Mykhaylo ZAGIRNYAK, Tetyana KORENKOVA, Iuliia ALIEKSIEIEVA

Kremenchuk Mykhailo Ostrohradskyi National University

Energy and resource saving control system for pumping station

***Abstract**. Energy and resource saving control system for pumping station is offered. Its formation is based on a complex approach to the estimation of power processes in all the elements of power channel, taking into account the real conditions of consumer operation and changing operating characteristics of hydraulic equipment. The system enables substantiation of the choice of power efficient operation conditions and expedience of hydraulic equipment further operation.*

***Streszczenie.** Artykuł dotyczy zagadnienia oszczędności energii I zasobów w stacji pomp, poprzez zastosowanie proponowanego systemu sterowania. Przy jego opracowywaniu zastosowano złożony sposób estymacji procesów energetycznych, biorący pod uwagę zarówno rzeczywiste warunki poboru przez odbiorcę jak i zmienną charakterystykę pracy urządzeń hydraulicznych. (**Oszczędzający energię i zasoby system sterowania dla stacji pomp**).*

Keywords: power conditions, pumping station, power losses distribution, power efficiency.
Słowa kluczowe: warunki energetyczne, stacja pomp, rozkład strat mocy, sprawność energetyczna.

Introduction

Pumping stations (PS) of water supply systems present a complicated electro-hydraulic system including a distribution network, pumping unit (an electric motor with a pump on a shaft), pipe fitting, a manifold pipeline system.

Operation conditions of water supply and drainage systems PS are determined by the schedule of consumption of the operating environment by consumers, constantly changing and depending on the population, enterprises routine of work, climatic conditions, season, day of the week, time of the day, etc [1].

To bring a pumping unit (PU) operating conditions in conformity with the current water consumption the change of the pump driving motor rotation frequency has been recently used more and more often. Controlled electric drive systems provide up to 10-50 % of energy saving, smooth variation of PU technological parameters, decrease of leakage [1, 2]. However, introduction of controlled electric drive alone does not result in the maximum effect.

Problem Statement

The purpose of the work consists in creation of energy and resource saving control system for PS providing energy-efficient PU power conditions taking into account the time-varying water consumption curve and operating characteristics of hydraulic equipment.

Research Method

Creation of PS energy and resource saving control system (ERSCS) (Fig. 1) is based on a complex approach to the estimation of power processes in all the elements of power channel, taking into consideration the method of regulation of capacity, water consumption schedule, changed operating characteristics of the pump and pipeline system [3].

The offered PS ERSCS provides the possibility to substantiate the expediency of hydraulic equipment further operation and to choose power efficient operating conditions by means of the power and technical and economic indices analysis in an ideal (with catalog operating head-flow and power characteristics) and a real (with factual operating head-flow and power characteristics) electromechanical complexes.

Master control formed by block 6 (Fig.1) of the model of water consumption predicted daily curve is described by a multifactor regressive dependence:

$$Q(t) = K + a_1 p_{cp}(t) + a_2 K_h(t) + a_3 K_{wd}(t) + \\ + a_4 K_{ys}(t) + a_5 T(t) + a_6 p_0(t) + a_7 S(t) + a_8 K_{br}(t) \tag{1}$$

where: K – model constant coefficient; $a_1,...a_8$ – regression coefficients; p_{cpp} – pressure in the consumer's pipeline, atm; K_t – day time coefficient; K_{wd} – week day coefficient; K_{ys} – year season coefficient; T – air temperature, ^oC; p_0 – atmospheric pressure, mm Hg; S – rainfall, mm; K_{br} – breakdown rate coefficient.

Two methods of technological parameter regulation: PU rotation frequency variation and throttling are used to match PS conditions and water consumption schedule in PS ERSCS.

In this connection block 4 presenting formation of predicted control actions assigns:

time dependence of relative rotation frequency variation

$$\nu(t) = \frac{-B_2 Q(t) + \sqrt{B_2^2 Q^2(t) - 4A_2(C_2 Q^2(t) - R_p Q^2(t))}}{2A_2}$$

where: A_2, B_2, C_2 – approximation coefficients depending on centrifugal machine design peculiarities and determined according to pump catalog head-flow characteristic $H(Q)$; R_p – system hydrodynamic resistance,

valve hydrodynamic resistance dependence on time

$$R_V(t) = A_2 + B_2 Q(t) - H_s / Q^2(t) + C_2 - R_p$$

where: H_s – system static head.

