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The Analysis of Operation Modes of Variable Speed Pump Units with Different Circuits of Turbomachine Connection

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Abstract: The scientific novelty of the proposed article lies in the development of the theory of analysis of the operation modes of group pump units operating on a long pipeline network with back pressure. This was achieved by creating electric equivalent circuits of group pump units based on the method of electrohydraulic analogy. Such equivalent circuits take into account pumps' connection circuits, the configuration of the pipeline network, and the method of regulating technological parameters. A method for determining the characteristics of pump units with series and parallel connection is proposed. The dependences of the power consumed by the pump units on the change in the frequency of rotation of the adjustable pump are obtained for various parameters of the hydraulic network. This makes it possible to determine the limits of energy-efficient regulation of pump discharge. Analytical expressions for determining the lower limit of the pump rotation frequency for various circuits of turbo mechanism connection and various numbers of pumps operating simultaneously on a pipeline network with back pressure are proposed. The necessary range of adjustment of the pump rotation frequency with different circuits for turbo mechanism connection and different numbers of hydraulic machines operating at the same time is determined. The analysis of the obtained modes of pump units is performed and the possibility of expanding the controlled properties of the group electric drive systems of turbomachines when changing the direction of the rotation frequency and reversing the liquid in the event of an emergency situation is shown.

Keywords: pump unit; electric equivalent circuit; method of electro-hydraulic analogy; range of rotation frequency regulation

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1. Introduction

Pumping units (PU) are machines of mass application which are widely used in many areas of economic activity: in municipal and industrial water supply; in power plants (hydraulic, thermal, nuclear, hydraulic storage); in the chemical and oil industries; mining, etc. Pumps, their electric drives (electric motors, power converters), and pipelines with regulating and shut-off fittings belong to the main equipment of pumping stations (PS) [1–4]. The main purpose of PU and complexes based on them is to provide consumers with the working product in the required quantity with given pressure. The operation of PU is characterized by a change in pressure, discharge and hydraulic resistance in accordance with the water consumption schedule [1–4].

In order to increase the energy efficiency of the work of PU, regulated electric drive (ED) systems are actively used which allow not only significant savings in electricity to be achieved, but also leaks and power losses to be reduced in transporting the working product, water hammers to be eliminated and the reliability of equipment to be increased [5–10].

Particular attention is paid to the issue of optimizing the energy consumption of pumping stations depending on the water supply regime, the actual conditions of operation of the PU, and the construction of systems for monitoring the energy efficiency of technological facilities [11–14]. Such systems of automatic control of PU ED must take into account the nonlinear properties of asynchronous electric drives of pumps, and be able to identify the current parameters of the electromechanical and hydraulic system during operation in order to achieve maximum efficiency [15–17].

Most often, PU refers to consumers of a group nature, where several pumping units (PU) work in parallel or in series on a common hydraulic network with back pressure. In the case of a group PU, it is advisable to equip one of the operating PUs with a variable-frequency ED.

The analysis [18–21] showed that there is currently no method for determining the pressure-discharge and energy characteristics of pumping units with different schemes of inclusion (parallel, series, or mixed connection) of the pump on the general pipeline network, as well as for calculating the necessary range of frequency regulation rotation of the variable-frequency pump as part of the group PU.

Taking into account the fact that the scientific novelty of the proposed work consists of the development of the analysis theory of the operation modes of group PUs working on a pipeline network of large length with back pressure by creating equivalent electrical schemes based on the principle of electrohydraulic analogy, the essence of the method lies in the similarity of the processes occurring in electrical and pipeline networks, which are long lines with distributed parameters. In this case, the main electrical equations are transformed into the corresponding hydraulic relations, based on which PU electric equivalent circuit is drawn up. The main features of applying this principle of analysis of hydromechanical and hydrodynamic devices are considered in several papers [22–26].

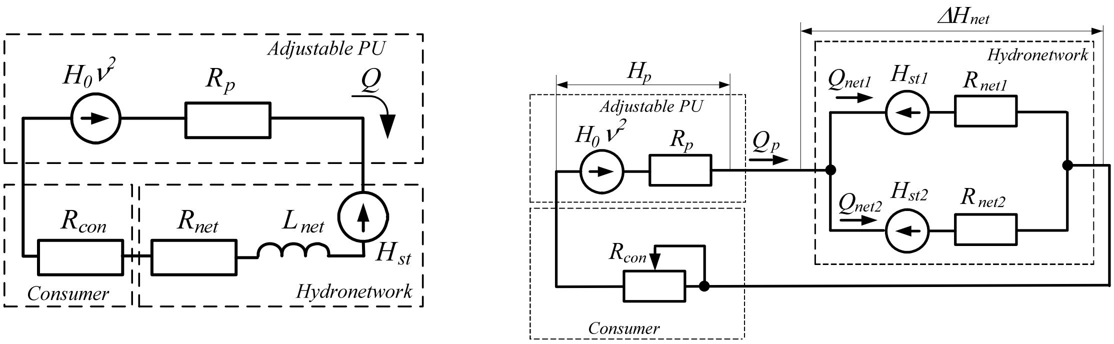
This approach provides an opportunity to determine the technological, mechanical and energy characteristics of pump units both in steady and non-steady (if the pipeline network is represented by RLC-sections) modes of operation, the permissible ranges of changes in the frequency of rotation of the pump, and the limits of energy-efficient regulation of pump discharge.

