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The assessment of the electrohydraulic complex power controllability with different rates of closing pipeline valves

***Abstract**. It is shown that failure to observe the required rate of control of the pipeline shut-off and control equipment results in the occurrence of surges, breakdowns, breaks of the pipeline pressure systems, which is associated with a decrease in the controllability of the entire electrohydraulic complex. A mathematical model for the research of the energy processes in electrohydraulic complex with different closing rates of pipeline valves is proposed. It is proved that abrupt closure of the valve accompanied by a break of the pipeline, results in a complete loss of controllability in the hydraulic system. A mathematical and graphical formalization of power controllability based on the root-mean-square estimates of the harmonic power components is proposed.*

Streszczenie.** W pracy pokazano, że kłopot w obserwacji wymaganego sposobu sterowania rurociągami i sterowanie wyposażeniem zespołu elektrohydraulicznego wynika z występowania przypływów, zatrzymań, zakłócenia ciśnienia w rurach, co jest skojarzone ze zmniejszeniem sterowności całego zespołu elektrohydraulicznego. Zaproponowano model matematyczny do badań procesów energetycznych w zespole elektrohydraulicznym różnymi sposobami zamykania zaworów. Wykazano, że nagłe zamknięcie zaworu towarzyszące uszkodzenie rurociągu prowadzi do całkowitej utraty sterowności systemu. Zaproponowano matematyczną i graficzną formalizację sterowności mocą, bazujące na ocenie błędu średnio-kwadratowego składników mocy.* ***(Ocena sterowności mocą układu elektrohydraulicznego z różnymi sposobami działania zamykających zaworów)

***Keywords:** electrohydraulic complex, surge, regulating valve, processes of energy conversion, power controllability*
***Słowa kluczowe:** zespól elektrohydrauliczny, przypływy, zawory, procesy konwersji mocy, sterowność mocy*

Introduction

Emergency shutdown or abnormal turning on of pumping units (PU), incorrect control of pipeline shut-off and control valves, abrupt actuation of check valves result in a rapid change in the liquid flow rate and may be accompanied by the occurrence of surges in pressure systems [1, 2]. The damage caused by pressure waves in water supply and disposal systems is especially significant in main pipelines of large length and diameter. Surges cause breaks of pipelines and depressurization of joints, failure of pump elements, breakdown of shut-off and control equipment, violation of pipeline fastening elements [3]. This results in the deterioration of the controllability of the whole electrohydraulic complex (EHC).

It should be noted that a surge is a complex phenomenon associated with the appearance of shock waves (pressure and head fluctuations), leading to unsteady hydraulic modes of operation [4]. A surge is accompanied by the transformation of energy processes in the pipeline network: at a sharp shutoff of the flow section the kinetic energy of the liquid is converted into the potential energy of elastic deformation. Under certain conditions, the rate of energy change can be so great, that it leads to catastrophic consequences. Therefore, it is relevant to analyze the EHC energy reaction to a change in control actions, which makes it possible to assess the risk of a surge and take timely measures to prevent or minimize it.

Research method

A mathematical model has been developed to research the energy processes in EHC with controlled pipeline valves. It includes a pump; a pipeline network represented by N number of sections with equal parameters; a stopcock with a variable-frequency electric drive (ED) installed in the last section of the hydraulic network; a consumer, at the entrance of which hydraulic resistance equivalent to the current water consumption is generated.

To describe the operation of the pump induction ED at frequency control a known model in $u, v, 0$-coordinates is used, wherein differential equations are presented in the form of flux linkage for a synchronous coordinate system. A quadratic moment of resistance created by the pump is generated on the motor shaft. The pipeline network is described by telegrapher's equations. The finite element method is used to solve them, which enables the transfer from equations with partial derivatives to differential analogs and the representation of the pipeline network as finite number of sections with equal parameters. A mathematical description of the model elements is given in [5].

The regulating valve installed at the last hydronetwork section is described by dependence of the form [6]:

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

where: A, B, C, D – the approximation coefficients depending on the type of the pipeline valves; ξ – the hydraulic resistance coefficient; β – the relative degree of the stopcock opening; ξ_0 – the coefficient of hydraulic resistance at the complete opening of the valves ($\beta = 1$).

The stopcock control law is described by the expression [6]:

(2) $$\beta(t) = 1 - \left(t/t_{sh}\right)^{1/n}$$

where n – the coefficient of the valves control intensity ($n \geq 1$); t, t_{sh} – the current time and the time of complete closing of the valves, respectively, s.

