad (13)$$

This criterion characterises “tight spots” in the water delivery system, especially in the mode of minimal water consumption, which can lead to damage to the water network and unproductive water consumption in the intra-house network. Here N is the set of water consumers. Total instant water consumption:

$$y_1(t) = \sum_{j\in L} q_j(t) = \sum_{i\in N} q_i(t) \quad (14)$$

The integral estimate of water consumption over a time interval [0, T] is calculated by analogy with the expressions, namely:

$$Z_1 = \int_0^T y_1(t)dt \quad (15)$$

or, if the incoming information is discrete:

$$Z_1 = \sum_{j=1}^{T} y_{1j}\Delta t_j \quad (16)$$

Estimation of total leakage in water supply systems:

$$y_2 = \sum_{j\in N} A(P_j - P_j^+)q_j \quad (17)$$

where A is the coefficient of unproductive water losses per unit pressure change. The main task of operational management is to ensure that the water delivery system fulfils its intended purpose. Managed variables for these networks are the parameters and structures of individual subsystems. Parameters and structure can be controlled on active elements (pumping stations) and distribution networks. Changes in the parameters and structure of consumers can be judged by changes in the parameters of water consumption processes. Thus, the task of operational management of the water delivery system is to compensate for changes in the structure and parameters of managed subsystems by changing the structure and parameters of consumers. Moreover, compensation for these changes should be carried out by minimising some functional losses in energy, cost, or reliability terms, while observing the corresponding set of restrictions.

The structure of the process of operational management of flow distribution in water supply networks can be presented in the form of two main stages or levels of management: 1) operational planning of flow distribution in the water supply network, considering the prevailing influence of some criterion on this planning period (minimum operating costs, reliable water supply to consumers, ensuring the criterion of quality of functioning according to the formula, which should be equal to one); 2) pressure stabilisation at dictating points in a given range. Solving the problem of operational management at each of these levels, as a rule, is spaced in time and space, requires a different amount and nature of operational information, the presence of mathematical models describing the object of management, various criteria and methods for solving management problems.

The authors will focus on the main tasks of water distribution, which are most widely used in solving the problems of designing and developing water supply networks. In the design process, the problem arises of choosing the optimal operating mode of pumping stations when they work together on the water supply network. Known: network structure; nodal flow rates (hence the total flow of water supplied to the network by pumping stations); pipeline diameters; length of main sections; geodetic marks; minimum allowable free heads at network nodes; number of pumping stations operating on the network, $l\geq1$. For the mathematical formulation of this problem, let us focus in more detail on the mathematical model of steady-state water distribution in the water supply network (Fig. 5).

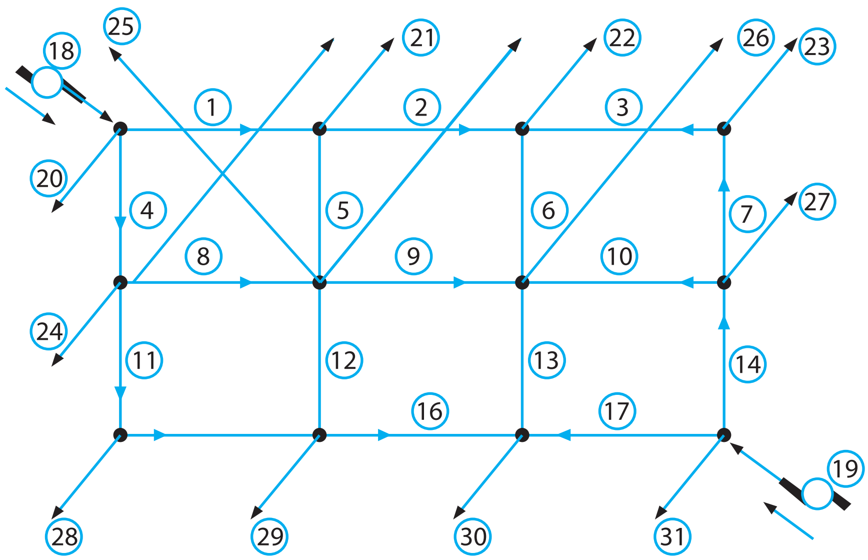

Figure 5. *Example of a water supply network and illustration of its division into three disjoint subsets*