The purpose of the paper is to develop a theoretical approach to determine the characteristics and range of regulation of the rotation frequency of a group pumping unit with various circuits of pumping unit connections to the general pipeline network.

2. Research Methods

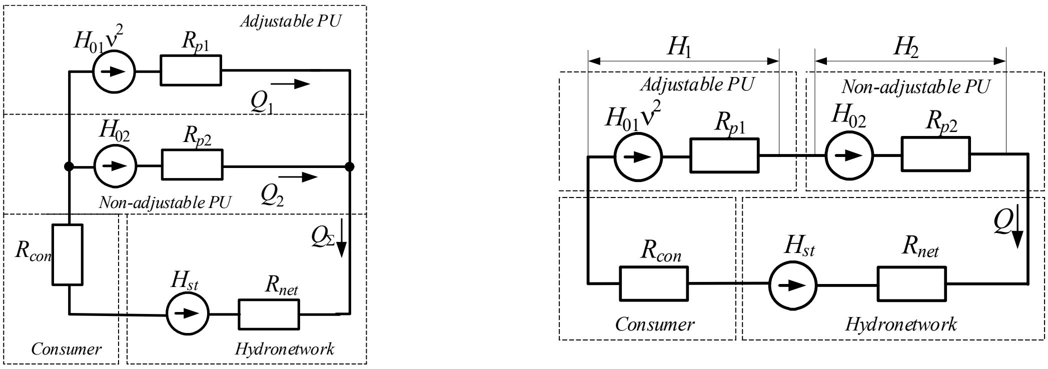
The following assumptions are used when constructing PU models describing static (steady) modes: the transported liquid is considered incompressible; the temperature of the liquid and, therefore, the density are unchanged; the velocity head is neglected due to its small value compared to the potential head; and pressure losses at local supports are neglected. A description of the characteristics of the pump unit in the presence of malfunctions and non-stationary phenomena is given in [27,28].

Using the method of electrohydraulic analogy allowed PU electric equivalent circuits to be obtained, taking into account the connection circuit (parallel or series) and turbomachines parameters, the configuration of the pipeline network, and the method of regulating technological parameters. Figures 1 and 2 demonstrate PU electric equivalent circuits, which describe the operation of one pump with a variable frequency of rotation on a non-branched pipeline with back pressure (Figure 1a); on a pipeline network of various configurations with a consumer at the end (Figure 1b), the operation of the PU, consisting of several turbomachines, connected in parallel (Figure 2a); or in series (Figure 2b). This approach allows determining the head and discharge at any point of the hydraulic network, as well as the head and power losses on the elements of the entire pumping complex.



(**a**) (**b**)

Figure 1. Electric equivalent circuits of PU operating on a pipeline network with back pressure (**a**) and on a branched pipeline (**b**).



(**a**) (**b**)

Figure 2. Electric equivalent circuits of PU with turbomachines operating in parallel (**a**) and in series (**b**) on a common pipeline.

The following designations are used in Figures 1 and 2: Q—discharge at the pump outlet, m^3/s; H_1, H_2—heads of adjustable and non-adjustable pumps, respectively, m; H_{01}, H_{02}—heads created by pumps at zero discharge, m; R_{p1}, R_{p2}—internal resistance of, respectively, adjustable and non-adjustable pumps, s^2/m^5; $\nu = \frac{\omega_i}{\omega_n}$—relative frequency of rotation of the adjustable pump impeller; ω_n, ω_i—rated and current values of the pump rotation angular frequency, respectively, s^{-1}; H_{st}—static head of the network, m; R_{net}, R_{con}—hydrodynamic resistance of the pipeline and consumer, respectively, s^2/m^5. In this case, the pump parameters are determined according to the passport characteristics of the turbomechanism; parameters of the pipeline network—the geometric configuration of the pipeline. At the same time, R_{con} depends on the current mode of water consumption and can change over time.

This approach makes it possible to draw up a group PU electric equivalent circuit not only for steady modes of operation, but also for the occurrence of wave processes in the pipeline network [22]. An example of such a regime can be cavitation processes that develop in pumping units and hydraulic networks in the presence of rarefaction in the pipeline, back pressure, on local supports, etc. [29].