PS power model block includes an ideal object model and a real object model (sign «′» is used in characteristic parameter designation). Power parameters are determined here when capacity is regulated by PU rotation frequency variation (index «ν» is used in parameter designation) and by liquid flow throttling in pressure header (index «r» is used in parameter designation).

Then pump shaft power

$$P_{sh\nu} = A_3 \nu^2 Q + B_3 \nu Q^2 + D_3 \nu^3;$$
$$P'_{sh\nu} = A'_3 \nu^2 Q + B'_3 \nu Q^2 + D'_3 \nu^3; \tag{2}$$
$$P'_{shr} = A_3 Q + B_3 Q^2 + D_3$$

where: A_3, B_3, D_3, A'_3, B'_3, D'_3 – approximation coefficients depending on centrifugal machine design peculiarities and determined according to catalog and factual pump power $P(Q)$ characteristic.

Hydraulic power at pump output

$$P_{ucp\nu} = \rho g Q H_\nu; \; P'_{ucp\nu} = \rho g Q H'_\nu; \tag{3}$$

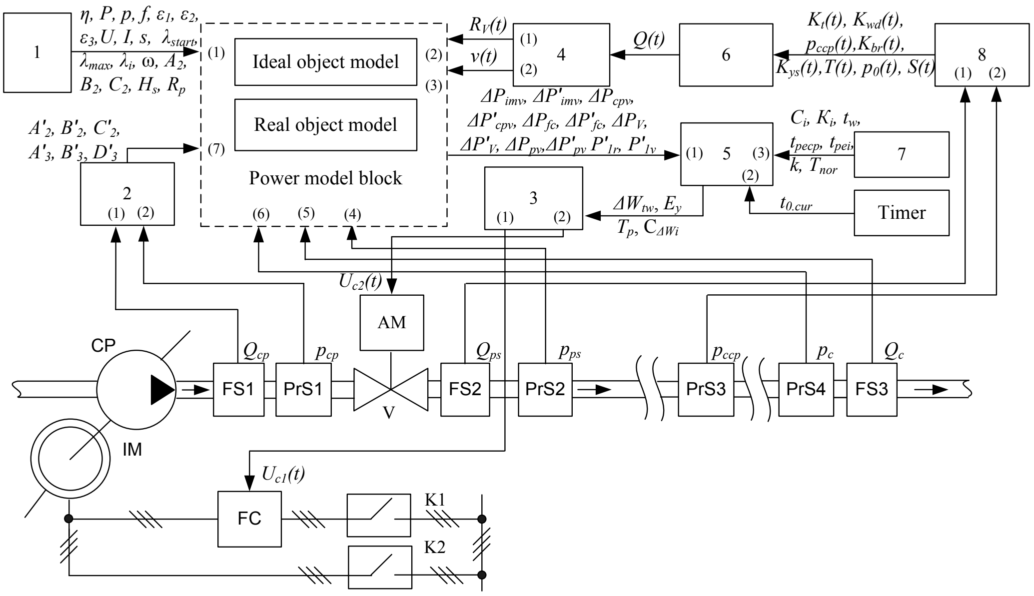

Fig. 1. Block diagram of PS energy and resource saving control system: CP – centrifugal pump; IM – induction motor; K1, K2 – switches; V – electrified valve; AM – valve actuating mechanism; FS1…FS3 – flow sensors; PrS1…PrS4 – pressure sensors; FC – frequency converter, 1 – PS parameter assignation block; 2 – block of pump factual operating characteristics determination; 3 – control and decision-making device; 4 – block of predicted control actions formation; 5 – block of technical and economic parameters determination; 6 – block of the model of water consumption predicted daily curve; 7 – block of economic parameters assignation; 8 – block of PS statistic parameters

$$P_{ucpr} = \rho g Q H_r \; ; \; P'_{ucpr} = \rho g Q H'_r .$$

where: ρ – fluid density; g – gravitational acceleration; $H_v=A_2v^2+B_2vQ+C_2Q^2$, $H'_v=A'_2v^2+B'_2vQ+C'_2Q^2$, $H_r=A_2+B_2Q+C_2Q^2$, $H'_r=A'_2+B'_2Q+C'_2Q^2$ – head-flow $H(Q)$ pump characteristics; A'_2, B'_2, C'_2 – approximation coefficients depending on centrifugal machine design peculiarities and determined according to factual head-flow $H(Q)$ pump characteristic.

