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The determination of the power of the stopcock variable-frequency electric drive, taking into account the hydraulic characteristic nonlinearity

***Abstract**. It is shown that the formation of an uneven rate of the pipeline valves control provides the minimum control time and the change of dynamic loads in the pipeline network within acceptable limits. The method for the determination of the electric motor power and the reduction rate of the reducer of the pipeline valves variable-frequency electric drive is proposed. This method takes into account the nonlinear dependences of the hydraulic and mechanical characteristics, the condition of the exclusion of overload at the torque and overheating of the stopcock induction motor.*

Streszczenie.** Zaproponowano metodę określania mocy napędu elektrycznego i redukcji szybkości w zaworze potokowym w przypadku napędu o zmiennej częstotliwości. Metoda uwzględnia nieliniowość składowych mechanicznych, zapewnia możliwość zapobiegania przeciążeniom i przegrzaniom. **Metoda określania mocy napędu zaworu o zmiennej częstotliwości uwzględniająca nieliniowość składowej hydraulicznej

Keywords: stopcock, hydraulic characteristic, frequency control, power, reduction rate, electric drive.
Słowa kluczowe: zawór hydrauliczny, napęd o zmiennej częstotliwości

Introduction

The operating modes of pumping complexes (PC) must be continuously changed due to the variable nature of the consumer operation, depending on the technological conditions of the enterprises, the time-varying schedule of water consumption, etc. Most often, PC output technological parameters are regulated by throttling the head with a stopcock located in the delivery pipe of the pump units or discharge manifold. The practice of operating pumping stations shows that the closing/opening of stopcocks, gates and hydraulic valves equipped with unregulated induction electric drive (ED) is carried out without observing the required rate and duration of control. It results in the occurrence of surges, increased dynamic loads in the hydraulic network, reduced controllability of the entire electro-hydraulic complex [1].

Conventional methods of reducing dynamic loads in pumping stations are characterized by the inability to control the rate of opening / closing of pipeline valves, eliminating the occurrence of surges in the system. In paper [2] the structure of the electromechanical system for reducing dynamic loads (ESRDL) in the PC based on the variable-frequency ED of shut-off-regulating stopcock equipped with a reserve power source is substantiated. ESRDL can be used to control valves both in normal (operational) modes when regulating head or capacity in accordance with current water consumption and in emergency operation modes associated with a sudden power outage, the occurrence of a surge.

The commercially available pipeline valves unregulated induction ED is meant to control valves of various types and designs, intended for operation in wide ranges of changes in the diameter of the pipeline and the pressure of the working medium. ED valve power is calculated according to expression:

$$P = \frac{\alpha M_{max} n}{9550 \eta i k} \tag{1}$$

where M_{max} – the maximum ultimate torque at the drive shaft, Nm; n – the rotation frequency of the drive shaft, rev/min; i – the reduction rate of the reducer; η – the efficiency of the reducer; k – torque overload coefficient of the motor; α – reserve coefficient taken equal to 1.1–1.5.

The analysis [3−5] revealed that when torque M_{max} on the pipeline valves ED shaft is determined, the change of the pressure in the working medium and the area of the actuator surface affected by the flow are neglected and taken as constant values.

In the reference literature, electric motors of the AOS2 series are given as ED fittings, the main catalog parameters of which are the rated power P_n and the time of complete opening/closing t_{close} of the valves.

It was found out in papers [5, 6] that when solving problems of reducing dynamic loads in a pipeline network, both in emergency and regulatory modes, it is advisable to use a variable-frequency electric drive of the stopcock. At the same time, more attention is paid to the technical implementation of the power converter and microprocessor control systems of valves ED, the algorithms for the effective control of power converters. However, the problems related to determining the power and reduction rate of the reducer of the valves variable-frequency ED, taking into account the nonlinear nature of its hydraulic and mechanical characteristics, were not analyzed.

Research method

Paper [2] contains theoretical substantiation of the possibility to reduce dynamic loads in PC, both in stationary and emergency modes, by controlling the rate of closure/opening of the stopcock, taking into account the complex non-linear nature of the change of hydraulic resistance coefficient ξ_{valve} depending on the relative degree β of its opening. The above said deserves special attention when analyzing energy conversion processes and assessing the energy controllability of the pump complex, when various kinds of oscillatory processes develop in the pipeline network [7−9]. In some cases, it is necessary additionally take into account possible alteration of the energy parameters of the drive induction motor, e.g. due to aging [10] and presence of defects [11].

