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Pump complex electric drive control system taking into account cavitation processes in the pipeline

***Abstract**. It has been determined that cavitation processes in a pump complex are characterized by gas-vapor mixture considerable power that may make up to 25% of hydraulic power of the liquid flow. A mathematical model of a pump complex electric drive control system with a device for recuperation of gas-vapor mixture energy is given. The obtained curves of pressure variation in the hydrosystem have proved the possibility of provision of cavitation protection for electrohydraulic complex by means of a variable-frequency electric drive.*

***Streszczenie.** Zostało wykazane, że procesy kawitacji w układzie pompowym są charakteryzowane przez opary gazu, podnoszące moc hydrauliczną o 25 procent. Pokazano model matematyczny systemu kontroli układu pomp wraz z urządzeniem do rekuperacji energii oparów gazowych. (Otrz7ymane krzywe zmienności ciśnienia w hydrosystemie wskazały na możliwość aplikacji ochrony kawitacyjnej w układzie elektrohydraulicznym przez użycie napęcu elektrycznego o zmiennej częstotliwości. (**System sterowania napędu elektrycznego zespołu pomp przy wykorzystaniu procesów kawitacji w rurze)**.*

Keywords: electrohydraulic complex, cavitation processes, controlled electric drive.
Słowa kluczowe: układ elektrohydrauliczny, procesy kawitacyjne, sterowany napęd elektryczny.

Introduction

If liquid flow pressures decreases or the temperature of the pumped medium changes, the operation mode of pump complexes (PC) is accompanied by development of cavitation processes in the pipeline system. Cavitation is characterized by periodic generation and collapse of cavitation cavities filled with vapor or gas. Such operation modes result in increased wear of hydraulic equipment, variation of PC process-dependent parameters, pipeline chocking and, consequently, growth of liquid transportation power losses [1, 2].

Conventional means of cavitation processes control are based on installation of pipeline protection, adding admixtures to the liquid, injection of liquid or air into the cavitation area [1]. However, such methods only result in reduction of destroying properties of cavitation and are rather complicated and expensive in application.

Paper [3] offers a method for determination of the limits of non-cavitation operation of a PC with a controlled electric drive (ED). It is based on the analyses of the joint conditions of the pump unit operation for the pipeline network and allows determination of the range of permitted values of variation of the pump ED rotation frequency when the displacement is regulated within the required limits.

Variable-frequency ED is rather widely used in PC of various purposes for automatic regulation of process variables. It enables control of appearance of cavitation areas and change of the pump rotation frequency aiming at provision of cavitation protection of hydraulic equipment. That is why improvement of PC power efficiency and reliability by means of development of a system for cavitation processes control by controlled ED in the problems of stabilization of the process variable at the consumer is topical.

Research method

Quantitative assessment of gas-vapor mixture energy at liquid pressure flow is performed below. The following parameters are adopted: head H_p = 62.5 m, displacement Q_p = 1250 m^3/hour, consumed power Np = 250 kW, liquid temperature T_V = 26 ^{0}C, pressure of saturated vapors P_{para} = 3361.06 Pa, pipeline diameter d_{pl} = 0.4 m, liquid density ρ = 1000 kg/m^3, cavitation critical number χ_{kr} = 700 of the pipeline section.

It is assumed that if displacement equals to Q consumption of gas-vapor mixture in the liquid flow makes $Q_{kav} = 0.15\ Q$ [2, 3]. Then hydraulic power of the gas-vapor mixture, W:

$$N_{kav} = p_{pot} Q_{kav} \,. \tag{1}$$

For the considered system, if pipeline pressure is p_{max} = 372780 Pa, displacement is Q_{max} = 0.347 m^3/s, gas-vapor mixture power is N_{kavmax} = 19.4 kW, which makes 7.8 % of the liquid flow power.

