1. Tetyana KORENKOVA[1], 2. Viktoriya KOVALCHUK[2], 3. Oleksandr SERDIUK[3], 4. Mohamed Zaidan Qawaqzeh[4]

Kremenchuk Mykhailo Ostrohradskyi National University (1)-(3)
Al-Balqa' Applied University (4)
ORCID: 1. 0000-0001-6425-8367; 2. 0000-0001-8013-6431; 3. 0000-0003-1532-4043; 4. 0000-0001-7027-5577;

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The system of the pumping plant hydrodynamic protection in the event of an emergency shutdown of the power supply

Abstract. *The structure of the system of hydrodynamic protection of the pumping plant in the event of an emergency shutdown of the power supply is proposed. The mathematical apparatus for determining the size of capacitive storage devices and the power of an active energy regulator is presented. A comparative analysis of time diagrams of the operation of the pumping plant during a sudden interruption of the power supply without capacitive storage devices and in their presence as part of the hydrodynamic protection system is performed.*

Streszczenie. *Zaproponowano konstrukcję systemu poprawy sterowności przepompowni w przypadku awaryjnego zaniku zasilania. Podano aparat matematyczny do określania wielkości zasobników pojemnościowych oraz mocy aktywnego regulatora energii. Dokonano analizy porównawczej przebiegów czasowych pracy przepompowni podczas nagłej przerwy w zasilaniu bez zasobników pojemnościowych i z ich obecnością w ramach zabezpieczenia hydrodynamicznego. (**System ochrony hydrodynamicznej pompowni w przypadku awaryjnego wyłączenia zasilania**)*

Keywords: pumping plant, emergency state, hydrodynamic protection, capacitive storage devices, hydro-turbine unit.
Słowa kluczowe: przepompownia, praca awaryjna, ochrona hydrodynamiczna, magazyny pojemnościowe, zespół hydroturbinowy.

Introduction

Mine water discharge facilities, communal water supply and drainage pumping plants (PP) belong to the first category of reliability facilities and are recognized as vital objects that do not allow a long interruption in operation [1].

A sudden disconnection of the electric drive (ED) of the pump from the power grid without previously closing the head stopcock or disc valve in the pipeline is one of the most negative consequences of emergency modes during PP operation. This causes long downtimes of pumping equipment, a decrease in efficiency and an imbalance of pump units (PU); the occurrence of high or low pressure waves in pumping mains; destruction of shut-off and regulating and safety fittings, pipeline networks, increased vibration of hydrodynamic equipment [2], [3].

The analysis [4], [5] revealed that in most cases the hydroprotection of water supply PP and water drainage installations by discharging part of the transported liquid is the most common method of artificially reducing the pressure due to the surge during emergency interruptions in the power supply. This function is performed by safety valves, rupture membranes, and overflow columns. Such means of hydraulic protection are characterized by actuation upon the fact of an accident, and their alternate opening/closing contributes to the maintenance of shock pressure in the system.

To implement the means of hydrodynamic protection of PP, reduce dynamic loads in the pipeline network, it is promising to use variable-frequency ED of the pumps and shut-off and adjustable valves, build automatic control systems based on them [6]–[10]. It should be noted that recently there have been many papers devoted to the development of control systems for asynchronous ED with asymmetry of stator windings [11], damages in the electrical circuit [12], and the creation of autonomous power supplies for electromechanical systems [13]. However, there are no solutions for the formation of ED protection devices from emergency modes, taking into account the peculiarities of the operation of technological mechanisms.

Taking into account the above, the search for effective methods of increasing PP controllability and protection in the event of a sudden interruption in the power supply is topical.

Research method

The issue of analyzing dynamic modes in the PP during a sudden power outage, determining the hydraulic system parameters in non-stationary modes is considered in [14], [15].