Characteristics of PU with variable frequency of rotation can be presented in the form of approximated analytical dependences with a sufficient degree of accuracy. The head-discharge characteristic with a clearly expressed maximum have the following form:

$$H = A_2\nu^2 + B_2\nu Q + C_2 Q^2 \tag{1}$$

when the $H - Q$ characteristic of the pump is flat, the expression for the head characteristic has the form of a quadratic parabola:

$$\mathrm{H} = \mathrm{H}_0\nu^2 - \mathrm{R}_\mathrm{p}\mathrm{Q}^2 \tag{2}$$

The power supplied to the shaft of the centrifugal machine:

$$P = A_3\nu^2 Q + B_3\nu Q^2 + D_3\nu^3 \tag{3}$$

Useful hydraulic power:

$$P_p = \frac{\rho g Q H}{1000} = \frac{\rho g\left(A_2\nu^2 Q + B_2\nu Q^2 + C_2 Q^3\right)}{1000} \tag{4}$$

Pump efficiency:

$$\eta_p = \frac{P_p}{P} = \frac{\left[\rho g\left(A_2\nu^2 Q + B_2\nu Q^2 + C_2 Q^3\right)\right]}{\left[1000\left(A_3\nu^2 Q + B_3\nu Q^2 + D_3\nu^3\right)\right]} \tag{5}$$

where in expressions (1)–(5), $A_2, B_2, C_2; A_3, B_3, D_3$ are approximation coefficients that depend on PU design features and are determined by the published characteristics of the pumps; ρ—liquid density, kg/m^3; $g = 9.81$ m/s^2—acceleration of gravity.

The characteristic of a hydraulic network with back pressure can be described by an equation of the following form:

$$H = H_{st} + R_{net} Q^2 \tag{6}$$

To analyze the modes of operation of PU with several pumps operating in parallel, the total head-discharge and energy characteristics of the pumps are used. The total $H - Q$ characteristic of parallel-operating PUs is built by adding the abscissas (feeds) of their characteristics at the same value of the ordinate (pressure). When the pumps operate together in parallel, an increase in discharge is achieved. Moreover, the flatter the network characteristic is, the greater the effect of increasing discharge is.

Based on the equivalent circuit (Figure 2a), in which non-adjustable and adjustable pumps are separated into two equivalent chains, with a flat head-discharge characteristic of the pumps, the following system of equations is valid:

$$\left.\begin{array}{l} H_{01} - H_{02}\nu^2 = R_{p1}Q_1^2 - R_{p2}Q_2^2; \\ H_{01} - H_{st} = R_{p1}Q_1^2 + R_{net}Q_3^2; \\ Q_1 + Q_2 = Q_3 \end{array}\right\} \tag{7}$$

where H_{01}, H_{02} are heads created by pumps at zero discharge, m; R_{p1}, R_{p2} are the internal resistance, respectively, of non-adjustable and adjustable pumps, s^2/m^5; and Q_1, Q_2, Q_3 are the discharges of non-adjustable and adjustable pumps and the total discharge of PU, respectively, m^3/s.

For the simplicity of the analysis, consider the case when PU contains two identical parallel operating turbomachines, one of which is adjustable: $H_{01} = H_{02} = H_0$, $R_{p1} = R_{p2} = R_p$. Then, we find the discharge from the first equation of system (7):

$$Q_1 = \sqrt{\frac{H_0\left(1 - \nu^2\right)}{R_p\left(1 - \alpha^2\right)}} \tag{8}$$

where $\alpha = \frac{Q_2}{Q_1}$.

We reduce the second equation of system (7) to the form:

$$H_0(1 - h) - Q_1^2 R_p\left(1 + \rho\left(1 + \alpha^2\right)\right) = 0 \tag{9}$$

where:

$h = \frac{H_{st}}{H_0}$—relative back pressure of the network;

$\rho = \frac{R_{net}}{R_b}$—relative resistance of the network.

As a result of solving Equation (9) with respect to α and further transformations, we obtain analytical expressions of the dependences of the PU discharge $Q_1(\nu),\ Q_2(\nu),\ Q_3(\nu)$ on the relative frequency of rotation with PU parallel connection.

The connection of pumps in series is used to increase the head that cannot be provided by one pump. Each of the serially connected turbomachines gives the same discharge, and PU general characteristic $H - Q$ is obtained by the sum of the ordinates (heads) of the characteristics of the pumps with the same value of the abscissa (discharge).

