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The variable-frequency electric drive of the pipeline valves in the problems of the reduction of dynamic loads in a pumping complex

***Abstract**. The structure of the electromechanical system of the dynamic loads reduction in the pumping complex by means of the use of a variable-frequency electric drive of the control stopcock is substantiated. A multifactor model of the forecast of the head increase in the hydrodynamic network for different rates of the pipeline valves control is obtained. The modes of the system operation at the standby energy supply of the stopcock electric drive from an uninterrupted power supply or a hydraulic flow active energy dissipator are considered.*

***Streszczenie.** W artykule opisano usprawnienie budowy układu elektromechanicznego redukcji obciążeń dynamicznych w kompleksie pompowym za pomocą napędu elektrycznego o zmiennej częstotliwości zaworu odcinającego. Otrzymano wieloczynnikowy model prognozy wzrostu wysokości podnoszenia w sieci hydrodynamicznej dla różnych prędkości sterowania zaworami rurociągu. Rozważane są tryby pracy układu przy zasilaniu rezerwowym napędu elektrycznego kranu z nieprzerwanego źródła zasilania lub rozpraszacza energii czynnej z przepływem hydraulicznym. (**Napęd elektryczny o zmiennej częstotliwości zaworów rurociągowych w problemach redukcji obciążeń dynamicznych w kompleksie pompowym**)*

Keywords: stopcock, dynamic loads, variable-frequency electric drive, uninterrupted power supply, hydraulic flow active energy dissipator.
Słowa kluczowe: kurek, obciążenia dynamiczne, napęd elektryczny o zmiennej częstotliwości, nieprzerwane zasilanie, hydrauliczny rozpraszacz energii czynnej

Introduction

Pipeline valves are the most important element of the technological equipment of hydraulic transport complexes (HTC) and perform protective, preventive and regulating functions. The pipeline valves control influences the nature of the transient processes in the hydraulic system both in ordinary (regulation, start) and emergency modes. Opening (closing) of stopcocks, latches, etc. is often carried out without observing the required rate and duration of the control, which results in the occurrence of increased dynamic loads and surges in the communication network, increased vibrations of the walls and the flowing route of the pump unit and the pipeline valves, considerable variation of the hydraulic moment on the pump shaft (up to 30-40 % of the steady value); sharp reduction to zero of the supply at the unit output; pressure inrush in the pipe line, exceeding the admissible values by 5-7 times. The mode of a sudden electric energy cutoff or the failure of the pipeline valve electric drive (ED) is especially hard, as in this case there occurs an active actuation of the check valve in the pumping station (PS) pressure header, and the pressure in the hydronetwork exceeds the rated value by 6-10 times [1, 2]. Such operating modes are characterized by low values of pump units (PU) efficiency, high losses of energy, decrease of the durability of the pipeline valves, pump equipment by 5-6 times and considerable material cost of the elimination of the consequences of the emergency. In this case it is possible to prevent the sudden failure of variable-frequency ED elements by using the methods of diagnostics of induction motors [3] and convertor semiconductor elements [4, 5].

The analysis [6-8] revealed that the existing methods of the reduction of dynamic loads in HTC with stop-control valves base on:

the increase of the time of stopcock shutting, observing the uniform rate of control;

the generation of the uneven rate of stop-control valves shutting with the velocity decreasing in time, which is performed discretely (in several stages) by means of the use of uncontrolled induction electric drive (ED) having several rotation frequencies.

The drawbacks of these methods include the absence of the possibility for the pipeline valves control, allowing the continuous alteration of the rate of generating the required trajectory of the valves shutting taking into account the nonlinear character of the valves hydraulic resistance dependence on the relative degree of its opening both in the regulation and emergency modes of its operation.

Research method

Failure to observe the required rate of control of the pipeline valves without taking into account their hydraulic characteristic results in the occurrence of surges in the pipeline network whose main parameters include:

the surge phase

$$T_{ph} = 2L/c\,; \tag{1}$$

the increase of the head in each phase

$$\Delta H_k = 2\Delta h_{fr}\left[\left(j - \left(l/\Delta h_{fr}\right)\sum_{i=1}^{k-1}\Delta H_i + \left(j\varphi_k/\varphi_0\right)^2\right) - \left(j\varphi_k/\varphi_0\right)\sqrt{1 + 2\left(j - \left(l/\Delta h_{fr}\right)\sum_{i=1}^{k-1}\Delta H_i\right) + \left(j\varphi_k/\varphi_0\right)^2}\right], \tag{2}$$