In Fig. 1 solid lines represent the curves of changes in PP parameters during a sudden interruption of the power supply. At a steady state of operation (Fig. 1, I-st section), the parameters at the pump output are equal to the rated ones, the pump moment of resistance is equal to the electric motor driving torque. At time moment t_1 there is a sudden shutdown of PP power supply. In pump ED system the electromagnetic torque drops to zero almost instantly, while the hydraulic moment on the impeller is preserved, which causes a decrease in the frequency of the rotor rotation, the supply and head of the pump (Fig. 1, IInd section). At time moment t_2 corresponding to zero discharge there is a change in the direction of liquid movement in the pipeline and in PU.

In the counterflow mode (Fig. 1, IIIrd section), the impeller is braked by the reverse flow, the pressure in the pressure pipeline increases. At time moment t_3 the rotor speed decreases to zero, and after an instant stop the rotor begins to accelerate in the opposite direction, the pump switches to turbine mode (Fig.1, IV-th section).

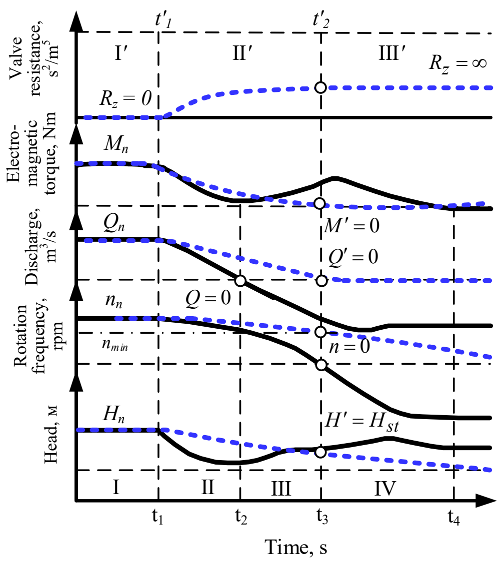

Fig. 1. Time diagrams of parameter changes during an emergency interruption in PU power supply

In order to exclude the appearance of surges in the system, the smooth stop of the PU and the gradual closing of the shut-off valves in the event of a sudden interruption in the power supply, a system of PP hydrodynamic protection with an emergency power source – a capacitive storage device and an active damper of the energy of the hydraulic flow is proposed. Its block diagram is given in Fig. 2. The principle of operation of the system consists in switching the power supply of the electric motors of the pump and the shut-off and regulating valve to capacitive storage devices installed in the power circuits of the corresponding EDs. At the same time, there is a simultaneous smooth decrease in the turbomechanism motor rotation frequency and the closing of the PU outlet stopcock without unacceptable pressure and discharge pulsations in the hydraulic system. The proposed system includes: centrifugal pump 1 with induction motor 2; switches 3, 4; frequency converters 4, 5 with DC intermediate links consisting of rectifiers 6, 7 with capacitive constant voltage filters $C1_p$, $C1_v$ and autonomous voltage inverters 9 and 10; shutter 11 with induction motor 12; pressure 13 and discharge 14 sensors at the pump outlet; two blocks 15, 16 for assigning the maximum allowable head value H_{max} and the minimum allowable discharge value Q_{min}, respectively; control device 18 with two computing blocks 20, 21 for determining the derivatives and direction of the change of head and discharge signals, as well as the time to reach the maximum allowable head value Δt_1 and the minimum allowable discharge value Δt_2 at the pump outlet, respectively; step-down transformer 24.

Voltage sensor 17 records the moment of PP power cut-off. Control device 18 with a built-in backup power source 19 forms control signals U_1, U_2 for keys 22, 23 to opeerate in the power circuits of the corresponding frequency converters and transfers the power supply of the electric drives of the pump and the outlet shutter to capacitive storage $C2_p$, $C2_v$. Control device 18 generates control signal U_3 on the autonomous voltage inverter 9 for smooth reduction of the rotation frequency of the pump electric motor and control signal U_4 on an autonomous voltage inverter 10 for smooth closing of the throttle valve without unacceptable pressure and discharge pulsations.