Let the set E of arcs of the water supply network graph consist of three subsets: real arcs M corresponding to pipeline sections; fictitious active arcs L corresponding to network inputs (pumping stations); fictitious passive arcs N corresponding to network outputs (consumers).

$$M = \{1, \ldots, 17\}, m = 17 \tag{18}$$

$$L = \{18, 19\}, 1 = 12 \tag{19}$$

$$N = \{20, \ldots, 31\}, n = 12 \tag{20}$$

$$E = M \cup L \cup N \tag{21}$$

$$E = \{1, \ldots, 31\}, e = 31 \tag{22}$$

Let any vertex of the graph be an input or output (water supply or intake in the water network). The zero vertex is the initial (input) for the pumping station and the final vertex is used for water supply or intake to consumers' water networks (fictitious).

$$h_j = -P_j, \, (j \in L) \tag{23}$$

$$h_j = P_j, \, (j \in N) \tag{24}$$

Each of the areas j ($j \in L \cup N$) will be characterised with two values q_j and P_j and called the input nodal flow rate and pressure if $j \in L$, or the initial nodal flow rate and pressure, if $j \in N$. In other words, the node number matches the section number of the corresponding network input or output. If on plot j ($j \in L \cup N$) the pressure is set, then this section will be considered as the source of the pressure difference $h_j=-P_j(j \in L)$ and $h_j=P_j(j \in N)$ with internal resistance $S_j=0$. If a flow rate is set in this section, then it will be considered a current source q_j with an internal resistance $S_j=\infty$.

Here is a comparison with the formula for pressure losses in the pipeline:

$$h_j = S_j q_j^n \tag{25}$$

where S_j is hydraulic resistance of the site.

For the actual section of the pipeline, the following ratio will be fair:

$$h_j = S_j \, sgn(\, q_j) \left| q_j \right|^{\chi_j} \, (j \in M) \tag{26}$$

Thus, a mathematical model of a water supply system with many nodes will have the form:

$$f_r = S_r \, sgn \, q_r \, |q_r|^{\chi_r} + h_r^{(r)} + \sum_{i \in M_1} b_{1ri} (S_i \, sgn \, q_i \, |q_i|^{\chi_i} + h_i^{(r)}) -$$

$$- \sum_{i \in L_1} b_{1ri} P_i + \sum_{i \in N_1} b_{1ri} P_i = 0 \quad (r \in M_2) \tag{27}$$

$$f_r = -P_{\sum_{i \in M_1} b_{1ri} (S_i \, sgn \, q_i |q_i|^{\chi_i} + h_i^{(r)}) - r} \tag{28}$$

$$- \sum_{i \in L_1} b_{1ri} P_i + \sum_{i \in N_1} b_{1ri} P_i = 0 \quad (r \in L_2) \tag{29}$$

$$q_i = \sum_{r \in E_2} b_{1ri} q_i \quad (i \in E_1) \tag{30}$$

Now let us move on to the mathematical formulation of the problem of optimising the operating mode of pumping stations when they work together on the water network:

$$y = \sum_{j \in N} (P_j^{(H)} - P_j^{(H)+}) \to \min_{\Omega} \tag{31}$$

$$q_i = \sum_{r \in M_2 \cup L_2 \cup N^{(\sigma)}} b_{1ri} q_i + Q_i^+ \quad (i \in E_1) \tag{32}$$

$$Q_i^+ = \sum_{r \in N} b_{1ri} q_i^+ = const \, \, (i \in E_1) \tag{33}$$

$$q_j = q_j^+ \quad (j \in N) \tag{34}$$

$$P_j^{(H)} \geq P_j^{(H)+} \quad (j \in N) \tag{35}$$

The value of S_j is determined here by one of the well-known formulas or empirically, as the result of measurements and solutions to the parametric identification problem. Mathematically, this is a nonlinear programming problem with constraints in the form of equalities and one-way constraints of variables. The authors will solve it as follows: firstly, this problem will be solved, provided that the costs at pumping stations are known; then, based on this programme, the cost grid for the (l-1) pumping station can be searched, where l is the number of these stations.