In PC operation mode with pressure p_{min} = 176666 Pa and displacement Q_{min} = 0.12 m^3/s, gas-vapor mixture power N_{kavmin} = 3.2 kW (1.28 % of the liquid flow power).

Analysis of the obtained results revealed that cavitation processes in PC are characterized by gas-vapor mixture considerable power making up to 8% of hydraulic power of the liquid flow in maximum displacement modes. In PC with background for more developed cavitation the gas-vapor mixture power may reach 25% of the liquid flow power. In this connection it is expedient to work out devices and control systems for cavitation processes in PC by means of efficient use of cavitation cavities energy.

Fig. 1 shows a functional diagram of automatic control system (ACS) of PC ED at development of cavitation processes in the pipeline, where the following designations are adopted: FC – frequency converter; IM – induction motor; P – pump; CV – check valve; S_1, S_2 – stopcocks at the pump suction and flow rate tubes, respectively; EDRGME – electromechanical device for recuperation of gas-vapor mixture energy; AABD – air automatic bleeding device ; R – receiver; PS_1, PS_2 – pressure sensors in the receiver and pipeline reference point, respectively; S_3 – regulating valve; EM – electric machine; CD – EM control device; ED – regulating valve electric drive; AT– air turbine; EG – electric energy generator; TD – device for tie-in between the generator and the power grid; LC – logic controller; $\beta(t)$, $f(t)$ – signals of assigning the degree of regulating valve opening and displacement voltage frequency, respectively; C – consumer.

The basic task of such ACS of PC ED consists in stabilization of pressure at the pipeline network reference point and accumulation of gas-vapor mixture energy generated during development of cavitation processes in the pipeline, with its further recuperation. The above said can be realized by means of automatic bleeding of the air from the liquid flow into the receiver.

Regulating valve provides regulation of the pressure in the receiver and power at the input of the air turbine. The latter transforms the energy of gas-vapor mixture into electric one by means of an electric generator installed on the same shaft with the turbine.

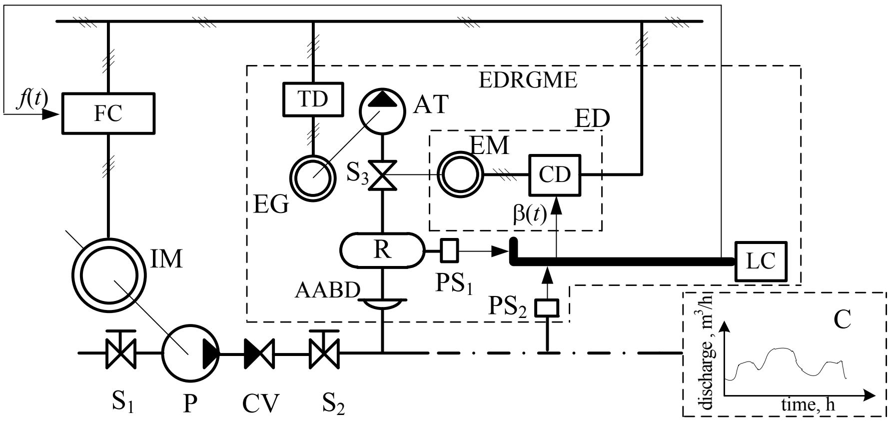

Fig. 1. Functional diagram of ACS of PC ED

Mathematic modelling

A mathematical description of a model of a PC with a pump variable –frequency electric drive, a hydrodynamic network presented by three pipeline sections and a cavitation channel is given in [3, 4].

Let us consider in more detail a mathematical description of EDRGME, whose input parameters include head H_1 at the output of the first section of the hydronetwork and current volume V_{kav} of cavitation cavities.