Consider the conditions for calculating the size of capacitive storage devices and the power of PP active regulator. In the event of a sudden power outage, when the pump supply drops sharply to zero, PU relative rotation frequency is equal to the minimum permissible rotation frequency of the electric motor of the regulated unit:

(1) $$\nu_{min} = \sqrt{H_{st}/H_0}$$

where H_{st} – static head; H_0 – the head developed by the pump at zero discharge.

Then the consumed power corresponds to the idling power of the turbomechanism, which is determined by the creation of pressure H_0 at zero performance, frictional losses in the bearings, pump impeller:

(2) $$P_0 = D_3 \nu_{min}^3$$

where D_3 – coefficient of approximation of the power characteristic of the pump (determined by the published data).

The closing time of the shut-off and regulating valve, which excludes the occurrence of a surge:

(3) $$t_{cl} \geq T_f$$

where $T_f = 2L/C_v$ – surge phase; L – pipeline length; $C_v = c_l \Big/ \sqrt{1 + \dfrac{\varepsilon}{E}\psi}$ – the speed of propagation of the shock wave at a constant along the diameter length and thickness of the pipeline wall; c_l – the speed of sound in liquid (for water c_l = 1425 m/s); ε – the modulus of volume elasticity of liquid (for cold water ε = 2.1×10^4 kgs/cm^2); E – the modulus of elasticity of the pipeline wall material (for steel E = 2.1×10^6 kgs/cm^2, for cast iron E = 1×10^6 kgs/cm^2); $\psi = d/\delta$ – the dimensionless coefficient that takes into account the deformability of the walls of the water pipe; d – pipeline diameter; δ – thickness of pipeline walls.