The initial data to optimise the mode of operation of the designed pumping stations when they work together in the network are: the structure of the network; the location of the inputs and outputs of the network, as well as the supply and flow of water in them; the parameters of the main sections: the length of the pipeline, the diameter of the pipeline, geodetic marks of the beginning and end of the pipeline section; the relationship between the pressure losses and the flow rate of the corresponding section of the water network; the minimum allowable free heads on fictitious sections (network outputs).

The purpose of the calculation is to determine the pressure at the inputs of the network and the water distribution in it that provides the specified water flow rates at the inputs and outputs of this network. Obviously, this problem has many solutions. For an unambiguous solution (the most economical one), it is necessary to determine the so-called dictating point of the network, at which the free head obtained as a result of the solution should be equal to the minimum allowable one.

Let us formulate this problem mathematically:

$$t = \sum_{j \in L} h_j^{(a)} q_j \to \min_{\Omega} \tag{36}$$

$$f_r = S_r \, sgn \, q_r \, |q_r|^{\chi_r} + \sum_{i \in M_1} b_{1ri} S_i \, sgn \, q_i \, |q_i|^{\chi_i} = 0 \quad (r \in M_2) \tag{37}$$

$$f_r = S_r \, sgn \, q_r \, |q_r|^{\chi_i} - h_r^{(a)} + h_r^{(r)} + h_1^{(a)} + \sum_{i \in M_1} b_{1ri} (S_i \, sgn \, q_i \, |q_i|^{\chi_i} + h_i^{(r)}) = 0 \tag{38}$$

$$q_i = \sum_{r \in M_2} b_{1ri} q_i + Q_i \; (i \in E_1) \tag{39}$$

$$Q_i = \sum_{r \in L_2 \cup N \cup N^{(\sigma)}} b_{1r1} q_i^+ = const \quad (i \in E_1) \tag{40}$$

$$h_j^{(H)} \geq h_j^{(H)+} \quad (j = N) \tag{41}$$

Here, the equations of the mathematical model are formulated with the following network encoding: the graph tree is selected in such a way that fictitious sections of the network, sections with active sources become chords. In this case, the real sections will partially become chords, and partially – tree branches. Branches of a tree with a pump are assigned the number 1; L, M, and N are indicated by many indexes of sections: those with active sources, main ones (water network sections), and fictitious ones, respectively. At the same time $L=L_1 \cup L_2$, $M=M_1 \cup M_2$, $N=N_2$, $L=\{1\}$, (1 and 2 are the indexes of tree branches and chords, respectively), and for any closed loop B, contains the backbone sections of the network:

$$h_r^{(r)} + \sum_{i \in M_1} b_{1ri} h_i^{(r)} = 0 \quad (r \in M_2) \tag{42}$$

where $q_j = q_j^+ = const \; (j \in L \cup N), h_j^{(r)} (j \in M)$ – the difference of geodetic marks between the end and beginning (j) of the main section. In the above mathematical model, it is assumed that sections with active sources are directed from a fictitious node to the network, and fictitious sections are directed vice versa.

The purpose of the analysis is to construct the transfer function of the control object, consider the impact of the pipeline on the water supply process, and analyse the possibilities of switching from a distributed pipeline model to a concentrated one to reduce the order of the transfer function of the water supply system. To study the dynamics of processes, the authors will consider the transfer function of the water supply system as an object of control. The facility includes a pumping unit and pipelines. The pump unit consists of a pump and an electric motor.

A block diagram of the water supply management system is shown in Figure 6.

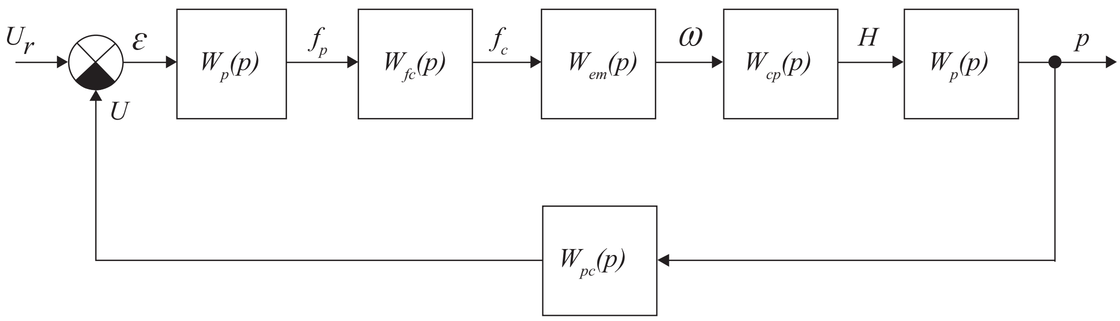

Figure 6. *Block diagram of the water supply management system*

The transfer function of a frequency converter is defined as:

$$W_{fc}(p) = \frac{f_c(p)}{f_p(p)} = \frac{k_{fc}}{(T_{fc}p + 1)} \tag{43}$$

where T_{fc} – time of the frequency converter; k_{fc} – frequency converter gain coefficient. The transfer function of an asynchronous electric motor will have the form:

$$W_{em}(p) = \frac{\omega(p)}{f(p)} = \frac{k_{em}}{(T_{em}p + 1)} \tag{44}$$

where T_{em} – electromechanical time of the electric motor; k_{em} – gain of the electric motor coefficient. The electromechanical time constant will be determined by the formula:

$$T_{em} = \frac{J\omega_0}{M_n} \tag{45}$$

where ω_0 – angular velocity of the rotor at the rated power supply frequency; M_n – starting torque of the motor. The transfer function of the centrifugal pump will have the form:

$$W_p = \frac{H(p)}{\omega(p)} = \frac{k_p}{(T_p p + 1)} \tag{46}$$

where H is the head of the centrifugal pump; T_p is the pump time constant; the pump time constant will be defined as:

$$T_p = \frac{4(d_2 - d_1)}{\left(\Omega z_p \ln\left(\frac{d_2}{d_1}\right)\right)} \tag{47}$$

where d_1 is the input diameter of the circular grid of the pump; d_2 is the output diameter of the circular grid of the pump; Ω is the relative velocity of fluid movement in the interscapular space; z_p is the number of blades of the circular grid; k_p is the pump gain. The transfer function of a strain gauge pressure transmitter is described by the gain coefficient:

$$W_{pc}(p) = \frac{U(p)}{P(p)} = k_{pc} \tag{48}$$

where k_{pc} is the gain of the pressure converter; U is the output voltage of the converter proportional to the pressure signal. The water supply system is a distributed system: the pressure in pipelines does not spread instantly and changes not only in time but also in space. Processes in a water supply system with pipelines are described by partial differential equations. A system of equations can be written:

$$-\frac{\partial p}{\partial x} = \rho\left[\frac{\partial u}{\partial t} + F(u,x)\right] \tag{49}$$

$$-\frac{\partial p}{\partial t} = \rho c^2 \frac{\partial u}{\partial x} \tag{50}$$

where p is the average cross-sectional pressure; u is the fluid flow rate; t is the time; x is the coordi-nate along the pipeline length; ρ is the density of the liquid; c is the speed of sound in the liquid, considering the elasticity of the pipeline walls; $F(u, x)$ is a nonlinear function of viscous friction.

The speed of sound in a liquid is defined as:

$$c = \sqrt{\frac{E_1}{\rho}\left(1 + \frac{d}{\delta}\cdot\frac{E_1}{E_2}\right)^{-1}} \tag{51}$$

where E_1 is the volume modulus of elasticity of the liquid; E_2 is the modulus of elasticity of the pipe material; d is the inner diameter of the pipeline; δ is the wall thickness of the pipeline.

$$F(u,x) = \frac{\lambda}{2d}\cdot|u|\cdot u \tag{52}$$

where λ is the coefficient of hydraulic resistance, which depends on the Reynolds' number. The Reynolds' number can be determined by the formula:

$$\lambda = \frac{ud}{v} \tag{53}$$

where v is the kinematic viscosity of the liquid. To simplify the analysis and synthesis of control systems, it is proposed to replace the distributed part of equation (1.53), (1.54), namely the pipeline with a net delay link, provided that the pipeline is trunking and does not have significant branches that considerably affect its dynamic properties.

$$G_h = \frac{H(s,l)}{H_0(s)} = e^{-\frac{1}{v}s} \tag{54}$$

$$G_Q = \frac{Q(s,l)}{H_0(s)} = \sqrt{\frac{(gS/c^2)_j}{(1/gS)_j}}\cdot e^{-\frac{1}{v}s} \tag{55}$$

where G_h is the head transfer function of the pipeline; G_Q is the feed transfer function of the pipeline; v is the signal distribution speed.