On the basis of the equivalent circuit of units operating in series (Figure 2b), provided that the discharge is regulated by varying the rotation frequency of only one of the pumps, the following system of equations is true:

$$\left.\begin{array}{l} H_{01} + H_{02}\nu^2 - H_{st} = R_{p1}Q^2 + R_{p2}Q^2 + R_{net}Q^2; \\ H_1 = H_{01} - R_{p1}Q^2; \\ H_2 = H_{02}\nu^2 - R_{p2}Q^2; \\ H_3 = H_1 + H_2. \end{array}\right\} \quad (10)$$

As with the parallel operation of PU, we assume that $H_{01} = H_{02} = H_0$, $R_{p1} = R_{p2} = R_p$. Then, from the first equation of the system, we find (10):

$$Q = \sqrt{\frac{(H_0 + H_0\nu^2 - H_{st})}{(2R_p + R_{net})}}. \quad (11)$$

By substituting expression (11) into the other equations of system (10) and performing the appropriate transformations, we obtain the dependences of PU heads $H_1(\nu)$, $H_2(\nu)$, $H_3(\nu)$ on the relative rotation frequency in the case of turbomachines connected in series.

3. Results

Figure 3 demonstrates curves of changes in discharge and head of two identical D2000-100 pumps with the following parameters: discharge $Q_{nom} = 2000\ \mathrm{m^3/h}$, $H_{nom} = 100$ m, $n_{nom} = 980$ rev/min, power $P_{nom} = 760$ kW, and approximation coefficients $A_3 = 1181.818$; $B_3 = -619.834$; $D_3 = 150$ with flat characteristics of changing the frequency of rotation of the impeller of one of them at different parameters of the hydraulic network $h = var, \rho = var$ and PU connection in parallel (Figure 3a) and in series (Figure 3b).

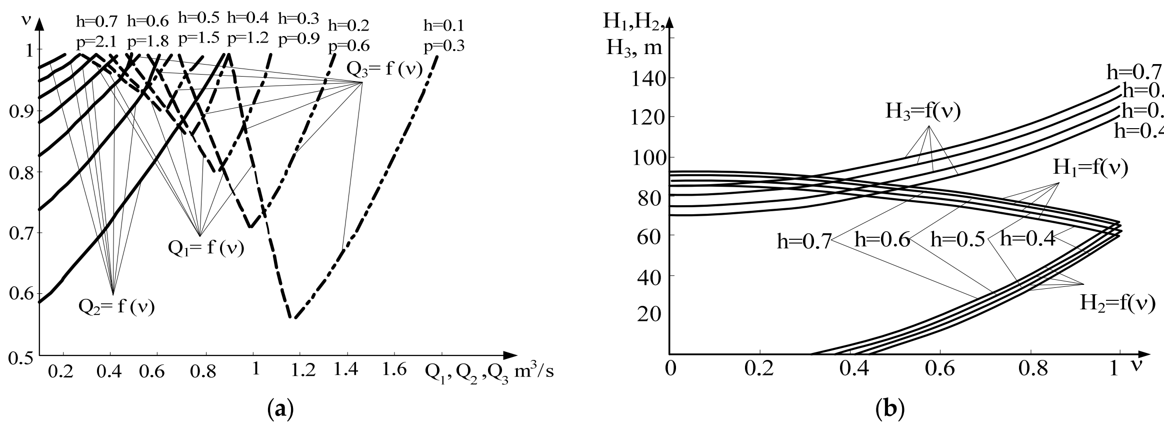


Figure 3. Curves of the dependence of the discharge (**a**) and head (**b**) of pump units with parallel (**a**) and series (**b**) connections of turbo mechanisms on changes in the relative frequency of rotation of the adjustable pump and various parameters of the hydraulic network.

Figure 4 shows the dependence of the power consumed by PU on the change in the relative frequency of rotation of the impeller of the adjustable unit.

As a result of the analysis of the obtained characteristics, it is determined that a change in the rotation frequency of one of the pumps leads to a change in the technological (head and discharge) and energy (power) parameters of not only the adjustable PU, but also the non-adjustable turbo mechanism. It is determined that with a decrease in the rotation frequency, the total power consumed by PU noticeably decreases both with parallel and series connections of turbomachines, and the smaller the value of relative back pressure h

in the pipeline, the wider the range of the power change. So, when the relative frequency of rotation is reduced by 10% from the rated and back pressure in the hydraulic network $h = 0.4$, the reduction in the total power consumed by PU is 23% in the case of parallel and 16% in the case of the series connection of PU in the common pipeline.