where L – the pipeline length, m; $c = c_l\Big/\sqrt{1+(E_l/E_p)\Psi}$ – the speed of the surge propagation, m/s; E_l – the module of the liquid volume elasticity; E_p – the module of the pipe wall material elasticity; $c_l = \sqrt{E_l/\rho}$ – the speed of sound propagation in the liquid, m/s; Ψ – the coefficient taking into account the deformability of the pipeline walls; ΔH_i – the increase of the head in each phase before the considered one, m; $j = \upsilon_0 c/\left(2g\Delta h_{fr}\right)$ – the impact parameter of the pipeline; υ_0 – the initial speed of the liquid flow in the pipeline before valves shutting, m/s; Δh_{fr} – the friction head losses along the pipeline length, m; $\varphi_k = 1\Big/\sqrt{\xi_p + \xi_v\left(\beta_k\right)}$ – the coefficient of the pipeline system speed at the current relative degree of opening β_k of the stopcock, $k = 0, 1, \ldots$; ξ_p – the coefficient of the hydraulic resistance of the pipeline network.

An efficient way of the reduction of the dynamic loads in HTC consists in the generation of an irregular rate of the valves opening (shutting)

(3) $$\beta(t) = 1 - \left(t/t_{cl}\right)^{1/n},\ n \ge 1,$$

taking into account the hydraulic resistance coefficient ξ_v nonlinear dependence on the relative degree β of the pipeline valves opening

(4) $$\xi_v(\beta) = A\left((1/\beta)-1\right)^C + B\left((1/\beta)-1\right)^D + \xi_0,$$

where n – the coefficient of the valves control intensity; t_{cl} – the time of the valves complete shutting; A, B, C, D – the approximation coefficients depending on the type of the pipeline valves; ξ_0 – the coefficient of hydraulic resistance at the complete opening of the valves ($\beta = 1$).

Fig. 1 contains the head relative increase $\Delta h = \Delta H / \Delta H_{dir}$ dependences on control intensity coefficient n for different values of valves shutting t_{cl}, where ΔH_{dir} – the increase of the head at a direct surge ($t_{cl} \le T_{ph}$). The analysis of the obtained curves revealed that at $n = 1 \div 7$ in the hydrosystem there appear considerable dynamic loads characterized by sharp change of pressure in the pipeline network, often exceeding the rated value by $60 \div 90\%$; at $n = 7 \div 20$ the pressure in the commutation network changes within the admissible limits – up to $20 \div 25\%$ of the rated value.

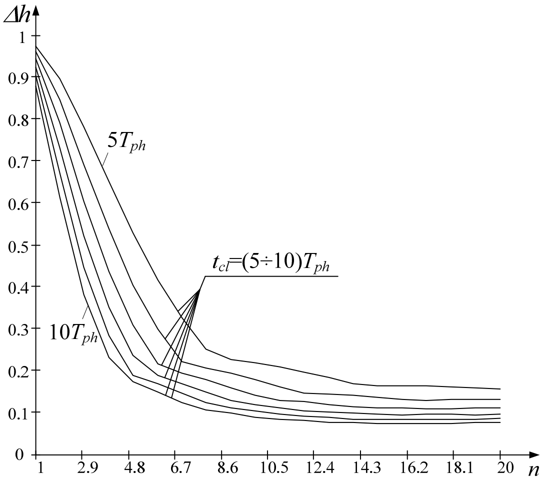

Fig. 1. Head relative increase Δh dependence on the valves control intensity coefficient n at different shutting time t_{cl}, multiple of surge phase T_{ph}

Fig. 2 contains the functional diagram of the electromechanical system of the reduction of dynamic loads (ESRDL) based on the variable-frequency electric drive (ED) of the stop-control valve with a standby power supply at a sudden collapse of supply voltage of the pump unit (PU).

Such a system can be used to control the valves both in standard (operation) modes at the regulation of the head or capacity in accordance with the current water consumption, and in emergency modes caused by sudden cutoff of the electric energy, occurrence of surges.