The stopcock resistance moment M_{valve} dependence on relative degree β of its opening and electric drive supply voltage frequency f (Fig. 1), taking into account the nonlinear nature of the change $\xi_{valve}(\beta)$, is also an important characteristic of the pipeline valves.

The analysis of the curves revealed that at section $0.2 \le \beta \le 1$ moment M_{valve} changes linearly; at section, where $\beta \le 0.2$, there is a significant growth of M_{valve} at the decrease of relative degree of opening β.

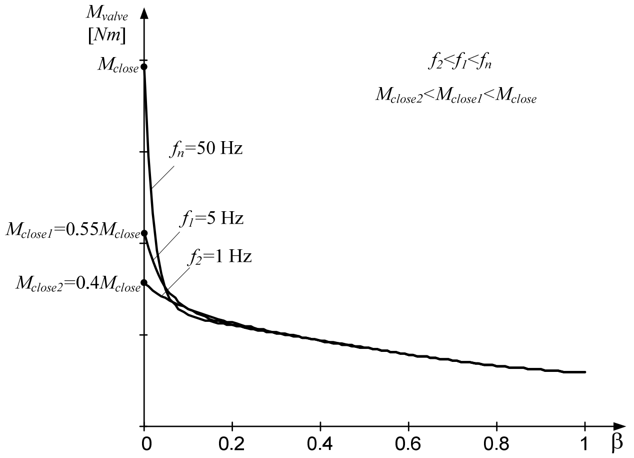

Fig. 1. The dependence of stopcock resistance moment M_{valve} on relative degree β of its opening at different supply voltage frequencies f

The graphs demonstrate that when the stopcock closes with ED rated supply voltage frequency of $f_n = 50\,Hz$, the moment M_{valve} takes the highest value M_{close} at the complete closing of the stopcock $\beta = 0$. When the supply voltage frequency decreases to $f_1 = 5\,Hz$, the value of moment M_{valve} reduces to value M_{close1}, which is lower than M_{close} by 1.8 times. Further reduction of the supply voltage frequency results in significant decrease of moment M_{valve}, which at $f_2 = 1\,Hz$ and $\beta = 0$ takes value M_{close2}, which is lower than M_{close} by 2.5 times.

To control dynamic loads in the pipeline network the change in time of the increase in the head at the stopcock is taken into account by expression:

(2)
$$\Delta H_k\left(t\Big|_{t=kT_{ph}}\right) = 2\Delta h_{fr}\left[\left(j - \left(\sum_{i=1}^{k-1}\frac{\Delta H_i}{\Delta h_{fr}}\right) + \left(\frac{j\varphi_k}{\varphi_0}\right)^2\right) - \left(\frac{j\varphi_k}{\varphi_0}\right)\sqrt{1+2\left(j-\sum_{i=1}^{k-1}\frac{\Delta H_i}{\Delta h_{fr}}\right)+\left(\frac{j\varphi_k}{\varphi_0}\right)^2}\right]$$

where $\Delta H_k\left(t\Big|_{t=kT_{ph}}\right)$ – the increase in the head at the stopcock, determined at time moments $t = kT_{ph}$, multiple of phase T_{ph} of the surge; $k = 1, 2, \ldots$; $j = \frac{\upsilon_0 c}{2g\Delta h_{fr}}$ – the pipeline impact parameter; υ_0 – the velocity of the liquid flow in the pipeline before closing of the valve, m/s; Δh_{fr} – friction head losses along the pipeline length, m; $\varphi_{0,k} = 1\Big/\sqrt{\xi_{fr} + \xi_{valve}(\beta)}$ – the coefficient of the velocity of the pipeline system with a stopcock; $\xi_{valve}(\beta) = A(1/\beta - 1)^C + B(1/\beta - 1)^D + \xi_0$ – the stopcock hydraulic resistance coefficient dependence on the relative degree of its opening.

It is shown in [2] that value $\Delta H_k(t)$ decreases at the nonlinear rate of the stopcock control: at section $0.1 \le \beta \le 1$ – with constant supply voltage frequency f, equal to 50 Hz; at $\beta \le 0.1$ – $f = \mathrm{var}$, which is described by dependence:

(3)
$$\beta(t, f) = 1 - \frac{t}{t_{close}}$$

where $t_{close} = \frac{0.9Nip}{f_n} + \frac{0.1Nip}{f_{\beta\le 0.1}}$ – the time of complete closing, s; f – the current supply voltage frequency of the stopcock electric drive, Hz; N – the number of spindle turns required for the complete opening/closing of the valves; p – the number of ports of the induction motor (IM); $f_{\beta\le 0.1}$ – the supply voltage frequency at section $\beta \le 0.1$, Hz.