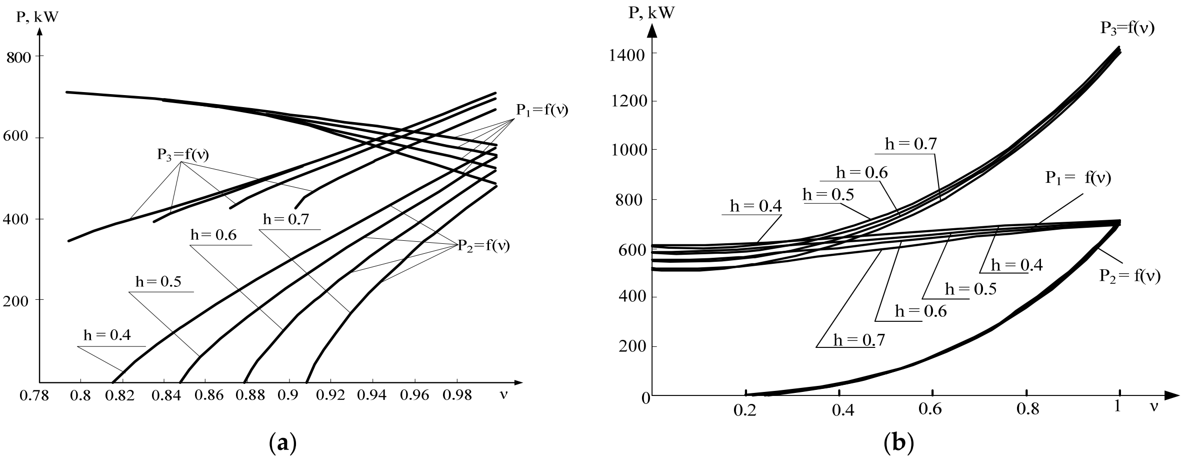


Figure 4. Curves of changes in power on the shaft from the relative frequency of rotation of the adjustable pump in parallel (**a**) and series (**b**) connections of PU: P_1 = f(ν)—the power of a non-adjustable PU; P_2 = f(ν)—the power of an adjustable PU; and P_3 = f(ν)—total power consumed by turbomachine.

Using the expression (5), it is also possible to estimate the energy efficiency of the PU operation, taking into account the change in the set of the following factors: the parameters of the pipeline network, the switching scheme of the turbomachines, the number of pumps working at the same time, and the type of their pressure-discharge characteristics.

Curves of changes in the efficiency of the pumps as a function of the frequency of rotation of the regulated unit when the turbo mechanisms are turned on in parallel and in series are shown in Figure 5.

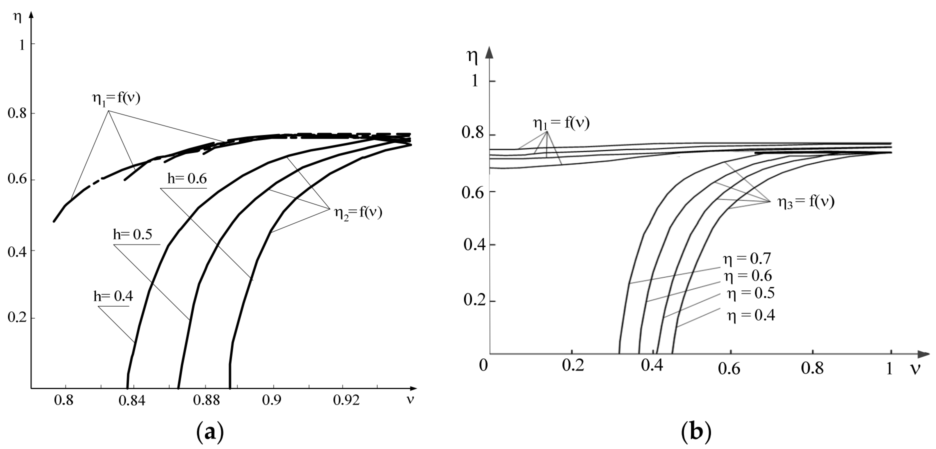


Figure 5. Curves of changes in the efficiency from the relative frequency of rotation of the adjustable pump in parallel (**a**) and series (**b**) connections of PU: η_1 = f(ν)—the efficiency of a non-adjustable PU; η_2 = f(ν)—the efficiency of an adjustable PU.

To determine the lower limit of the range of regulation of the rotation frequency of a pump for any schemes of inclusion of turbomechanisms, it is necessary to construct their joint pressure-discharge characteristics.

Figure 6 shows the graph of a single working centrifugal unit on a hydraulic network with back pressure when adjusting productivity by changing the frequency of rotation of the pump impeller, where the curves I, I′, I″, I‴ are pressure-flow characteristics of the pump when the rotation frequency changes; II—is curve the pressure-flow characteristic of the hydraulic network.

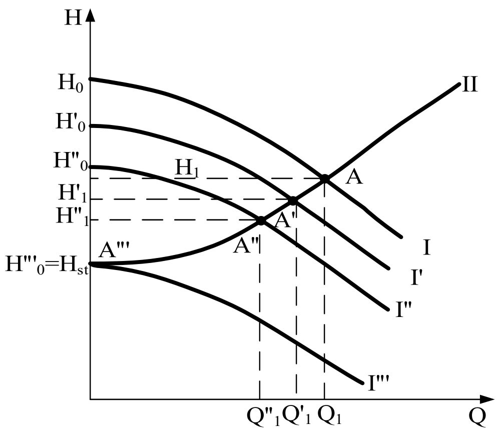


Figure 6. Characteristics of the common operation of the pump on the pipeline network when the rotation frequency changes.