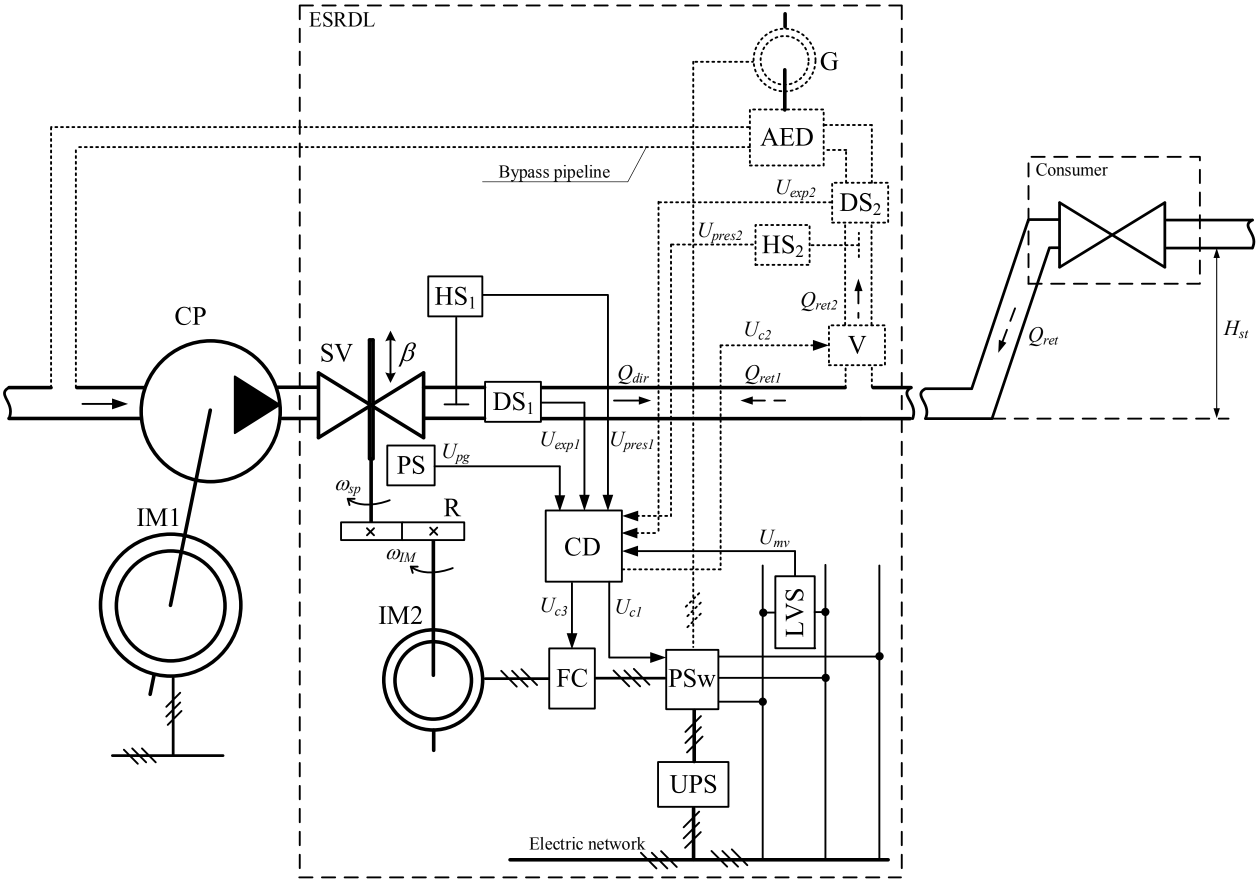

Fig. 2. ESRDL functional diagram

This system includes: stop-control valves SV, installed at the output of the centrifugal pump CP with a driven induction electric motor IM1; frequency convertor FC, connected to the induction driven motor of the valves IM2, whose shaft is connected to their spindle via reducer R; bypass pipeline rigged with hydraulic valve V, hydraulic flow active energy dissipator AED with electric generator G on one shaft; head sensors HS1, HS2 and discharge sensors DS1 and DS2 mounted in the pump delivery pipe before AED; position sensor PS of the sluice of the SV pipeline valves; line voltage sensor LVS; uninterrupted power supply UPS; power switch PSw; control device CD.

At sudden cutoff of power supply of electric motors IM1 and IM2 and appearance of liquid counterflow in the hydrosystem under the action of static head H_{st} the control device generates control signal U_{c1} at the power switch to connect the frequency convertor with the uninterrupted power supply.

As an alternative variant, ESRDL can be additionally equipped with a hydraulic flow active energy dissipator. In this case, at sudden voltage cutoff in HTC and occurrence of liquid counterflow the control device generates signal U_{c2} to open the hydraulic valve. A part of the flow is sent via the bypass pipeline to the active energy dissipator (hydroturbine) with an electric generator mounted on one shaft. At the initial time moment after opening of the hydraulic valve, due to the low value of reverse flow Q_{ret2} there may not be enough output electric power of the generator to shut the valves completely:

$$P_G = \rho g H_2 Q_{ret\,2} \eta_{ACE} \eta_G , \tag{5}$$

where H_2 – the head at AED, m; η_{ACE}, η_G – the efficiencies of the active energy dissipator and the generator, respectively; ρ – the density of the operating environment, kg/m^3; g – the acceleration of gravity, m/s^2.