It is known that:

$$v = \frac{1}{\sqrt{(1/gS)_j\cdot(gS/c^2)_j}} \tag{56}$$

where j is the j fragment of the pipeline; S is the cross-sectional area of the pipeline; d is the diameter of the pipeline; l is the length of the pipeline piece; λ is the dimensionless coefficient of resistance of the pipeline.

If the control point is set at some distance along the pipeline, in addition to the signal delay, some pressure drop will also be present, which depends on the resistance of the pipeline and the speed of fluid movement. Based on this, the pipeline gain is determined using the equation:

$$k_p = \frac{vS}{p} \tag{57}$$

where k_p is the gain coefficient of the pipeline; v is the speed of fluid movement in the pipeline;

$$v = \frac{Q}{S} \tag{58}$$

where p is the pressure at the end of the pipeline; S is the cross-sectional area of the pipeline. Now the pipeline transfer function can be represented as follows:

$$W_p(p) = \frac{P(p)}{H(p)} = k_p e^{-p\tau} \tag{59}$$

Since there is a clean delay in a water supply system with a long pipeline, it is necessary to ensure the stability of the control system. Considering that the length of the pipeline does not exceed a critical value and the system is stable, observable, and controlled, then the transfer function of the pipeline can be described using a first-order aperiodic link:

$$W_p(p) = \frac{P(p)}{H(p)} = \frac{k_p}{(T_p p + 1)} \tag{60}$$

Since an open control system is used in further studies, the transfer function of an open water supply control system acquires the following form:

$$W(p) = \frac{k_{fc}k_{em}k_p k_p k_{pc}}{(T_{fc}p+1)(T_{em}p+1)(T_p p+1)(T_p p+1)} \quad (61)$$

The transfer function of the object (1.65) has the fourth order, which complicates the study and construction of control systems, so it is proposed to replace the transfer function of the frequency converter with a gain factor, given that the vector method of controlling an asynchronous motor is used. Then the control object takes its final form:

$$W(p) = \frac{k_{fc}k_{em}k_p k_p k_{pc}}{(T_{em}p+1)(T_p p+1)(T_p p+1)} \quad (62)$$

The transfer function of the water supply facility (1.66) has the third order and can be used in further research.

Let us consider a single-circuit closed water supply system. To make a model, a pump unit was selected that has the following parameters: T_m=0.026 – electromechanical time constant of an asynchronous electric motor with a short-circuited rotor; T_p=0.231 – pump time constant; T_{tc}=0.01 – pump time constant; k_m=5.061 – motor gain factor; k_p=5.22 – pump gain factor; k_{tc}=0.99 – pump gain factor; $T3=T_m T_p T_{tc}$=0.00006006; $T2=T_m T_p+T_m T_{tc}+T_p T_{tc}$=0.00231; $k1 = k_m k_p k_{tc}$=26.15423.

Existing water supply system regulators use only continuous functions in the control signal. The use of continuous functions in the control signal does not allow switching the water supply system to a given state in the shortest possible time. To ensure maximum performance, the proportional control law must be used. However, given the fact that the control influence in a real water supply system cannot be large, according to the engineering requirements, a restriction is imposed on it for the adequacy of the model. A block diagram of the control system using the proportional law is shown in Figure 7.