At the nominal speed of rotation, the mode of operation of the pump on the hydraulic network is determined by the point A of the intersection of curves I and II. At the same time, PU discharge is equal to Q_1, and the pressure is H_1. When the frequency of rotation of the adjustable pump is reduced, the point of the operating mode moves according to the characteristic of network II. At the point A$'''$, discharge Q of the pump is decreased to zero. This mode corresponds to the extreme lower limit of the range of rotation frequency adjustment, determined by the value of the relative critical rotation frequency.

In this case, the equality of pressures is fair: $H_0''' = H_{st}$:

$$A_2\nu_{kr}^2 + B_2\nu_{kr}Q + C_2Q^2 = H_{st} + R_{net}Q^2 \tag{12}$$

Substituting $Q = 0$ into expression (12), we obtain:

$$\nu_{kr} = H_{st}/A_2 \tag{13}$$

where ν_{kr} is the relative critical frequency of rotation of the electric drive of the regulated unit.

We reduce expression (13) to the following form:

$$\nu_{kr} = \sqrt{h} \tag{14}$$

where $h = H_{st}/A_2$ is the relative back pressure of the pipeline network.

Thus, the range of adjustment of the frequency of rotation of the pump impeller does not depend on the resistance of the hydraulic network, but is determined only by the static component of the pressure H_{st}. So, for the D2000-100 pump at h = 0.4, the relative critical frequency is $\nu_{kr} = 0.63$, and the range of rotation frequency adjustment is 37% below the nominal; at $h = 0.6$, $\nu_{kr} = 0.77$ and the pump rotation frequency adjustment range is 23%; at $h = 0.8$, $\nu_{kr} = 0.89$, the pump rotation frequency adjustment range is 11%.

The proposed method of determining the characteristics of PU as part of the group turbomachines made it possible to determine the extreme lower limit of the pump speed control range for any circuits of connection of turbo mechanisms. As an example, Figure 7 shows the head-discharge characteristics of PU with two identical D2000-100 pumping units operating in parallel. At constant rotation frequency $\nu = 1.0$ of both pumps, the total PU discharge (point A at curve 3) equals $Q_\Sigma = Q_3 = Q_1 + Q_2$. When the frequency of rotation of the adjustable pump changes (curve 2$'$), the total PU discharge equals Q_3' (point A$'$ at curve 3$'$). In this case, the discharge at the output of the pumps, respectively, is

$$Q_1 = Q_{1\nu};\ Q_2 = Q_{2\nu}'.$$

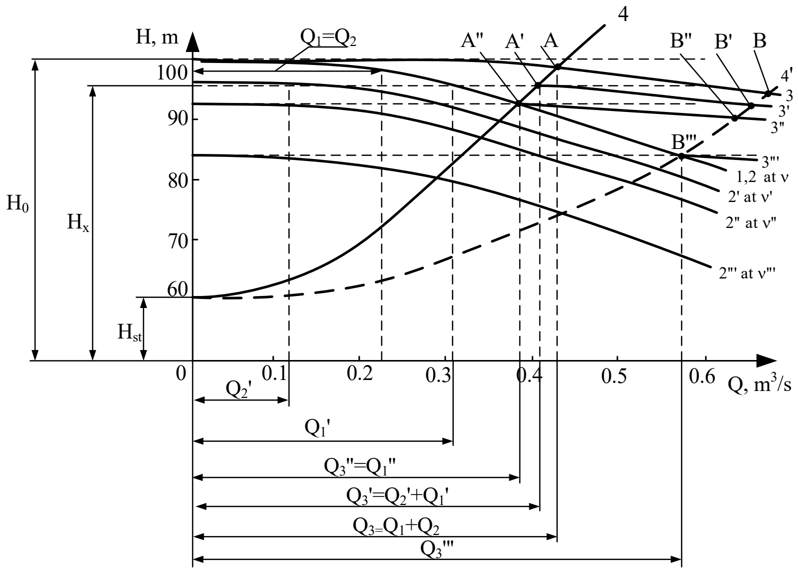


Figure 7. Characteristics of pumps operating in parallel for the general pipeline network: 1, 2—head characteristics of two D2000-100 PUs; 2′, 2″, 2‴—head-discharge characteristics of the adjustable pump at the relative frequency of rotation ν′, ν″, ν‴, respectively; 3, 3′, 3″, 3‴—total head-discharge characteristics of the pump assembly; 4, 4′—characteristics of the hydraulic network with relative parameters h = 0.6, ρ = 4.33 and h = 0.6, ρ = 1.44, respectively; A, A′, A″—points of the PU operating mode at the relative frequency of rotation ν′, ν″, ν‴, respectively (ρ = 4.33); B, B′, B″, B‴—points of the PU operating mode at the relative frequency of rotation ν′, ν″, ν‴, respectively (ρ = 1.44); $Q_3{'}$, $Q_3{''}$, $Q_3{'''}$—the value of the total discharge of PU.