When $P_G \geq P_{FC}$, where P_{FC} – the power of the frequency converter, the control device generates control signal U_{c1} on the power switch to supply the initial data of the generator terminals to the frequency converter input.

Then one searches for the optimal values of control intensity coefficient n_{opt} and stopcock shutting time $t_{cl.opt}$ corresponding to such a rate of control at which the head in the pipeline near the stopcock $\left(H_1 + \Delta H_{k\max}\right)$ is lower than the maximal admissible value of the head $\Delta H_{\max.pos}$ in the hydrosystem, where H_1 – the value of the head at the stopcock in the steady mode, m; $\Delta H_{k\max}$ – the maximal increase of the head during the time of the valves control, chosen out of the array of values ΔH_k, corresponding to the set parameters n, t_{cl}, υ_0.

Assuming $\Delta h = \Delta H_{k\max} / \Delta H_{dir}$, $\tau = t_{cl} / T_{ph}$, we make a multi-factor model of the form:

$$\begin{aligned} \Delta h(n,\tau,\upsilon_0) &= a_0(\upsilon_0) + a_1(\upsilon_0)n + \\ &+ a_2(\upsilon_0)\tau + a_3(\upsilon_0)n^2 + a_4(\upsilon_0)\tau^2 + \\ &+ a_5(\upsilon_0)n\tau + a_6(\upsilon_0)n^3 + a_7(\upsilon_0)\tau^3 + \\ &+ a_8(\upsilon_0)n\tau^2 + a_9(\upsilon_0)n^2\tau, \end{aligned} \tag{6}$$

where $a_k(\upsilon_0) = b_{0k} + b_{1k} n^2(\upsilon_0) + b_{2k} e^{-\upsilon_0}$ –approximation coefficients, $k = 0, 1, 2, \ldots, 9$; Δh – relative head increase; τ – relative time of valves shutting multiple of surge phase T_{ph}.

Parameters n, τ, υ_0 of model (6) vary within the ranges of $n = 1 \div n_{\max}$, $\tau = 1 \div \tau_{\max}$, $\upsilon_0 = 0.2 \div 5$ m/s, where $n_{\max} = 12$, $\tau_{\max} = 10$ – the maximal values of the control intensity coefficient and the relative time of valves shutting, respectively.

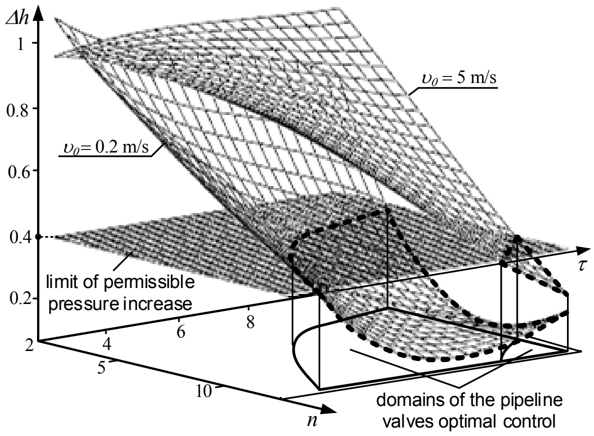

Fig. 3. The domains of the pipeline valves optimal control

Fig. 3 contains the pipeline valves optimal control domains obtained depending on the variation of the relative values of head increase Δh, shutting time τ and valves control intensity coefficient n at the change of the liquid flow initial speed $\upsilon_0 = 0.2 \div 5$ m/s and maximal admissible value of the head $\Delta H_{\max.pos}$ in the hydrosystem.

At the moment of liquid counterflow ($Q_1 < 0$)under the action of static head H_{st} in the hydrosystem due to a sudden collapse of electricity supply ($U_{mv} = 0$)of the induction electric motors IM1 and IM2, the current parameters of the surge are calculated by readings H_1, Q_{ret1}, of the corresponding head sensor HS1 and discharge sensor DS1:

surge phase T_{ph} determined from expression (1);

the reverse speed of the flow through the stop-control valves

$$\upsilon_{ret1} = 4Q_{ret1} / \left(\pi d^2\right); \tag{7}$$

the increase of the pressure at a direct surge

$$\Delta H_{dir} = c\upsilon_{ret1} / g , \tag{8}$$

where d – the pipeline diameter, m.

