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 naglej 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 hydroturbiny.

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 wave in pumping mains; destruction of shut-off and adjustable valves, build automatic control 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 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, II-st 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](image-url)
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 a hydraulic motor 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 \( C_{1p}, C_{1t} \), 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 \( H_{\text{max}} \) and \( Q_{\text{min}} \), respectively; control device 18 with a built-in backup power source 19 forms control signals \( U_1, U_2 \) for keys 22, 23 to operate 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 \( C_{2p}, C_{2t} \). 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:

\[

v_{\text{min}} = \sqrt{\frac{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:

\[

P_3 = D_3 v_{\text{min}}^2
\]

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:

\[

t_{cl} \geq T_f
\]

where \( T_f = 2L/C_v \) – surge phase; \( L \) – pipeline length; \( C_v = c_l \sqrt{1 + \frac{\epsilon}{E}} \) – 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); \( \epsilon \) – the modulus of volume elasticity of liquid (for cold water \( \epsilon = 2.1 \times 10^4 \) kgs/cm²); \( E \) – the modulus of elasticity of the pipeline wall material (for steel \( E = 2.1 \times 10^6 \) kgs/cm², for cast iron \( E = 1 \times 10^6 \) kgs/cm²); \( \psi = d/d' \) – the dimensionless coefficient that takes into account the deformability of the walls of the water pipe; \( d \) – pipeline diameter; \( d' \) – 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:

\[ W_n = P_n T_f. \]

The value of capacity of the storage device \( C_{1p} \) in the power circuit of the pump ED:

\[ C_{1p} = 2W_p / U_n^2 \]

where \( U_d = K_u U_f \) – the voltage supplied to the voltage inverter; \( K_u \) – circuit coefficient (for a three-phase bridge circuit \( K_u = 3\sqrt{6/\pi} = 2.34 \)); \( U_f = U_n / \sqrt{3} \) – 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 \( C_{2s} \) in the power circuit of the frequency converter of the shut-off and regulating valve ED:

\[ C_{2s} = 2W_v / U_n^2 \]

where \( W_v = P_{adv} T_f \) – the energy required for the smooth closing of the shut-off and regulating valve; \( P_{adv} \) – 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’ – PU head-discharge characteristics at different rotation frequencies; 2–2’ – the characteristics of the hydronetwork at various degrees of closure of the shut-off and regulating valve; 3–3’ – the curves of power consumed by PU.

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 \( A_1 \rightarrow A_2 \rightarrow A_6 \) 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 \( B_1 \rightarrow B_2 \rightarrow B_3 \). With a simultaneous decrease in the rotation frequency (curves 1–1’) and changing the position of the shut-off and regulating valve (curves 2–2’) the operating mode is described by curve \( A_1 \rightarrow A_2 \rightarrow A_4 \rightarrow A_5 \rightarrow A_6 \), 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 \( B_1 \rightarrow B_2 \rightarrow B_3 \rightarrow B_4 \), where lower value corresponds to the power of 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 \( R_s = \infty \), 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 \( P_u = 800 \) kW, supply \( Q = 3200 \) m³/hour, head \( H = 75 \) m, rated voltage \( U_n = 6 \) kV, rated rotation frequency \( n_i = 980 \) rev/min, approximation coefficient \( D_t = 420 \), minimum permissible relative pump rotation frequency \( v_{min} = 0.667 \); hydraulic network with counter-pressure \( H_{pz} = 40 \) m, \( L = 5000 \) m, \( d = 0.8 \) m, \( C_i = 1015 \) m/s, \( T_f = 9.855 \) s; parallel shut-off and regulating valve with electric motor power \( P_{adv} = 5.5 \) kW the calculated value of the capacitive storage device in the variable-frequency ED of the pump \( C_{1p} \) was 37 mF, in the power circuit of the valve ED \( C_{2s} = 1.65 \) 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 dampen 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]:

\[ H_t = H_0 v_t^2 + \alpha + B) v_t Q_t + \frac{R_d}{\alpha^2} Q_t^2. \]

Power on the turbine shaft:

\[ P_1 = \rho g H_0 Q_t \eta_t \]

where in expressions (7), (8): \( H_0, R_d \) – 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

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.

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the hydroturbine); \( \alpha_i \) – relative opening of the turbine guide apparatus; \( \nu_i \) – the relative frequency of rotation of the turbine; \( \eta_i, \alpha_{opt}, \nu_{opt} \) – current and optimal values of the opening of the guide apparatus and the frequency of rotation of the turbine wheel, respectively; \( H_i, Q_i \) – the head and discharge of the turbine; \( \eta_i \) – turbine efficiency; \( \rho \) – density of the working medium; \( g = 9.81 \text{ m/s}^2 \) – acceleration of gravity.

The turbine head is assumed to be equal to the maximum possible head excess \( \Delta H_{\text{max}} \) in the pipeline when a surge occurs in the system: \( H_i = \Delta H_{\text{max}} \). The parameters and, accordingly, the power of the hydroturbine are regulated by changing the relative opening \( \alpha \) 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:

\[
\Delta H_{\text{max}} = H_{\text{th}} + \left( \frac{A}{\alpha} + B \right) Q_{\text{cur}}^2 + \frac{R_{\text{if}}}{\alpha^2} Q_{\text{cur}}^2
\]

where \( Q_{\text{cur}} \) – the current value of PA supply.

We find from the last expression:

\[
\alpha_i\left(Q_{\text{cur}}^2 \Delta H_{\text{max}}\right) = -\frac{AQ_{\text{cur}}^2}{2R_{\text{if}}Q_{\text{cur}}^2} + \frac{\sqrt{A^2Q_{\text{cur}}^4 - 4R_{\text{if}}Q_{\text{cur}}^2(BQ_{\text{cur}} + H_{\text{th}} - \Delta H_{\text{max}})}}{2R_{\text{if}}Q_{\text{cur}}^2}
\]

So, in the event that the excess head in the mains pipeline amounts to \( \Delta H_{\text{max}} = 45.50 \text{ m} \), it is possible to select a radial-axial hydroturbine with power \( P = 180 \text{ kW} \), discharge \( Q_i = 1.48 \text{ m}^3/\text{s} \), rotation frequency \( n = 255 \text{ rev/min} \), efficiency \( \eta_i = 0.934 \), diameter \( D = 1 \text{ m} \), the optimal value of the opening of the guiding apparatus \( \alpha_{opt} = 38 \text{ mm} \).

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 hydodynamic protection of the pump 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.

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