When motor speed is gradually reduced, discharge Q_2 of the other pump decreases to zero. Value ν″ and point A″ of curve 3″ correspond to this mode. In this case, the total discharge of PU is $Q_1 = Q_3{''}$. Point A″ determines the relative critical rotation frequency, which corresponds to the lower limit of the rotation frequency adjustment range. The head created by the pump with adjustable rotation frequency is as follows:

$$H_x = H_0 \nu_{kr}^2 \tag{15}$$

Since the equality of heads created by the adjustable and non-adjustable pumps is observed at point A″, the following is true for this mode:

$$H_0 \nu_{kr}^2 = H_0 - R_p Q_1^2 \tag{16}$$

where $Q_1 = \sqrt{\frac{R_p(H_0 - H_{st})}{(R_p + R_{net})}}$.

The obtained dependence made it possible to conclude that with an increase in back pressure h and resistance ρ of the hydraulic network, the range of frequency regulation decreases. So, with the network parameters h = 0.6, ρ = 1.44 (curve 4′ Figure 6), the value of the relative critical frequency is equal to $\nu_{kr} = 0.91$, and the adjustment range is 9%; but with the same value of back pressure h = 0.6, the resistance of the network is three times greater, ρ = 4.33 (curve 4 Figure 6), the value of the relative critical frequency is equal to $\nu_{kr} = 0.96$, and the adjustment range is 4%. The results of the research showed that the limits of the regulation of the frequency of rotation of turbomechanisms when they work together are different from the values typical for units working individually, where $\nu_{kr} = \sqrt{h}$ and does not depend on R_b and R_{net}.

Using the last equation, after performing the transformation, we determine the relative critical frequency of rotation of the adjustable unit:

$$\nu_{kr} = \sqrt{\frac{(\rho + h)}{(1 + \rho)}} \tag{17}$$

In the case when PU contains several n non-adjustable units connected in parallel and one adjustable, the expression for determining the relative critical frequency of rotation of the motor of the adjustable pump has the following form:

$$\nu_{kr} = \sqrt{\frac{(\rho n^2 + h)}{(1 + \rho n^2)}} \tag{18}$$

Figure 8 shows the curves of changes in the relative critical rotation frequency depending on the number of simultaneously operating PUs. So, it is obtained that the range of adjustment of the adjustable unit rotation frequency is noticeably narrowed when there is one adjustable and several n non-adjustable PUs working in parallel on PA with equal values of head H_0 and internal resistance R_b. So, for D2000-100 pumps at $n = 1$, $\rho = 4.33$, $h = 0.6$, the value of the relative critical frequency of rotation of the adjustable unit $\nu_{\mathrm{kr}} = 0.96$; at $n = 2$ and the same parameters of the network, $\nu_{\mathrm{kr}} = 0.989$; at $n = 3 - \nu_{\mathrm{kr}} = 0.995$, etc. Thus, the performed analysis revealed that with an increase in the number of operating units, the range of adjustment of the frequency of rotation of the pump impeller significantly decreases.

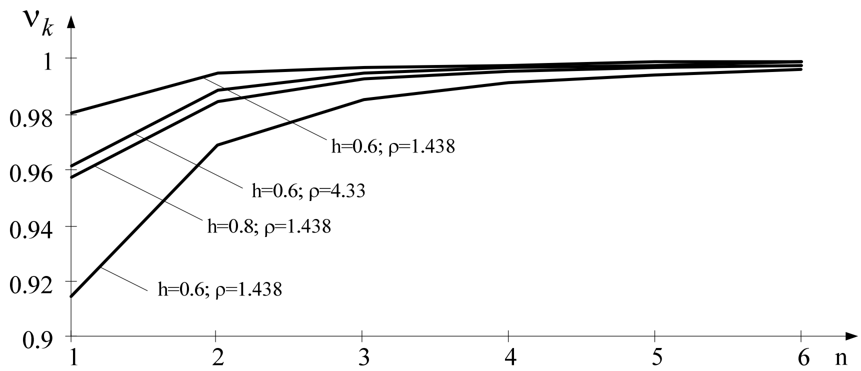


Figure 8. Curves of changes in the relative critical rotation frequency depending on the number of simultaneously operating PUs.