PS output hydraulic power

(4) $$P_{ups\,v} = P_{ucp\,v} = \rho g Q H_v \; ; \; P'_{ups\,v} = \rho p_{ps} Q_{ps} \; ;$$

$$P_{upsr} = \rho g Q (H_r - \Delta H_V) \; ; \; P'_{upsr} = \rho g Q (H'_r - \Delta H'_V)$$

where: $\Delta H_V=H_1-H_s-R_pQ^2_1$, $\Delta H'_V=H'_1-H_s-R_pQ^2_1$ – valve head losses; H_1, Q_1 – head and capacity corresponding to throttle position with hydraulic resistance equal to R_V.

Hydraulic power in consumer network

(5) $$P_{uc\,v} = P_{ups\,v} - \Delta P_{p\,v} \; ; \; P'_{uc\,v} = \rho p_c Q_c$$

where: $\Delta P_{pv}=\rho g Q \Delta h_l/1000$ – power losses at the pipeline section; $\Delta h_l=\lambda l v^2/(2gd)$ – length head losses; λ – hydraulic resistance coefficient (Darcy coefficient) depending on the fluid flow condition; d – pipeline diameter; l – pipeline length; v – average fluid velocity.

IM total power losses

(6) $$\Delta P_{\Sigma im\,v} = \Delta P_{s\,v} + \Delta P_{cop\,v} + \Delta P_{mech\,v} \; ;$$

$$\Delta P'_{\Sigma im\,v} = \Delta P'_{s\,v} + \Delta P'_{cop\,v} + \Delta P'_{mech\,v} \; ;$$

$$\Delta P'_{\Sigma imr} = \Delta P_{sn} + \Delta P'_{copr} + \Delta P_{mechn}$$

where: $\Delta P_{s\,v}$, $\Delta P'_{s\,v}$, $\Delta P_{s\,n}$, $\Delta P_{cop\,v}$, $\Delta P'_{cop\,v}$, $\Delta P_{cop\,r}$, $\Delta P_{mech\,v}$, $\Delta P'_{mech\,v}$, $\Delta P_{mech\,n}$ – current and rated power losses in steel, copper and mechanical power losses in IM.

CP power losses

(7) $$\Delta P_{cp\,v} = P_{sh\,v} - P_{ucp\,v} \; , \; \Delta P'_{cp\,v} = P'_{sh\,v} - P'_{ucp\,v} \; .$$

Valve hydraulic power losses

(8) $$\Delta P_V = P_{ucpr} - P_{upsr} \; , \; \Delta P'_V = P'_{ucpr} - P'_{upsr} \; .$$

Hydraulic power losses at the pipeline section

(9) $$\Delta P_{p\,v} = P_{ups\,v} - P_{uc\,v} \; , \; \Delta P'_{p\,v} = P'_{ups\,v} - P'_{uc\,v} \; .$$

FC total power losses

(10) $$\Delta P_{\Sigma fc} = \Delta P_{rec} + \Delta P_{in} + \Delta P_{tr} \; ,$$

$$\Delta P'_{\Sigma fc} = \Delta P'_{rec} + \Delta P'_{in} + \Delta P'_{tr}$$

where: ΔP_{rec}, $\Delta P'_{rec}$, ΔP_{in}, $\Delta P'_{in}$, ΔP_{tr}, $\Delta P'_{tr}$ – power losses at inverter, rectifier and transformer of FC, respectively.

Power consumed by PU when rotation frequency is regulated

(11) $$P'_{1v} = P'_{sh\,v} + \Delta P'_{\Sigma im\,v} + \Delta P'_{\Sigma fc} \; .$$

Power consumed by PU when fluid flow is regulated in the pressure header by throttling

(12) $$P'_{1r} = P'_{shr} + \Delta P'_{\Sigma imr} + \Delta P'_V \; .$$

Block 5 of technical and economic parameters determination calculates:

electric power economy when capacity is regulated by variation of PU rotation frequency and throttling the fluid flow in the pressure header during time t_w of operation in the calendar year

(13) $$\Delta W_{tw} = (P'_{1r} - P'_{1v}) t_w \; ;$$

explicit costs of power losses in the *i*-th PS element (in IM $C_{\Delta Wim}$, $C'_{\Delta Wim}$, FC $C_{\Delta Wfc}$, $C'_{\Delta Wfc}$, CP $C_{\Delta Wcp}$, $C'_{\Delta Wcp}$, valve $C_{\Delta WV}$, $C'_{\Delta WV}$, pipeline $C_{\Delta Wp}$, $C'_{\Delta Wp}$) during time t_{pei}, corresponding to the assigned period of estimating the change of operating characteristic of PS *i*-th element

(14) $$C_{\Delta W_i} = k t_{pei} \Delta P_i \; ; \; C'_{\Delta W_i} = k t_{pei} \Delta P'_i \; .$$

In control and decision-making device 3 the explicit costs of power losses for PS *i*-th element in real $C'_{\Delta Wi}$ and ideal $C_{\Delta Wi}$ objects models are compared with the cost C_i of new PS equipment.