EHC parameters: the pump rated head H_{pn} = 104 m, discharge Q_{pn} = 1.6 m^3/s, the consumer hydraulic resistance R_{cn} = 40.65 s^2/m^5; the velocity of the shock wave propagation c = 1000 m/s, length L = 5000 m, diameter d = 1.2 m, the number of the sections N = 20 and specific parameters r_0 = 0.052 s^2/m^6, l_0 = 0.0392 s^2/m^3, c_0 = 407.747 m^{-1} of the pipeline; the power of the stopcock induction electric drive P_{sn} = 5.2 kW, rotation frequency n_{sn} = 1500 rev/min, the approximation coefficients of the stopcock hydraulic characteristic A = 0.505, B = 1.868, C = 2.35, D = 1.4, the coefficient of hydraulic resistance with complete opening of the valves ξ_0 = 0.05. The rate of the stopcock control is set by different times for the complete closure of the valves t_{sh1} = 250 s, t_{sh2} = 20 s, t_{sh3} = 5 s.

Figs. 1, 2 contain head $H(t)$ and discharge $Q(t)$ time-variable curves at the pump output and pipeline network with different rates of the stopcock closure at time moment t = 40 s. As a result, it was found out that the stopcock control with the rate equal to t_{sh1}, is accompanied by an insignificant excess of the head in the pipeline; with closure time t_{sh2} there is a sharp increase of the pressure in the stopcock. It exceeds the value of the pump rated head by 2.5 times. At the control time equal to t_{sh3}, a surge occurs in the hydronetwork, which results in the breakdown of the pipeline and complete outflow of the liquid.

For the considered cases Fig. 3 contains the curves of instantaneous hydraulic power $p_h(t)$ at the pump output and at the 19-th section of the pipeline network, defined as the product of the pressure $H(t)$ and discharge $Q(t)$ signals at the corresponding EHC element.

The instantaneous power theory was used to analyze the processes of energy conversion in EHC during water hammer, which is successfully applied in the problems of diagnostics and identification [8] of the electrical devices parameters, to compensate for the reactive component of power [9, 10], etc.

A harmonic analysis of the power time function made it possible to represent the hydraulic power signal in the form of a trigonometric series [11]:

$$p_h(t) = \sum_{r=1}^{R} P_{r0} + \sum_{r=1}^{R} P_{ra} \cos(\Omega_r t) + \sum_{r=1}^{R} P_{rb} \sin(\Omega_r t) \tag{3}$$

where: r, R – the number and the quantity of harmonics of the hydraulic power signal, respectively; P_r, P_{ra}, P_{rb} – the amplitude values of constant and orthogonal cosine and sine components of the pump hydraulic power signal, respectively; Ω_r – the circular frequency.

The root-mean-square value of the time function of power is used for assessing the quality of energy conversion processes in EHC [11]:

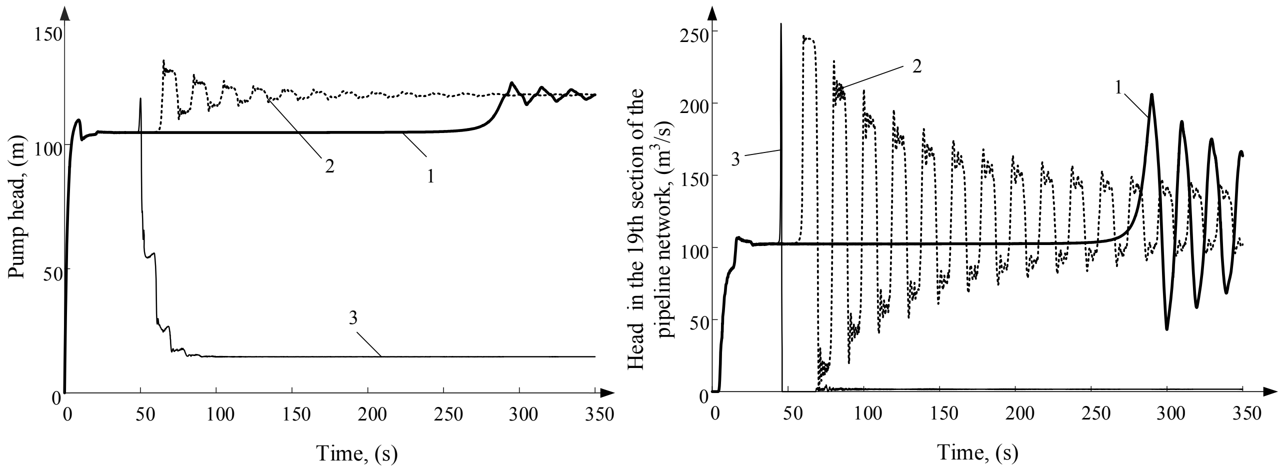
$$P_e = \sqrt{1/T \int_0^T p_h^2(t)dt} = \sqrt{\left(\sum_{r=1}^{R} P_{r0}\right)^2 + \left(\sum_{r=1}^{R} P_{ra}\right)^2 \Big/ 2 + \left(\sum_{r=1}^{R} P_{rb}\right)^2 \Big/ 2}. \tag{4}$$