Analytical expressions for determining the lower (critical) limit ν_{kr} of the changes in the relative frequency of rotation of the pump for the circuit of series turbo mechanism connections are obtained in a similar way (Table 1).

Table 1. Analytical expressions for determining ν_{kr}.

PU individual operation	$\nu_{kr} = \sqrt{h}$, where $h = \frac{H_{st}}{H_0}$; $\rho = \frac{R_{net}}{R_p}$;
PU parallel operation:	
– Two identical pumps – Two PUs with different parameters – n PUs operating simultaneously	$\nu_{kr} = \sqrt{\frac{(\rho+h)}{(1+\rho)}}$; $\nu_{kr} = \sqrt{\frac{(\rho+h_1)}{h_2(1+\rho)}}$, where $h_1 = \frac{H_{st}}{H_{01}}$; $h_2 = \frac{H_{02}}{H_{01}}$; $\rho = \frac{R_{net}}{R_p}$; $\nu_{kr} = \sqrt{\frac{(\rho n^2+h)}{(1+\rho n^2)}}$;
PU series operation:	
– Two identical pumps – Two PUs with different parameters – n PUs operating simultaneously	$\nu_{kr} = \sqrt{\frac{(1-h)}{(1+\rho)}}$; $\nu_{kr} = \sqrt{\frac{[\varepsilon(1-h)]}{[\xi(1+\rho)]}}$, where $\varepsilon = \frac{H_{01}}{H_{02}}$; $\xi = \frac{R_{p1}}{R_{p2}}$. $\nu_{kr} = \sqrt{\frac{(n-h)}{(n+\rho)}}$, where $h = \frac{H_{st}}{H_{01}}$; $\rho = \frac{R_{net}}{R_{p1}}$;

As a result of the conducted research, it is possible to determine the necessary range of regulation of the pump rotation frequency for various connection circuits (parallel or series) of the PU, and a different number n of simultaneously operating turbo machines on a pipeline network with time-varying parameters, which makes it possible to substantiate the choice of an appropriate circuit of a variable-frequency ED. Thus, with the parallel operation of pump units, the required range of rotation frequency adjustment is no more than 10% below the rated one. With an increase in the number of operating turbo machines and with an increase in the parameters of the pipeline system, it narrows significantly—to fractions of a percent. This indicates the impracticality of introducing a frequency-regulated electric drive. In this case, a more effective scheme of the adjustable electric drive is to change the supply voltage using a thyristor voltage regulator. With the series operation of the pumps, the technological range of adjusting the speed of the turbo mechanism in order to change the head from the maximum value to zero is much wider and is 60–70% below the rated speed. Thus, the most effective way of regulating the operating modes of the PU is smooth and automatic, according to the dictating technological parameter, and the change in the rotation frequency of the pump motor with the necessary parameters of the starting and start-up control characteristics, which leads to the wide use of adjustable and start-controlled electric drives of pump complexes.

In addition to the above, it should be noted that under the condition when $\nu < \nu_{kr}$, the discharge (head) created by the adjustable pump with PUs connected in parallel (series) becomes less than zero. Then, the hydraulic power of the adjustable pump is also negative. This means that the pump goes into turbine mode. In this case, the range of regulation of PU performance is expanding.

Taking into account the above, the analysis of the operation of the pump as a turbine and the drive in the energy recovery mode is of interest in the tasks of expanding the control possibilities of pump complexes of various purposes, increasing the controllability of pumping stations in non-stationary modes of operation [30,31].

The obtained theoretical results are confirmed by experimental research on the basis of the PU physical model whose description and technical characteristics are given in [15].

4. Conclusions

Electric equivalent circuits for pump assemblies, based on the method of electrohydraulic analogy, and taking into account the connection circuit and parameters of pumping units, the configuration of the pipeline network, as well as the method of regulating technological parameters, have been proposed. This makes it possible to determine the head and discharge at any point of the hydraulic network, as well as the head and power losses at the elements of the pump complex.

The method for determining the characteristics of pump units when changing the frequency of rotation of the drive electric motor of one of the turbo mechanisms as part of group pump assemblies operating on a pipeline network with back pressure has been developed. This has enabled the determination of the limits of energy-efficient control of the technological parameters of the pump unit with a variable-frequency electric drive.

The analytical expressions for determining the range of regulation of the pump rotation frequency with different connection circuits (parallel or series) of pump units, changing the number of turbo machines operating at the same time on a pipeline network with different parameters, have been obtained. The analysis of common modes of operation of parallel and serially connected pump units allowed the determination of the lower limit of the change in the frequency of rotation of the pump, upon reaching which the hydraulic machine can be transferred to the turbine mode. This makes it possible to expand the regulatory and protective properties of the group electric drive systems of pump assemblies when changing the direction of the rotation frequency and liquid reversal in the event of an emergency power outage.

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