AABD published characteristic is presented by an approximation polynomial of the form:

(2) $$Q_{otv} = a_{vo} + b_{vo}\Delta p - c_{vo}\Delta p^2$$

where a_{vo}, b_{vo}, c_{vo} – approximation coefficients of the AABD published characteristic (in the analyzed case the approximation coefficients equal to $a_{vo} = 2.21 \cdot 10^{-5}$, $b_{vo} = 5.49 \cdot 10^{-9}$, $c_{vo} = 3.12 \cdot 10^{-15}$), Q_{otv} – AABD output, m^3/s, $\Delta p = p_{pot} - p_{res}$ –pressures difference at the AABD input p_{pot} and output p_{res}, Pa, p_{pot} – liquid flow pressure, Pa, p_{res} – receiver pressure, Pa.

It has been obtained that determination coefficient with the use of the approximation polynomial (2) made 0.986.

Value of flow rate of gas-vapor mixture entering the receiver, m^3/s:

(3) $$\Delta Q_{otv} = Q_{kav} - \left| Q_{kav} - Q_{otv} \right| .$$

Receiver accumulating gas-vapor mixture is represented by a transfer function:

(4) $$W_{res}(p) = \frac{p_{res}(p)}{\Delta Q_{otv}(p) - Q_{tyr}(p)} = \frac{k_{res}}{T_{res}p + 1}$$

where Q_{tyr} – turbine output, m^3/s, $T_{res} = V_{res} / \Delta Q_{otv}$ – receiver time constant, s, V_{res} – receiver volume, m^3, $k_{res} = \frac{c\rho}{S_{res}}$ – receiver proportionality coefficient, kg/s·m^4, c – velocity of sound in the medium, m/s, S_{res} – receiver area, m^2, ρ – gas density, kg/m^3.

The amount of gas-vapor mixture flowing through the regulating valve depends on the degree of its opening and is determined by an expression of the form:

(5) $$Q_{kl} = \beta Q_{tyr}$$

where Q_{kl} – flow rate of gas-vapor mixture, entering through the turbine input, m^3/s, β – degree of the regulating valve opening.

Pressure at the turbine input and losses in it, respectively, Pa:

(6) $$p_{tyr} = p_{res} - \Delta p_{set} ;$$

(7) $$\Delta p_{tyr} = R_{tyr} Q_{tyr}^{\ 2}$$

where $\Delta p_{set} = R_{set} Q_{kl}^{\ 2}$ – pipeline pressure losses, Pa, R_{set} – air resistance, kg/m^7, R_{tyr} – turbine aerodynamic resistance, kg/m^7.

Rotation moment developed by the turbine, Nm:

(8) $$M_{tyr} = \frac{p_{tyr} Q_{kl} \eta_{tyr}}{\omega_{tyr}}$$

where η_{tyr} – air turbine efficiency, ω_{tyr} – angular rotation frequency of the air turbine wheel, s^{-1}.

For the simplicity of the mathematical model the electric generator is represented by a dc machine. Then resistance moment and EMF developed by dc generator are determined by expressions of the following form, Nm and V, respectively:

(9) $$M_{cg} = k\Phi_g I_g ;$$

(10) $$E_g = k\Phi_g \omega_{tyr}$$

where k – structural coefficient, Φ_g – magnetic flux of the dc generator, Wb, I_g – current flowing along the generator armature circuit, A.

Operation of turbine-generator system is described by transfer functions of the form:

(11) $$W_{tyr}(p) = \frac{Q_{tyr}(p)}{p_{tyr}(p) - \Delta p_{tyr}(p)} = \frac{1/R_{tyr}}{T_{tyr}p + 1} ;$$

(12) $$W_{t\omega}(p) = \frac{\omega_{tyr}(p)}{M_{tyr}(p) - M_{cg}(p)} = \frac{1}{J_{tg}p} ;$$

(13) $$W_g(p) = \frac{I_g(p)}{E_g(p) - U_n(p)} = \frac{1/R_g}{T_g p + 1}$$

where J_{tg} – inertia moment of the air turbine-generator system, kgm^2, U_n – load voltage, V, R_g – resistance of the generator armature circuit, Ohm, T_g – generator time electromagnetic constant, s, T_{tyr} – turbine time constant, s.