To analyze the EHC energy reaction to different rates of pipeline valves control a power controllability coefficient is proposed [11]:

$$k_{pc} = P_{ep} / P_{ef} \tag{5}$$

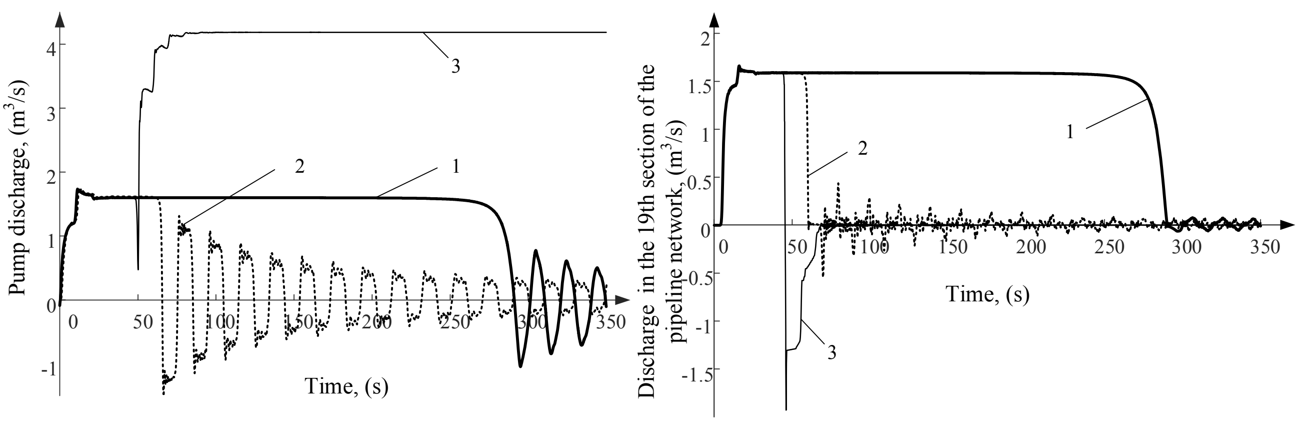
where P_{ep} – the power root-mean-square value at valve closing time corresponding to the certified value; P_{ef} – the power root-mean-square value at valve closing time different from the certified value.

Table 1 demonstrates the root-mean-square values of the hydraulic power harmonic components at the pump output and at the section of the pipeline network for different rates of stopcock closing, and Fig. 4 contains a graphical interpretation of the energy conversion processes in EHC for the considered cases.



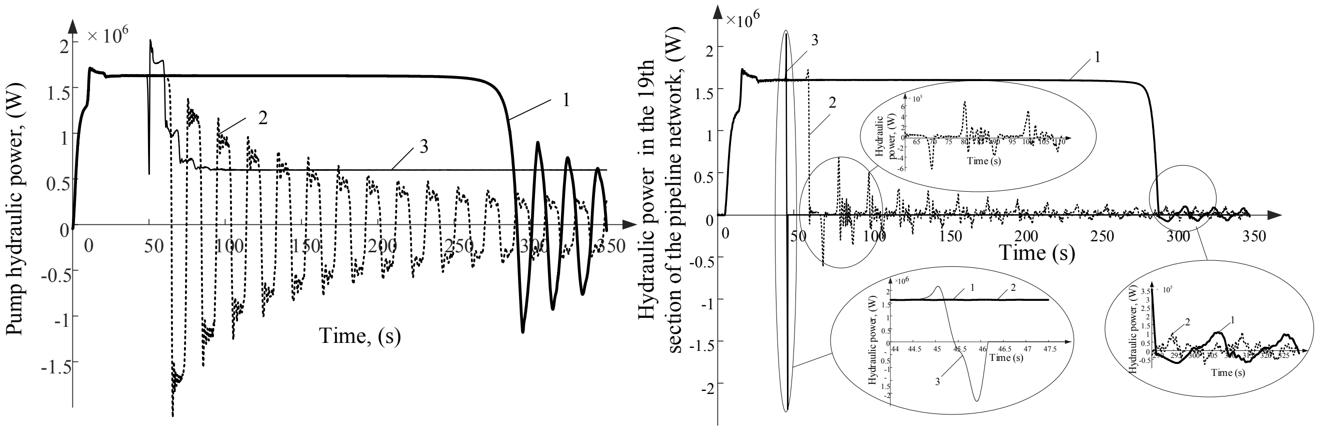
a) b)