Under condition of $(C'_{\Delta Wi}-C_{\Delta Wi}) \geq C_i$ a decision is taken to substitute PS *i*-th element for a new one.

Under condition of $(C'_{\Delta Wi}-C_{\Delta Wi}) \leq C_i$ annual saving rate E_y and pay-off period T_p are calculated.

When $T_p \leq T_{nor}$, where T_{nor} – rated pay-off period, a decision is taken about regulation of the output by variation of rotation frequency and a control action $U_{c1}(t)$ is formed on FC to provide the required water consumption curve $Q(t)$.

When $T_p \geq T_{nor}$ – capacity is regulated by throttling the fluid flow in the pressure header and a control action $U_{c2}(t)$ on the valve V actuator is formed to provide water consumption $Q(t)$ required curve.

Modeling Results

Estimation of PS ERSCS efficiency is made on a PS mathematical model with rated pumping capacity of Q_n =0.556 m^3/s; head of H_n = 100 m; power of P_n = 800 kW.

Water consumption curve $Q(t)$ is a task signal. Technological parameter regulation is carried out by formation of control actions on FC $v(t)$, when pump electric motor rotation frequency changes, and on valve actuator $R_V(t)$ when fluid flow is throttled at the pump output.

FC is determined by a first order aperiodic link with formation of a square law of voltage and frequency change $U/f^2=const$; IM is presented by a mathematical model in $u, v, 0$ – coordinates [4].

The pump is determined by a differential equation taking the turbomechanism inertia into consideration:

$$T_{cp}dH_{ps}(t)/dt + H_{ps}(t) = k_{cp}H_{cp}(t), \quad (15)$$

where: k_{cp}, $T_{cp}=J_{cp}\omega_n/M_n$ – pump transfer constant and time constant, respectively; J_{cp} – pump inertia moment; ω_n – PU rated angular velocity; M_n – motor rated moment; H_{ps} – head at PS output.

When hydrodynamic network is modeled, a principle of electric hydraulic analogy is used. This principle is based on the solution of wave equations and reducing them to difference dependences [4]:

$$\begin{cases} H_{ps} - H_1 + l_0 l_{p1} dQ_{ps}/dt + r_0 l_{p1} Q_{ps}\left|Q_{ps}\right| = 0; \\ dH_{ps}/dt + c_0(Q_{ps} - Q_1)/l_{p1} = 0; \\ H_1 - H_c + l_0 l_{p2} dQ_1/dt + r_0 l_{p2} Q_1\left|Q_1\right| = 0; \\ dH_1/dt + c_0(Q_1 - Q')/l_{p2} = 0; \end{cases} \quad (16)$$

where: $r_0=\lambda/(2gS^2d)$ – specific hydraulic resistance of the pipeline section; $c_0=c^2/(Sg)$, $l_0=1/(Sg)$ – pipeline specific parameters; $\lambda=0.11(k_e/d)^{0.25}$ – dimensionless coefficient of pipeline resistance; k_e – coefficient of pipe irregularity; $S=\pi d^2/4$ – cross-section area; c – speed of sound propagation in the medium (for water c=1450 m/s); l_{p1}, l_{p2} – pipeline first and second sections length, respectively; H_{ps}, H_1, H_c – head at PS output, at the first section output and at the consumer; Q_{ps}, Q_1, Q' – capacity at PS output, at the first section output and at the consumer.

Fig. 2 shows curves representing capacity changes at PS ERSCS input $Q(t)$ and output $Q_c(t)$, as well as controlled parameters $v(t)$, $R_V(t)$.

PS ERSCS mathematical model allows estimating distribution of power losses in all the links of technological complex with different systems of capacity regulation and changed operating characteristics of the pump.

Fig. 3 shows power losses curves when capacity is regulated by variation of rotation frequency with the catalog and changed characteristics of the pump (Fig. 3,a) and by throttling (Fig. 3,b).