The value of supply voltage frequency $f_{\beta\le 0.1}$ is determined on the condition of the exclusion of the surge in the pipeline:

(4)
$$\left(H_0 + \Delta H_k(t)\right) \le \Delta H_{max}$$

where ΔH_{max} – the maximum admissible increase of the head in the hydrosystem.

To shut the stopcock it is necessary to apply the following torque to its spindle:

(5)
$$M = M_1 + M_2,$$

where $M_1 = Q_\Sigma r_{mid} tg(\alpha_1 + \varphi)$ – the friction moment occurring in the thread, Nm; $M_2 = Q_\Sigma f_b r_{mid}$ – the friction moment in the bush bearing, Nm; Q_Σ – total axial effort depending on the operation pressure p of the medium and area S of the wedge surface subjected to the liquid pressure, N; r_{mid} – an average radius of the thread, m; α_1 – the angle of cutting ascent; φ – the angle of friction in the spindle thread; f_b – the coefficient of friction on bearings.

For uncontrolled valves, moment M is determined from the condition of constancy of values S and p. In this case, p is assumed equal to the working medium pressure in a steady mode. When the stopcock variable-frequency electric drive is used, it is necessary to take into account the change of area S and pressure p of the liquid.

For the case of a cylindrical pipeline, the change of area S of the stopcock disk surface subjected to the action of liquid pressure p at the change of the relative degree of opening of the pipeline valves β will be of the form:

(6)
$$S(\beta) = \left(\pi(D + 2b)^2/8\right)\left(2\arccos(\beta) - \sin\left(2\arccos(\beta)\right)\right).$$

Taking into account expressions (2), (5), (6) and the analysis of forces acting on the stopcock wedge (Fig. 2), we got the stopcock resistance moment M_{valve} dependence on time t and relative degree β of its opening:

(7)
$$M_{valve}(t,\beta) = \rho g\left(H_0 + \Delta H_k(t)\right) \times \left(\frac{(D_{in} + 2b)^2}{8}\left(2\arccos(\beta) - \sin\left(2\arccos(\beta)\right)\right) f_c + \frac{k\pi\left(D_{out}^2 - D_{in}^2\right)}{4} - mg + \pi d_{sp} 0.4h + \pi d_{sp}^2/4\right) \times \left(r_{mid} tg(\alpha_1 + \varphi) + f_b r_{mid}\right),$$

where H_0 – the head at the stopcock in the steady mode before the start of closing (at $\beta = 1$), m; ρ – the medium density, kg/m^3; D_{in} – the internal diameter of the sealing ring, m; b – the width of the sealing ring, m; D_{out} – the external diameter of the sealing ring, m; f_c – the coefficient of friction on the sealing surface; d_{sp} – spindle diameter, m; h – gasket height, m;

m – sluice mass, kg; g – acceleration of gravity, m/s^2.

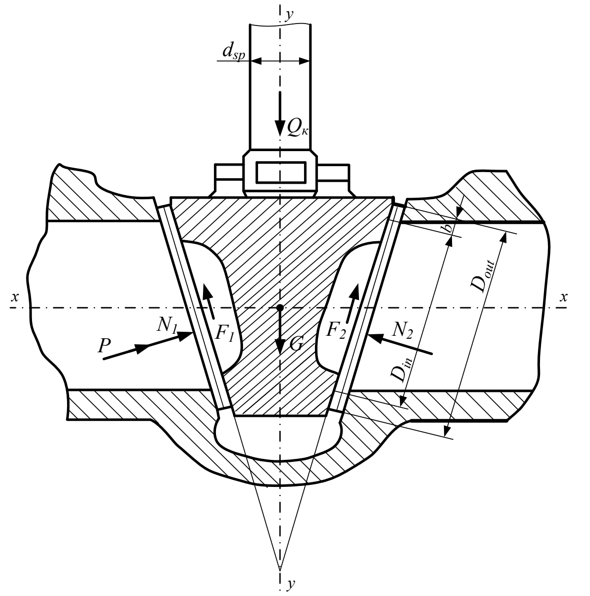

Fig. 2. Forces acting on the stopcock wedge: Q_w – component of axial effort Q_Σ for overcoming the forces acting on the stopcock wedge; P – the force of the hydrostatic pressure of the medium; N_1, N_2 – the reaction of the sealing surface of the body at the input and output of the working medium, respectively; F_1, F_2 – friction forces; G – gravity

Long-term operation of the valves unregulated induction ED without thermal overloads is impossible due to the short period of time of its continuous operation (0.1÷21.5 min) and limited overload capacity ($\lambda = 2 \div 2.8$).