Fig. 1. The head time-variable curves at the pump output (a) and at the pipeline network (b) with different rates of the stopcock closure at: 1 – t_{sh1} = 250 s; 2 – t_{sh2} = 20 s; 3 – t_{sh3} = 5 s



a) b)

Fig. 2. The discharge time-variable curves at the pump output (a) and at the pipeline network (b) with different rates of the stopcock closure at: 1 – t_{sh1} = 250 s; 2 – t_{sh2} = 20 s; 3 – t_{sh3} = 5 s



a) b)

Fig. 3. The hydraulic power time-variable curves at the pump output (a) and at the pipeline network (b) with different rates of the stopcock closure at: 1 – t_{sh1} = 250 s; 2 – t_{sh2} = 20 s; 3 – t_{sh3} = 5 s

Table 1. The root-mean-square values of the hydraulic power and the power controllability coefficients

At the output of the19th pipeline network section			
	5 s	20 s	250 s
P_e	$7.997{\cdot}10^5$	$6.17{\cdot}10^5$	$9.124{\cdot}10^4$
P_0	$4.797{\cdot}10^5$	$5.09{\cdot}10^5$	$7.385{\cdot}10^4$
P_a	$2.786{\cdot}10^5$	$1.79{\cdot}10^5$	$1.981{\cdot}10^4$
P_b	$5.761{\cdot}10^5$	$2.994{\cdot}10^5$	$4.978{\cdot}10^4$
k_{pc}	0.09	0.167	1.0
At the pump output			
	5 s	20 s	250 s
P_e	$1.703{\cdot}10^6$	$1.15{\cdot}10^6$	$4.475{\cdot}10^5$
P_0	$1.697{\cdot}10^6$	$1.035{\cdot}10^6$	$3.981{\cdot}10^5$
P_a	$9.772{\cdot}10^4$	$4.253{\cdot}10^5$	$1.067{\cdot}10^5$
P_b	$1.033{\cdot}10^5$	$2.671{\cdot}10^5$	$3.163{\cdot}10^5$
k_{pc}	0.33	0.84	1.0

The analysis revealed that increase in the rate of the pipeline stopcock control results in significant increase in the root-mean-square values of the hydraulic power P_{ef} (Table 1). It is especially noticeable in the pipeline network section directly near the source of disturbance – the adjustable stopcock.

So, the effective value of the hydraulic power at t_{sh2} = 20 s increases by 6.76 times in comparison with power, when stopcock closes during the time t_{sh1} = 250 s, taken as the certified value. At a stopcock control rate equal to t_{sh3} = 5 s, P_{ef} increases by 8.76 times. The above said is confirmed by the growth of the energy volume in the hydraulic system (Fig. 4) and, respectively, decreasing of EHC power controllability coefficient (Table 1). So, at the certified value of the stopcock control rate, equal to t_{sh1} = 250 s, power controllability coefficient is k_{pc} =1.0. It corresponds to a mode when head fluctuations in the pipeline lie within the permissible values and do not result in emergency situations. At t_{sh2} = 20 s shock waves arise in hydronetwork, which results in decrease of EHC power controllability: k_{pc} = 0.167; at t_{sh3} = 5 s the fluid flow energy reaches the peak values and a surge occurs in the pipeline network. It leads to an almost complete loss of control at this section of the EHC pipeline network: k_{pc} = 0.09 (pipeline rupture and fluid outflow).