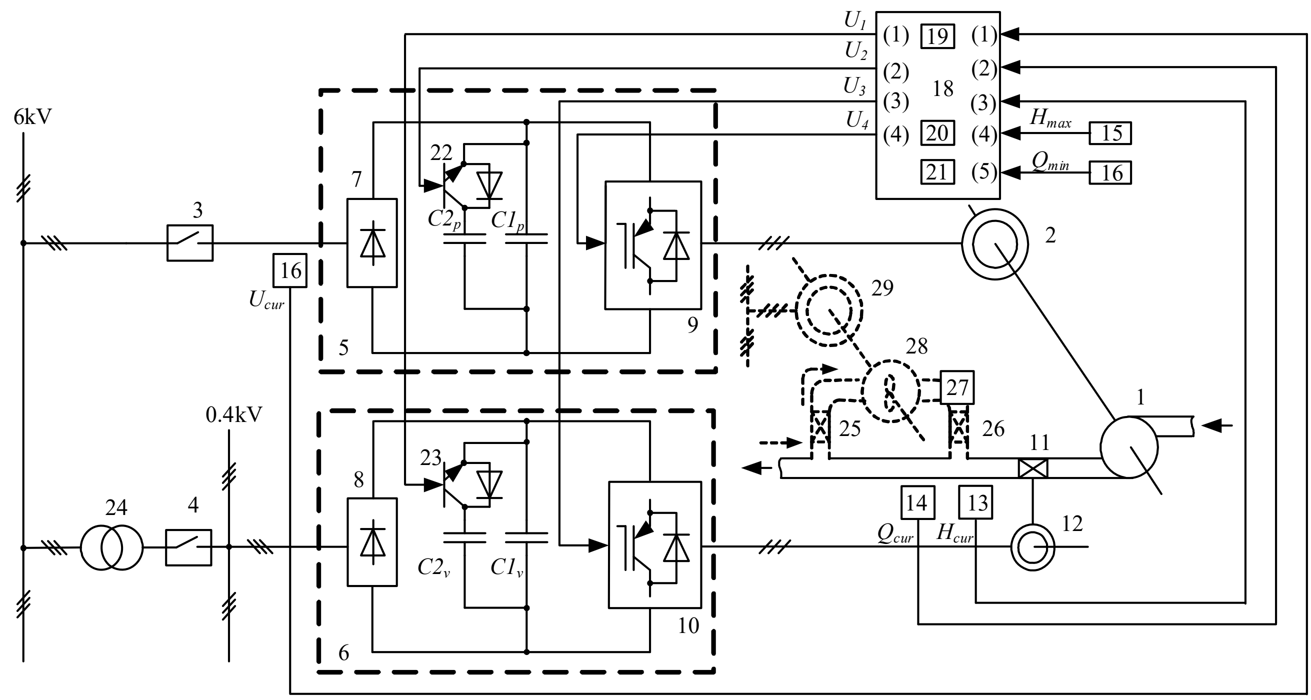

Fig. 2. Block diagram of the system of PP hydrodynamic protection in the event of an emergency shutdown of the power supply

The capacity of the storage devices is selected from the condition of maintaining the minimum permissible pump rotation frequency, which excludes the liquid counterflow mode. At the same time, the closing time of the shut-off and regulating valve must not be less than the shock phase in the pipeline to prevent the occurrence of a surge in the hydraulic system.

The energy required for a smooth PU stop:

(4) $$W_n = P_0 T_f \, .$$

The value of capacity of the storage device $C1_p$ in the power circuit of the pump ED:

(5) $$C1_p = 2W_p \big/ U_d^2$$

where $U_d = K_u U_f$ – the voltage supplied to the voltage inverter; K_u – circuit coefficient (for a three-phase bridge circuit $K_u = 3\sqrt{6}\big/\pi$ =2.34); $U_f = U_n \big/ \sqrt{3}$ – the current value of the voltage on the load; U_n – the voltage of the supply network (the rated voltage of the pump ED).

The value of capacity of the storage device $C2_v$ in the power circuit of the frequency converter of the shut-off and regulating valve ED:

(6) $$C2_v = 2W_v \big/ U_d^2$$

where $W_v = P_{edv} T_f$ – the energy required for the smooth closing of the shut-off and regulating valve; P_{edv} – the power of the electric motor of the shut-off and regulating valve.

The graphs of the joint operation of the pump assembly (PA) and the hydronetwork when the PA electricity is turned off are shown in Fig. 3, where: 1–1^{V} – PU head-discharge characteristics at different rotation frequencies; 2–$2^{/V}$ – the characteristics of the hydronetwork at various degrees of closure of the shut-off and regulating valve; 3–$3^{/V}$ – the curves of power consumed by PU.

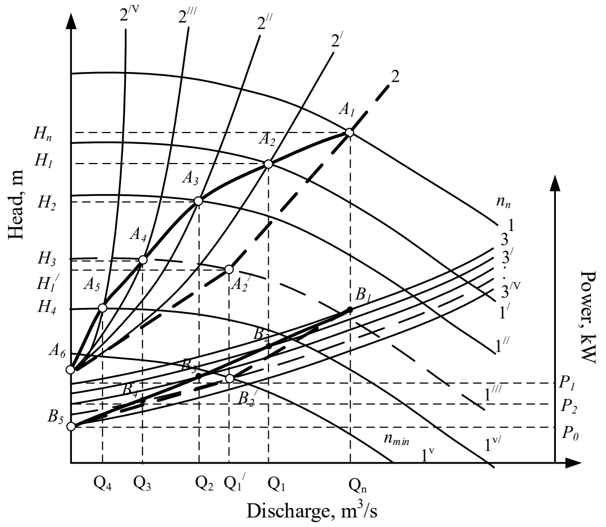

Fig. 3. PA characteristics when the electricity is turned off and the rotation frequency of the PU is reduced and the shut-off-regulating valve is closed