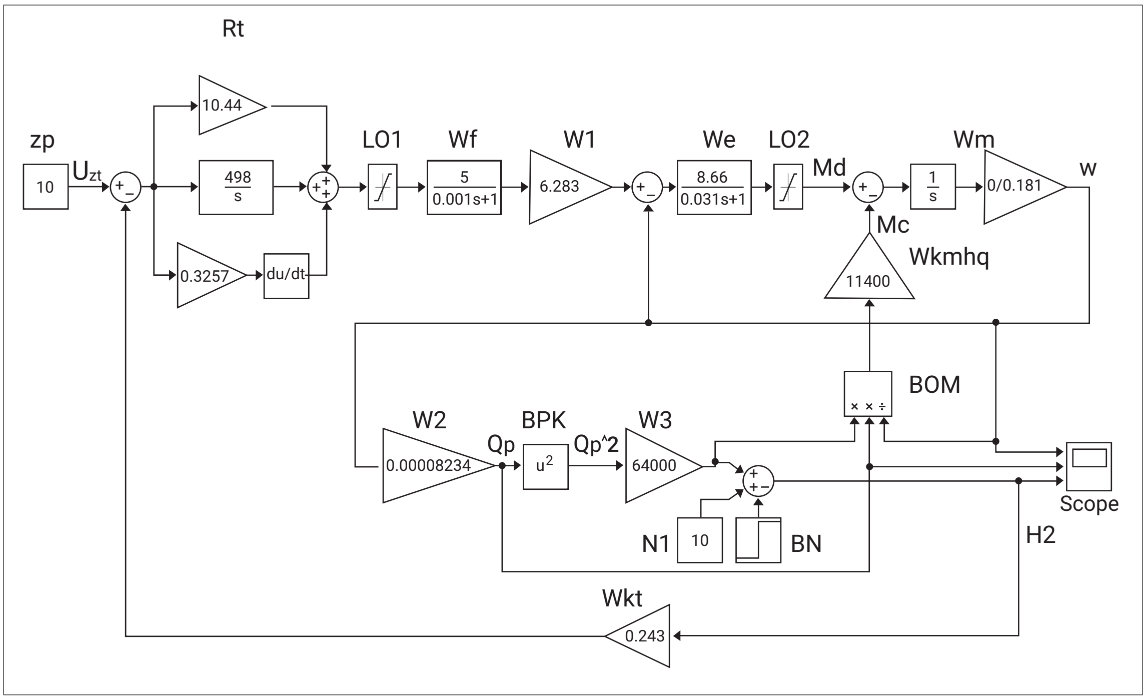

Figure 7. *Computer model of a pumping station with pressure feedback*

Modelling shows that existing regulators in water supply systems do not considerably improve the constant pressure in the pipeline when there is uneven water consumption. This is explained by the fact that the regulator slows down the transition process to prevent the system from becoming unstable but it does not consider fluctuations at the input. Operation of the water supply system in transition mode and state stabilisation mode is possible using a regulator with a variable structure and parameters. The authors will conduct a study of such a regulator. A block diagram of such a regulator is shown in Figure 8.

The graph of transients in the water supply system using the regulator is shown in Figure 9.