Energy reaction at the pump output, when stopcock control in a pipeline network differs from the case considered above by higher values of power controllability coefficient, is shown in Table 1. This is caused by less pronounced wave processes due to the remoteness of the pump from the source of disturbance.

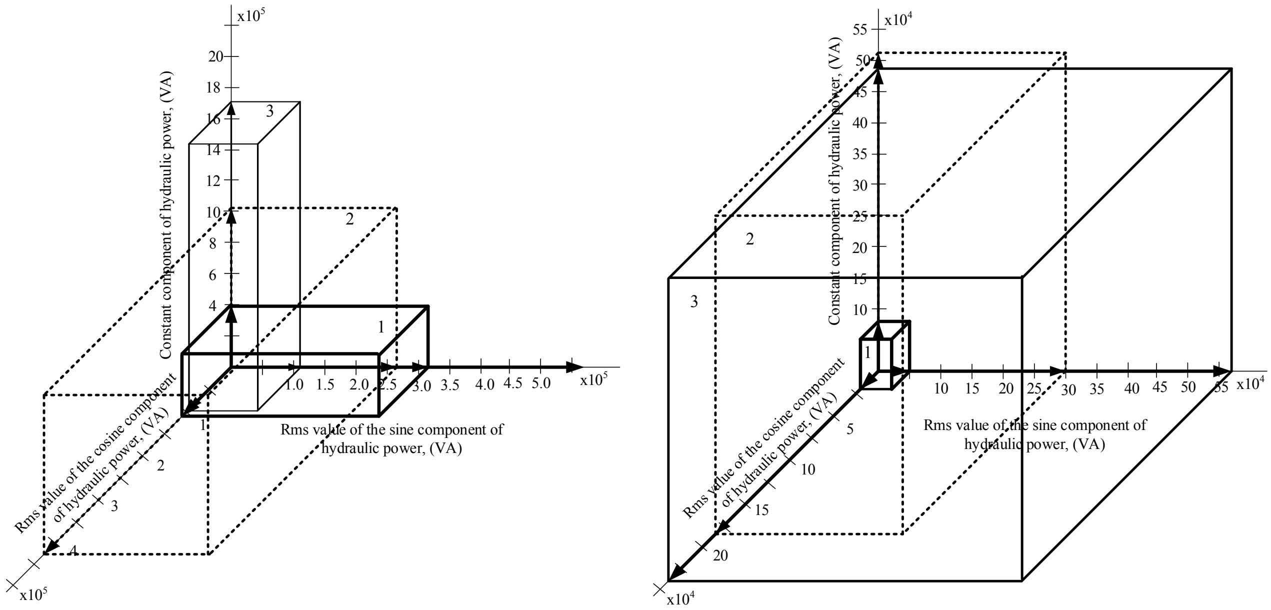
Thus, the rate of the stopcock control significantly affects the energy conversion processes at all EHC elements. At sharp closing (opening) of the shut-off and regulating valves, the wave processes in the pipeline network because an increase of variable harmonic components in power signals. It is accompanied by a decrease of hydrosystem power controllability.

Obviously, the increase of the EHC power controllability should be based on using the means of the stopcock variable-frequency electric drive, enabling formation of such a rate of closing (opening) of the pipeline valves, which eliminates increased shock loads in the hydraulic system [12].

Conclusions

It has been shown that if the required rate of the stopcock control is not observed, wave processes occur in the hydraulic network, which causes a surge and in some cases a breakdown of the pipeline.

It has been found out that wave processes in the pipeline network result in an increase in the variable components in the power signals. It is accompanied by an increase in the root-mean-square power values and, in turn, a decrease in the power controllability of the electrohydraulic complex.



a) b)

Fig. 4. The diagrams of the energy volume of hydraulic power alteration at the pump output (a) and at the pipeline network (b) with different rates of the stopcock closure at: 1 – t_{sh1} = 250 s; 2 – t_{sh2} = 20 s; 3 – t_{sh3} = 5 s (with pipeline breakdown)

To analyze the hydrosystem energy reaction with different rates of the pipeline stopcock closure (opening) it has been proposed to use a power controllability coefficient. It is based on the ratio of the root-mean-square power values in a system with the stopcock certified closing time and at a time other than the certified one.

It has been shown that a surge is characterized by a sharp deformation of the energy volume with increasing the variable power components and in fact, a complete loss of controllability of the entire electrohydraulic complex.

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