Substituting $T_{ph}, \upsilon_{ret1}, \Delta H_{dir}$ into (6), we determine the optimal values n_{opt} and $t_{cl.opt}$ for the generation of control signal U_{c3} on the frequency convertor aiming at the provision of the stopcock shutting rate resulting in the change of the head in the pipeline network within the admissible limits.

The obtained multifactor model of the forecast of the relative increase of the head in the hydrosystem for different rates of the valves control is suitable for a wide class of hydrotransport systems with different parameters of the pipeline network (diameter, length, head losses along the length, etc.) and the ranges of the variation of the speeds of the liquid flow. The said deserves especial attention in the problems of the improvement of the pumping complex controllability at the development of wave processes in the pipeline network [9], the identification of the hydrosystem parameters in unsteady operation modes, etc. [10, 11].

Conclusions

We have proposed an approach to the reduction of the dynamic loads in the hydrotransport complex both in operation and emergency modes by means of control of the rate of the stop-control valves shutting.

An electromechanical system of the decrease of the dynamic loads in the pipeline network, based on the control stopcock variable-frequency electric drive with the use of the standby power of the uninterrupted power supply or an active hydroflow energy dissipator, has been worked out. This system makes it possible to eliminate the inadmissible increase of pressure in the pipeline, to efficiently use the energy of the reverse liquid flow, to extend the life span of the technological equipment, to improve the reliability of functioning of the whole pumping complex.

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REFERENCES

[1] Roy J.K., Roy P.K., Basak P. Water hammer protection in water supply system: A new approach with practical implementation // Proceedings of ICCIA Kolkata. – 2011. – pp. 1–6.
[2] Bergant A., Simpson A.R. Water Hammer Analysis of Pumping Systems for Control of Water in Underground Mines // Proceedings of Mine Water Congress Ljubljana. – 1991. – pp. 9–20.
[3] Zagirnyak M., Mamchur D., Kalinov A. “A comparison of informative value of motor current and power spectra for the tasks of induction motor diagnostics”, IEEE 16th International Power Electronics and Motion Control Conference and Expositio, PEMC 2014, pp. 540–545, 2014.
[4] Zagirnyak M., Kalinov A., Maliakova M. “Analysis of instantaneous power components of electric circuit with a semiconductor element”, Archive of electrical engineering, 62, 3, pp. 473–486, 2013.
[5] Zagirnyak M., Maliakova M., Kalinov A. “Analysis of electric circuits with semiconductor converters with the use of a small parameter method in frequency domain”, COMPEL: The international journal for computation and mathematics in electrical and electronic engineering, 34, 3, pp. 808–823, 2015.
[6] Bazargan-Lari M. R. Developing optimal valve closure rule curve for real-time pressure control in pipes // Journal of Mechanical Science and Technology. – 2013. – Iss. 27 (1). – pp. 215–225.
[7] Jing-Yang Yu Optimal valve closure for long-distance water transmission / Jing-Yang Yu, Zheng-Yi Wu, Yi-Xing Yuan, Ming Zhao, Chen-Guang Wu // Sustain. Environ. Res. – 2010. – Iss. 20 (5). – pp. 287–291.
[8] Wu Juan Study on the dynamic characteristic of the controllable gate valve in the mine automatic draining system/ Wu Juan, Kou Ziming // Proceedings of ICAEE Beijing. – 2010. – pp. 35–39.
[9] M. Zagirnyak, V. Kovalchuk, T. Korenkova, “Power Model of an Electrohydraulic Complex with Periodic Nonlinear Processes in the Pipeline Network”, 2015 International Conference on Electrical Drives and Power Electronics (EDPE), Tatranská Lomnica, The High Tatras, Slovakia September 21-23, 2015, pp. 345-352. IEEE Catalog Number CFP15EDQ-USB, ISBN 978-1-4673-9661-5
[10] Zagirnyak M., Kovalchuk V., Korenkova T. Harmonic analysis of power in an electrohydraulic complex with nonlinear processes in the pipeline system, Proceedings of 2016 IEEE International Conference on Intelligent energy and power systems (IEPS), Kyiv, Ukraine, 2016, pp. 143–148.
[11] Zagirnyak M., Serdiuk A. and Korenkova T. Limits of noncavitation operation of an electrohydraulic complex with a variable-frequency electric drive, Przeglad Elektrotechniczny (Electrical review), 2015, no. 1, pp. 212–216.