When using a variable-frequency induction ED by changing IM stator voltage as a function of the supply frequency and slip, it is possible to ensure the constancy of the overload capacity and an increase of the critical torque of the motor by 2-4 times:

(8) $$M_{cr} = \frac{3}{2}\frac{U_1^2}{\omega_0}\frac{1}{X_2\left(\left(R_1/X_\mu\right)^2 + \left(1 + L_{1\sigma}/L_\mu\right)^2\right)},$$

where U_1 – IM stator phase voltage, V; ω_0 – the synchronous rotation frequency of the stator magnetic field, s^{-1}; R_1 – stator resistance, Ohm; $L_{1\sigma}$, L_μ – the leakage inductance of the stator and magnetization contour, Gn; X_2, X_μ – the inductive impedance of the rotor and magnetization contour, Ohm.

Fig. 3 contains mechanical characteristics of AOS2-41-4U3 motor used as a valve variable-frequency ED:

without taking into account the motor slip

(9) $$\gamma(\alpha) = \sqrt{\frac{\left(R_1\alpha + \sqrt{\left(r^2 + q^2\alpha^2\right)\left(\nu^2 + w^2\alpha^2\right)}\right)}{\left(R_1 + \sqrt{\left(r^2 + q^2\right)\left(\nu^2 + w^2\right)}\right)}};$$

taking into account the motor slip

(10) $$\gamma(\alpha, s) = \sqrt{\frac{\left(r^2 + q^2\alpha^2 + \left(\nu^2 + w^2\alpha^2\right)\frac{R_2^2}{s^2} + 2R_1\alpha\frac{R_2}{s}\right)}{\left(\left(\frac{R_2^2}{s^2} + X_2^2\right)\left(\nu^2 + w^2\right)\right)}}$$

where γ – the relative voltage of the stator; α – the relative frequency of the stator current; s – motor slip; R_2 – rotor resistance, Ohm; $\nu = R_1/X_\mu$; $w = \left(1 + L_{1\sigma}/L_\mu\right)$; $r = R_1\left(1 + \sigma_2\right)$; $q = X_\mu\tau$; $\tau = \tau_1 + \tau_2 + \tau_1\tau_2$ – total leakage coefficient; $\tau_1 = X_1/X_\mu$, $\tau_2 = X_2/X_\mu$ – the stator and rotor leakage coefficient, respectively; X_1 – the inductive impedance of the stator, Ohm.

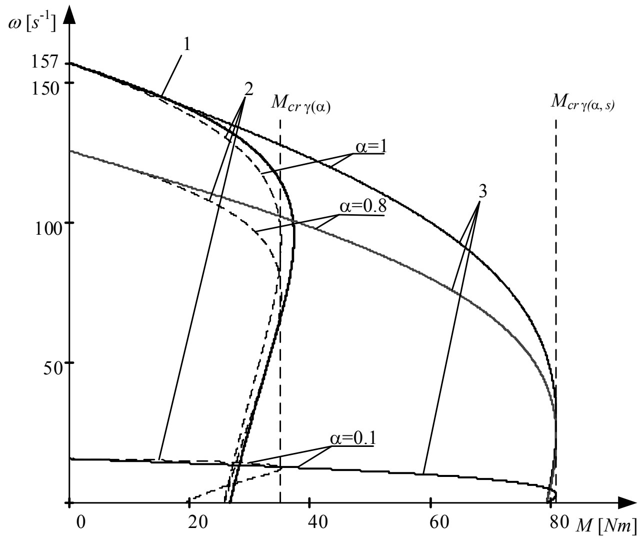

Fig. 3. The mechanical characteristics of AOS2-41-4U3 motor for different supply voltage frequencies: 1 – IM natural characteristic; 2, 3 – using the variable-frequency law, respectively, without taking into account the motor slip and taking into account the motor slip