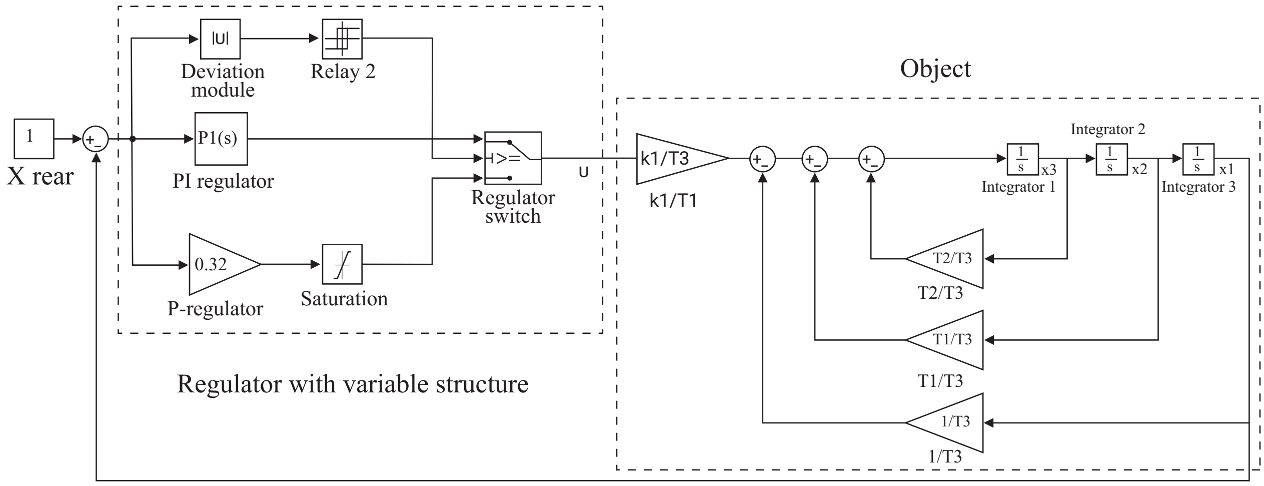

Figure 8. *Computer model of a pumping station with pressure feedback*

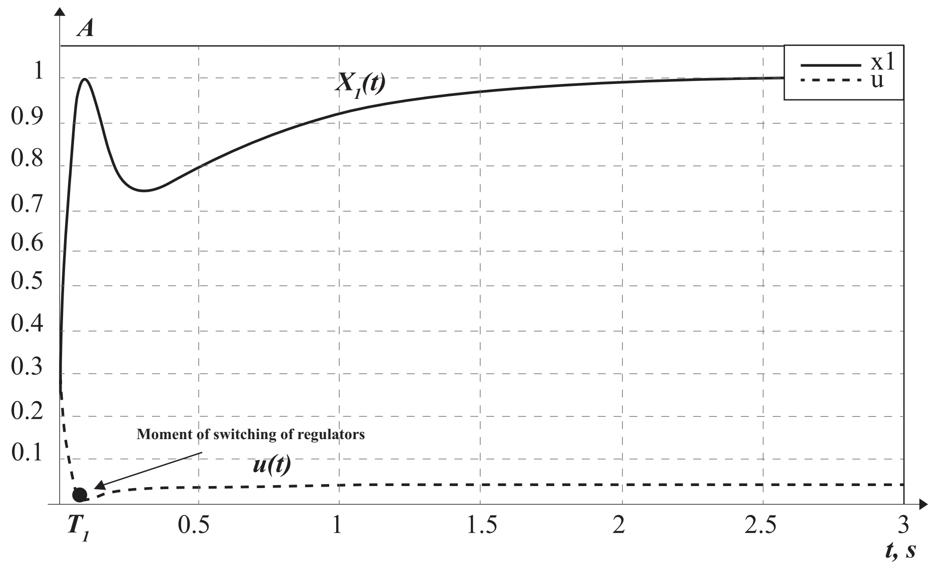

Figure 9. *Schedule of operation of the water supply system using a variable structure regulator*

Therefore, the use of regulators only using continuous functions in the control signal of the water supply system does not allow for a minimum transition time since an increase in the proportional coefficient will lead to unstable operation of the system. In a well-established mode, this regulator cannot minimise the efficiency functionality since it does not consider restrictions on derivatives and the amount of control influence. The regulator, which has a variable structure and parameters, allows achieving the specified quality indicators in the transition mode and state stabilisation mode, but the consequence of its use is an increase in the duration of control of the water supply process.

Let us consider modelling and studying the regulator in the transition mode of the water supply system. A block diagram of the model is shown in Figure 10.

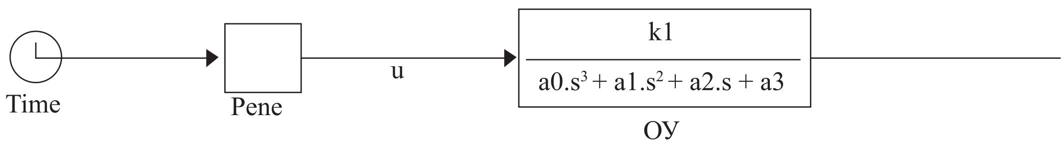

Figure 10. *Block diagram of a water supply system model using a discontinuous function*

The modelling results have shown that the transition process passes without fluctuations and overshoot. The transition time is 0.0311 seconds. Since two intervals and one switching are used for control, according to Feldbaum's theorem and Pontryagin's maximum principle, the trajectory of the system is optimal in terms of speed. During the modelling, only the transition mode was considered, so after the system went to the set value, the control was turned off and the movement of the system became free without external influence. The disadvantage of the control system that calculates the switching time is that it is necessary to have an accurate time counting device as part of the controller. The study and modelling of the water supply system at various gain parameters shows that the vector *K* also changes in proportion to the change in the system parameters, and the overall functionality is constant. That is, the value of the efficiency functional in this case does not depend on the gain of the transfer function. But changing the constant time also leads to a change in the values of the functionality.