Integral indices of the considered conditions are demonstrated by the diagram of PS power losses distribution (Fig. 4). Its analysis resulted in determination of components with the largest energy-saving reserve.

It was found out that, when capacity is regulated within 60 % down from the rated one by variation of rotation frequency (Fig.3, 4, a), PS total relative power losses are 15 % lower than when the fluid flow is throttled at the pump output (Fig.3, 4, b). The largest decrease of power losses are at the pump and the valve. The calculated pay-off period of the proposed system is 1.4 years.

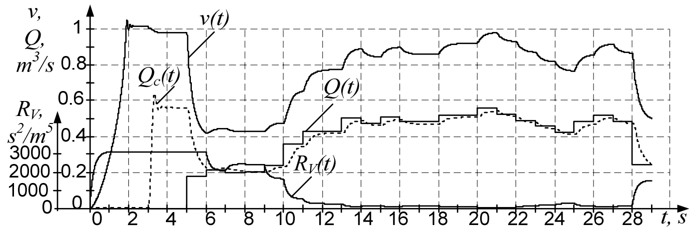

Fig. 2. Curves of capacity change at PS ERSCS input $Q(t)$ and output $Q_c(t)$, controlled parameters $v(t)$, $R_V(t)$ of PS

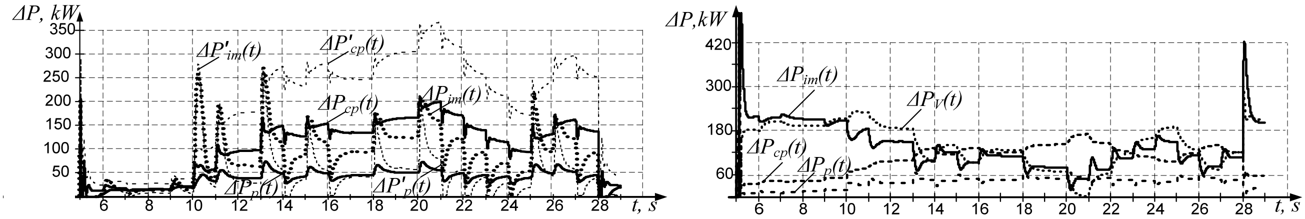

Fig. 3. Curves of power losses change when capacity is regulated by the variation of rotation frequency with catalog and changed operating characteristics of the pump (a) and by throttling (b)

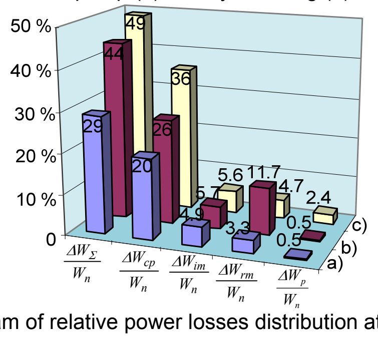

Fig. 4. Diagram of relative power losses distribution at PS elements: ΔW_Σ – PS total power losses; ΔW_{cp}, ΔW_{im}, ΔW_{rm}, ΔW_p – power losses at centrifugal pump, induction motor, due to regulation method, at pipeline, respectively; ΔW_n – induction motor rated losses

The analysis also showed that when the pump current operating characteristics deviate (up to 10 %) from the catalog ones due to wear (Fig. 4, c), it is expedient to change the pump as a new pump pay-off period does not exceed half a year.

Experimental verification

Fig. 5 shows a general view of a hydrotransport unit laboratory model including two centrifugal pumps equipped with three-phase IM with power consumption of 830 W each. With the aim of variation of impeller rotation frequency PU is equipped with a low-voltage three-phase FC. Regulating valves are installed in discharge and suction tubes of corresponding PU. Pressure at the pump output and in the pipeline is controlled by pressure sensors. To measure fluid flow in the laboratory complex a two-channel ultrasonic fluid meter is used.

Fig.5. General view of the hydrotransport unit physical model

Analysis of power processes in the hydrotransport unit power channel is carried out for the cases when PS parameters are regulated by throttling the fluid flow at the PU output and by variation of rotation frequency of the turbomechanism impeller in accordance with the assigned water consumption diagram (Fig.6).