The IM should be chosen according to the conditions:

exclusion of the overload on the torque

(11) $$M_{cr} \geq \frac{M_{valve\,\max}}{i}$$

where $M_{valve\,\max}$ – the maximum moment of resistance on the stopcock spindle, determined from expressions (2), (3) and (5) at $\beta = 0$, Nm;

inadmissible overheat of the motor

(12) $$M_{t_{close}} \geq M_{eq} = \frac{1}{i}\sqrt{\frac{1}{t_{close}}\int_0^{t_{close}} M_{valve}^2(t)\,dt},$$

where M_{eq} – the equivalent torque of the motor, Nm; $M_{valve}(t)$ – the time dependence of the stopcock resistance moment, which can be found by substitution of expressions (2) and (3) into (7); $M_{t_{close}} = M_n\sqrt{(a+1)\Big/\left(1 - e^{-t_{close}/T_{heat}}\right) - a}$ – the moment developed by IM without overheat during time t_{close} from expression (3); $a = k/\upsilon_n$ – the coefficient of losses; $\upsilon_n = 3I_{2n}'^2R_2' + 3I_{1n}^2R_1$ – the variable losses in the rated mode; $k = P_n\left(1 - \eta_n\right)/\eta_n - \upsilon_n$ – constant losses; $P_n, \eta_n, I_{1n}, I_{2n}'$ – rated power, efficiency, stator current and IM rotor reduced current, respectively, W, A; T_{heat} – the constant of the motor heat, s.

The reducer reduction rate is determined from equality $M_{cr} = M_{t_{close}}$. Its solution is point *A* whereat curves $M_{cr}(i)$ and $M_{t_{close}}(i)$ cross (Fig. 4).

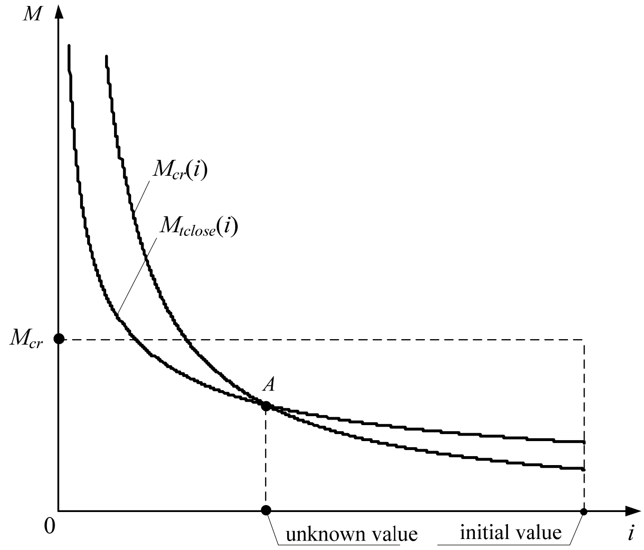

Fig. 4. Torque change curves from expressions (3) and (4), depending on the reducer reduction rate

The Table contains parameters and the choice of IM for a stopcock with a nonretractable spindle of the diameter $D = 1200$ mm, rated head $H_n = 100$ m and maximum admissible head increase in the hydrosystem $\Delta H_{\max} = 40$ m, calculated according to the standard (AOS2-41-4U3) and improved (4AS90L4U3) methods.

Table. The parameters of the pipeline valves ED

Motor type	P_n [kW]	*i*	t_{close} [s]	ΔH_k [m]
AOS2-41-4U3 (unregulated ED)	5.2	250	276	100
4AS90L4U3 (a part of a variable-frequency ED)	2.4	91	132	25

The analysis showed that the power of the IM of a variable-frequency ED of the stopcock, taking into account the nonlinear nature of the change in its hydraulic and mechanical characteristics, is 2.4 kW. This is 2.1 times less than the value of the power calculated using the standard method. The decrease in the reduction rate of the reducer of the pipeline valve variable-frequency ED by 2.7 times made it possible to reduce the time of complete closure of the valve by 2.1 times. At the same time, the increase in pressure in the hydraulic system is within acceptable limits and 4 times less than when using a stopcock unregulated ED.

Conclusions

It has been proved that an effective way to control dynamic loads in the pumping complex consists in the formation of an uneven rate of opening (closing) of the valves due to the significant moment of resistance in the section with a relative degree of opening $\beta \le 0.2$.

It has been shown that a decrease in the stopcock resistance moment (up to 2.5 times) at its complete closure is provided by a reduction in the frequency of the voltage supplied to the induction electric drive of the adjustable pipeline valves.

A method for determining the power of the electric motor and the reduction rate of the reducer of the variable-frequency electric drive of the pipeline valves has been proposed. It is based on:

taking into account the nonlinear dependences of the hydraulic and mechanical characteristics of the regulated pipeline valves;

meeting the conditions of exclusion of the overload on the torque and inadmissible overheat of the stopcock induction motor;

providing the minimum values of the pipeline valves control time and the increase in the head in the hydronetwork, with which a surge in the system is impossible.

The possibility of energy saving in hydrotransport complexes by applying a stopcock variable-frequency electric drive has been shown. This enables decreasing the power of the electric motor and the reducer reduction rate, ensuring a change in the pressure in the pipeline within acceptable limits.

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