Thus, the above control method provides a minimum of quality functionality in a well-established mode and shows the feasibility of using the device for analytical design of regulators in the water supply system.

CONCLUSIONS

In the paper, a study was conducted to assess the impact of the distribution and length of the pipeline network. The system of water supply and distribution is analysed, what criteria affect the correct performance of work and what problems may arise during operation for a long period of time are investigated. Based on the analysis, a mathematical model of the water supply system and a flow control model of the water supply system were developed. Since this paper examines the influence of the distribution and length of pipeline networks of the water supply system on the electric drive, the control of the water supply system was modeled based on existing regulators with a constant and variable structure. The results of modelling and experimental studies of the water supply control system have shown:

1. The use of discontinuous functions in the control signal in transient mode allows getting the optimal speed trajectory of the water supply system. The conducted studies have shown that the use of discontinuous functions can reduce the duration of the transition mode by 3.8 times compared to existing regulators and, therewith, ensure minimal deviation and overshoot.
2. The proposed steady-state regulator improves the quality of control compared to existing regulators. According to the modelling results, the value of the quality functionality was reduced by 7.6 times.
3. It was shown that based on the proposed methods, it is possible to create a regulator with a variable structure and minimise the transition time, as well as minimise the quality functionality in a stable mode. It is proved that switching regulators should be carried out depending on the deviation of the initial pressure value and, thus, determine the operating mode of the water supply system.

Main scientific and practical results, their significance.

1. The approach to building automated control systems using regulators with variable structure has been further developed, which, unlike the known ones, takes into account the distributed nature of the control object in space, which allows applying the obtained control laws to water supply systems and thereby increasing the efficiency and reliability of their operation.
2. A computer model of the water supply system has been developed, which, unlike the known ones, takes into account the distribution in the space of the pipeline network, which will increase the efficiency of the design process of such systems.

The main scientific results of the paper were presented at the All-Ukrainian competition of student scientific papers in the area of “Electromechanics”, which in 2021 was held remotely on the basis of the Dnipro State Technical University in Kamianske. As a result of the discussion, the paper “Improving the efficiency of distributed water supply systems by means of a regulated electric drive” received a diploma of the III degree.

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Підвищення ефективності роботи розподілених систем водопостачання засобами регульованого електропривода

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Анотація. Водопостачання насосної станції має задовольняти потреби споживача, які змінюються протягом доби, тому його продуктивність потребує коригування. Будь-яке відхилення продуктивності насосного агрегату від номіналу призводить до додаткових витрат на електроенергію. За таких умов велике значення у сфері водопостачання приділяється оптимізації роботи електроприводів насосної станції. Для регулювання продуктивності насосної станції часто вдаються до зміни кількості працюючих насосних агрегатів, двигуни яких запускаються безпосередньо від електричної мережі. На двигуни середньої та великої потужності діють технічні обмеження для прямого запуску, які доповнюються необхідністю підтримувати паузи між пусками, тому при забезпеченні необхідного значення продуктивності насосної станції дуже важливо враховувати особливості пуску насосних двигунів. Системи управління широко використовуються в області електроприводу та водопостачання, саме в цих сферах від ефективності роботи системи керування залежить кількість електроенергії, що буде споживатися технологічним процесом, або надійності його роботи. Відомо, що на насоси припадає приблизно половина всієї виробленої енергії, тому питання ефективних систем контролю є особливо актуальним у сфері водопостачання. Мета даної наукової роботи – підвищити надійність та ефективність роботи системи водопостачання за рахунок врахування під час керування електроприводами насосів, властивості розподіленості трубопровідної мережі, що дозволить узгодити роботу насосної станції, трубопровідної мережі та споживача. Для досягнення цієї мети було проведено дослідження оцінки впливу розподіленості та протяжності трубопровідної мережі. Також було проаналізовано систему подачі та розподілу води, досліджено які критерії впливають на коректне виконання роботи та які проблеми можуть виникати під час роботи в тривалий проміжок часу. Встановлено шляхи оптимізації роботи насосних станцій з метою підвищення економічності установок та їх енергоефективності. Розглянуто основні причини доцільності використання регульованого електроприводу для керування насосними агрегатами

Ключові слова: водопостачання, водопровід, приводи електронасосних станцій, математичні моделі електроприводу, насоси