It follows from the analysis of the obtained diagram of power and power losses distribution in hydrotransport unit (Fig. 7) that during operation according to the assigned day water consumption diagram (Fig. 2, diagram 1) with the depth of capacity regulation equal to 50% down from the rated (t_1+t_5=7 h) by variation of rotation frequency (Fig. 7, a) power consumption by hydrotransport unit P_1 is 15% lower than by throttling fluid flow at the pump output (Fig. 7, b). During operation according to water consumption curve (Fig. 6, diagram 2) with longer operation time (t_1+t_5=11 h) at the same depth of capacity regulation power consumption by hydrotransport unit is 25 % less.

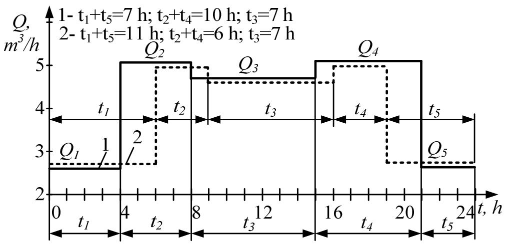

Fig. 6. Day water consumption diagrams: $Q_1...Q_5$ – water flow values at time moments $t_1...t_5$

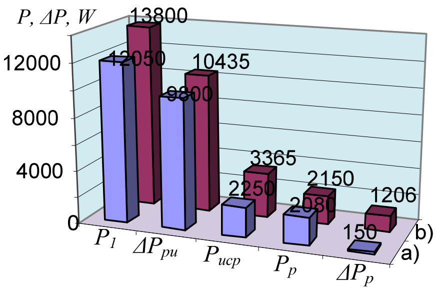

Fig. 7. Distribution of power and power losses in PS during operation according to water consumption diagram

As a result it was obtained that the greatest effect of energy and resource saving from frequency regulation can be seen in PU and in the pipeline; power losses ΔP_{pu} and ΔP_p are 1.1 and 8 times less, respectively.

Variation of pump operation characteristics on a physical model was made by changing the position of regulating valve installed in the turbomechanism suction tube. It allows shifting the operating point on pump characteristic $H(Q)$ and reducing head ΔH by 7 % from rated. The latter results in redistribution of power losses in hydrotransport unit (Fig. 9), power consumption growth by 12 %. With greater head reduction (up to 17 %) power consumption grows by 32 %.

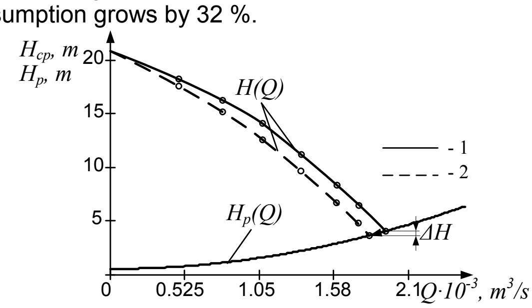

Fig.8. Head-flow pump catalog (1) and varied (2) operation characteristics

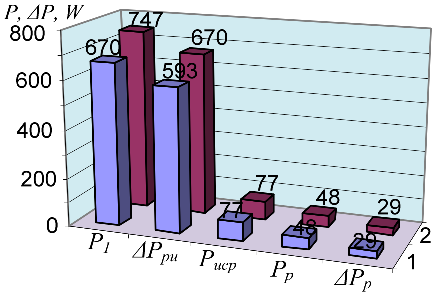

Fig. 9. Distribution of power and power losses in PS

Carried out experimental research confirms expediency of the complex approach to control of power conditions of municipal engineering PS, taking into consideration equipment time-variable operation characteristics, real consumer operating schedule, method of technological parameters control.

Conclusions

The proposed energy and resource saving control system for pumping station makes it possible:

to analyze the power and technical and economic indices for substantiation of the choice of the effective regulation method and the expediency of further operation of the hydraulic equipment;

to provide the required technological regulation law – hydraulic network pressure stabilization when the schedule of water consumption changes;

to predict the pump station water and power consumption for different variants of technological parameters regulation (by throttling, variation of rotation frequency, step-by-step control, combined control).

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***Authors**: rector of Kremenchuk Mykhailo, Ostrohradskyi National University and the Chairman and the Professor of Electric Machines Department Mykhaylo Zagirnyak, Pervomayskaya str. 20, Kremenchuk, Ukraine, 39600, E-mail: mzagirn@kdu.edu.ua; associate professor of Electric Drive and Control Systems Department Tetyana Korenkova, E-mail: tanyakorenkova@inbox.ru., assistant of Electric Drive and Control Systems Department Iuliia Alieksieieva, E-mail: aljual@mail.ru.*