EDRGME output parameters include: flow rate ΔQ_{otv}, of gas-vapor mixture taken off the liquid flow; maximum $N_{g\,max} = p_{tyr} Q_{kl}$ and current $N_g = U_n I_g$ recuperated power values depending on PC operation mode (regulation of electric generator power is performed by variation of degree β of opening of the regulating valve).

Research of dynamic processes was based on a mathematical model of PC with EDRGME when cavitation processes develop at the *i*-th section of the pipeline.

For PC with parameters: head $H_p = 62.5$ m, flow rate $Q_p = 1250$ m^3/hour, power consumption $N_p = 250$ kW, rotation frequency $\omega_p = 154.17$ s^{-1}, pipeline diameter $d_{pl} = 0.4$ m, pipeline length $l_{pl} = 2300$ m head-versus-time curves (Fig. 2), variation of power in PC (Fig. 3), PU mechanical parameters curves have been obtained (Fig. 4), where: $H_1(t)$ – $H_3(t)$ – head at corresponding sections of the pipeline; $N_d(t)$ – power supplied to the induction motor from the direction of the stator; $N_N(t)$ – pump power; $N_{s1}(t)$ – $N_{s3}(t)$ – power of the liquid flow at corresponding sections of the pipeline; $N_{kav}(t)$ – power losses caused by presence of cavitation processes in the pipeline; $N_g(t)$ – power of recuperation of gas-vapor mixture energy; $M_d(t)$ – moment developed by IM; $M_s(t)$ – resistance moment created by the motor; $\omega(t)$ – angular rotation frequency of the pump electric drive.

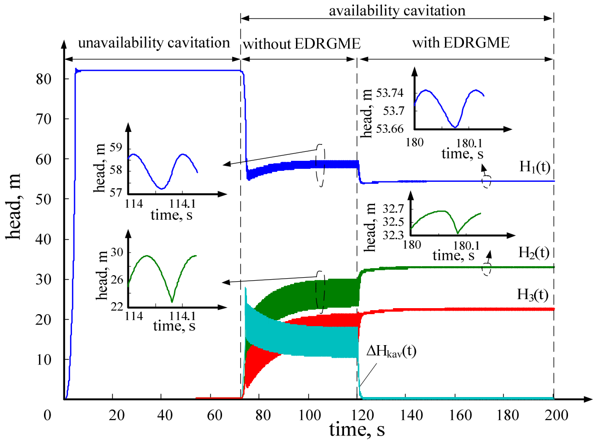

Fig. 2. Head-versus–time curves

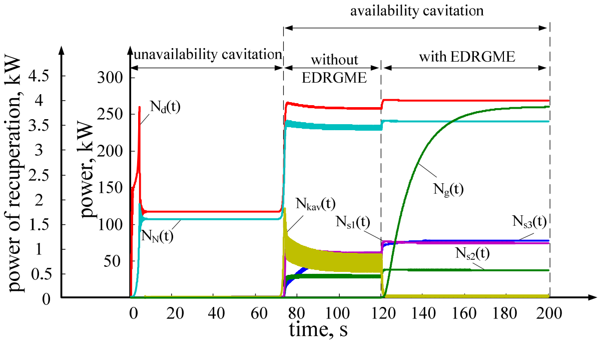

Fig. 3. Curves of power variation in PC

Sections of PC operation without cavitation and with its development are shown in Figs 2 – 4. In the latter case two modes are singled out. The first one is characterized by the presence of head loss due to cavitation. In the second one – head loss is minimized by including EDRGME. In this case recuperation power made 1.8 % of the flow hydraulic power.