With a sharp decrease in PU rotation frequency (curves 1, $1^{///}$) without changing the degree of opening of the shut-off and regulating valve, the operating mode of the pump changes according to curve A_1–$A_2^{/}$–A_6 and is accompanied by sharp jumps in the change of pressure from H_n to H_1' and discharge from Q_n to Q_1' in the hydrosystem; at the same time, the power consumed by the pump will change along the curve B_1–$B_2^{/}$–B_5. With a simultaneous decrease in the rotation frequency (curves 1–1^{V}) and changing the position of the shut-off and regulating valve (curves 2–$2^{/V}$) the operating mode is described by curve A_1–A_2–A_3–A_4–A_5–A_6, that makes it possible to reduce the drops of pressure and discharge at PU outlet, at the same time, the power consumed by the pump will change along the curve B_1–B_2–B_3–B_4–B_5, where the lower value corresponds to the power of idling PU at the minimum permissible rotation frequency of mechanism n_{min} .

Time diagrams in a system with a capacitive storage device in case of a sudden interruption in the power supply are shown in Fig. 1 by dashed lines. At time moment t_1' there is a gradual decrease in the pump rotation frequency to the minimum permissible value, eliminating the counterflow of liquid, with the simultaneous closing of the shut-off and regulating valve (Fig. 1, *II′*-nd section). At the same time, a gradual decrease in the discharge to zero and a decrease in pressure to a value equal to the static head is observed, which corresponds to the time moment t_2' (Fig. 1). At the next moment of time, when the shut-off and regulating valve is completely closed $R_z = \infty$, there is a further smooth stop of PU without unacceptable head and discharge pulsations (Fig. 1, *III′*-rd section).

The completed analysis revealed that, for example, for water supply system PP with a D3200-75 type pump of power P_n = 800 kW, supply Q = 3200 m³/hour, head H = 75 m, rated voltage U_n = 6 kV, rated rotation frequency n_n = 980 rev/min, approximation coefficient D_3 = 420, minimum permissible relative pump rotation frequency $\nu_{min} = 0.667$; hydraulic network with counter-pressure H_{st} = 40 m, L = 5000 m, d = 0.8 m, C_v = 1015 m/s, T_f = 9.855 s; parallel shut-off and regulating valve with electric motor power $P_{edv} = 5.5$ kW the calculated value of the capacitive storage device in the variable-frequency ED of the pump $C1_p$ was 37 mF, in the power circuit of the valve ED – $C2_v$ – 1.65 mF.

In order to reduce the excess pressure at the pump outlet due to an emergency shutdown of the power supply in the system (Fig. 2) it is possible to use an active damper of the energy hydraulic flow in the system. For this purpose, a hydro turbine 28 with an induction machine 29 on the shaft is installed in the PP bypass pipeline (dashed line, Fig. 2). The main task of the hydroturbine unit is to damper the energy of the reverse wave of the liquid flow with subsequent recuperation into the power network. The parameters of the hydro turbine unit are regulated by the guide device 27 installed at the inlet of the hydro turbine. The obtained electricity can be used to supply PP auxiliary electrical equipment or additional charge of capacitive storage devices.

The head-discharge (*H-Q*) characteristic of the hydroturbine can be described by dependence of the form [10]:

(7) $$H_t = H_{0t} \nu_t^2 + \left(\frac{A}{\alpha} + B \right) \nu_t Q_t + \frac{R_{vt}}{\alpha^2} Q_t^2 \, .$$

Power on the turbine shaft:

(8) $$P_t = \rho g H_t Q_t \eta_t$$

where in expressions (7), (8): H_{0t}, R_{vt} – the head at zero discharge and internal resistance of the hydroturbine, respectively; A, B – approximation coefficients depending on the type of hydroturbine and its design features (determined according to the published characteristics of the hydroturbine); $\alpha_t = a_t / a_{opt\,t}$ – relative opening of the turbine guide apparatus; $\nu_t = n_t / n_{opt\,t}$ – the relative frequency of rotation of the turbine; $a_t, n_t, a_{opt}, n_{opt\,t}$ – current and optimal values of the opening of the guide apparatus and the frequency of rotation of the turbine wheel, respectively; H_t, Q_t – the head and discharge of the turbine; η_t – turbine efficiency; ρ – density of the working medium; $g = 9.81$ m/s^2 – acceleration of gravity.

The turbine head is assumed to be equal to the maximum possible head excess $\Delta H_{\max}$ in the pipeline when a surge occurs in the system: $H_t = \Delta H_{\max}$. The parameters and, accordingly, the power of the hydroturbine are regulated by changing the relative opening α of the guide device. At the same time, the relative frequency of rotation of the turbine remains unchanged $\nu = 1.0$. Then equation (7) takes the form:

$$\Delta H_{\max} = H_{0t} + \left(\frac{A}{\alpha} + B\right) Q_{cur} + \frac{R_{vt}}{\alpha^2} Q_{cur}^2 \tag{9}$$

where Q_{cur} – the current value of PA supply.

We find from the last expression:

$$\alpha_t\left(Q_{cur}, \Delta H_{\max}\right) = \frac{-AQ_{cur}}{2R_{vt}Q_{cur}^2} + \frac{\sqrt{A^2Q_{cur}^2 - 4R_{vt}Q_{cur}^2(BQ_{cur} + H_{ot} - \Delta H_{\max})}}{2R_{vt}Q_{cur}^2}. \tag{10}$$

So, in the event that the excess head in the mains pipeline amounts to $\Delta H_{\max} = (45..50)$ m, it is possible to select a radial-axial hydroturbine with power P_t = 180 kW, discharge Q_t = 1.48 m^3/s, rotation frequency n = 255 rev/min, efficiency $\eta_t = 0.934$, diameter D = 1 m, the optimal value of the opening of the guiding apparatus $a_{opt\,t} = 38$ mm.

Thus, the development of hydroprotection systems based on the means of a regulated ED, the possibility of research them using virtual laboratories [16] makes it possible to reduce the accident rate of electrical equipment and, accordingly, extend its service life.

Conclusions

The structure of the system of hydrodynamic protection of the pumping plant in the event of an emergency shutdown of the power supply has been proposed. The system makes it possible to prevent the occurrence of a surge in the pipeline, liquid counterflow and increased pressure pulsations by simultaneous control of the pump electric motor rotation frequency and the position of the throttle valve. In order to reduce dynamic loads in the pipeline network in the event of a sudden power outage, an active water flow energy damper based on an adjustable hydroturbine unit is switched.

Analytical expressions for calculating the value of capacity of the storage device in the power channel of the electric drive of the pump and the shut-off and regulating valve, as well as the power of the hydroturbine unit, have been obtained. The possibility of increasing the controllability of the electrohydraulic equipment of pumping plants in unsteady modes of operation has been demonstrated based on the obtained time diagrams and characteristics of the pump assembly.

Authors: Chairman of Electric Drive and Control Systems Department of Kremenchuk Mykhailo Ostrohradskyi National University Tetyana Korenkova, Pershotravneva str. 20, Kremenchuk, Ukraine, 39600, E-mail: tanya74kor@gmail.com; Senior lecturer of Electric Drive and Control Systems Department of Kremenchuk Mykhailo Ostrohradskyi National University Viktoriya Kovalchuk, Kremenchuk, Ukraine, 39600, E-mail: viktoriya_kovalch@ukr.net; Associate Professor of Electric Drive and Control Systems Department of Kremenchuk Mykhailo Ostrohradskyi National University Viktoriya Kovalchuk, Kremenchuk, Ukraine, 39600, E-mail: serduk@link.pl.ua; Associate Professor of Electrical and Electronics Engineering Department of Al-Balqa' Applied University Mohamed Zaidan Qawaqzeh, Maan, Jordan, E-mail: qawaqzeh@bau.edu.jo;

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