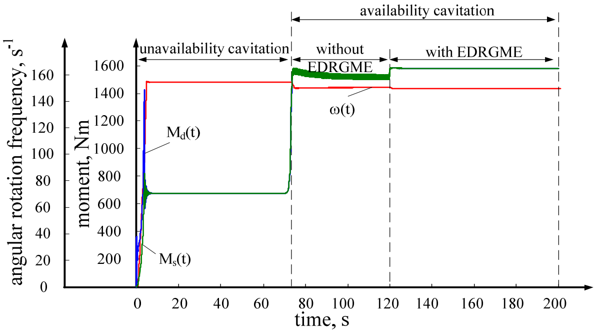

Fig. 4. PC mechanical parameters-versus-time curves

The obtained dynamic head-versus-time and PC hydraulic power-variation curves proved the possibility of reduction of power losses caused by presence of cavitation processes with simultaneous recuperation of gas-vapor mixture energy. It enabled substantiation of the ways of improvement of PC efficiency taking into consideration cavitation processes in the pipeline network:

decrease of the flow velocity below the critical value determined by expression $\upsilon_{kr} = \sqrt{2(p-p)/\rho\chi_{kr}}$;

bleeding of gas-vapor mixture released from the liquid with simultaneous possibility of its energy recuperation.

Realization of the first variant is possible due to a pump controlled electric drive, the second variant implies installation of EDRGME in the places where most air is accumulated in the pipeline.

During operation of water supply systems PC it is often necessary to support pressure at the consumer at a required level. Taking into consideration the above said, the closed-loop automatic control system of PC ED is to meet the following requirements:

provision of pressure stabilization at the consumer where head deviation Δh must not exceed 1%;

minimization of pipeline power losses N_{kav} caused by cavitation processes;

provision of the maximum value of recuperated power N_g of the gas-vapor mixture.

To meet the above mentioned requirements to creation of the closed-loop ACS of PC ED a quality criterion of the following form is proposed:

$$I = \int_0^t \left(K_h \Delta h(t) + K_n \Delta N_{kav}(t) + K_g \Delta N_g(t)\right) dt \rightarrow min \tag{14}$$

where K_h, K_n, K_g – weight coefficients, $\Delta h(t)$ – head discrepancy, p.u., $\Delta N_{kav}(t)$ – relative value of power losses caused by presence of cavitation processes, p.u., $\Delta N_g(t)$ – discrepancy according to power of gas-vapor mixture recuperation, p.u.

The first component in (14) is caused by the necessity of minimization of head deviation at the consumer from the assigned value, p.u.:

$$\Delta h(t) = \frac{H_{zad}(t) - H_{tek}(t)}{H_{zad}(t)}$$

where $H_{zad}(t)$, $H_{tek}(t)$ – assigned and current head values, respectively, m.

The second component is connected with provision of minimum relative value of power losses caused by presence of cavitation processes in the hydrosystem, p.u.:

$$\Delta N_{kav}(t) = \frac{N_{kav}(t)}{N_{NK}(t)}$$

where $N_{NK}(t)$ – current value of power consumed by PC without cavitation processes in the pipeline, kW, $N_{kav}(t)$ – hydraulic power losses caused by presence of cavitation processes in the pipeline, kW.

The third component characterizes deviation of the power of gas-vapor mixture recuperation from the maximum possible value, p.u.:

$$\Delta N_g(t)=\frac{\left|N_{g\,max}(t)-N_g(t)\right|}{N_{g\,max}(t)}$$

where $N_{g\,max}(t)$, $N_g(t)$ – maximum and current values of recuperated power, kW.

Figs. 5 – 7 contain the following curves: head-versus-time, variation of power, moment on the motor shaft, angular rotation frequency and resistance moment created by the pump. Operation sections of PC without cavitation and during its development are shown here. In the latter case control signals for stabilization of the head at the required level are formed with simultaneous minimization of losses due to EDRGME operation. It has been obtained that in the considered case the accuracy of head stabilization at the consumer is in the range of $(0.01\ldots0.03)H_{zad}$.

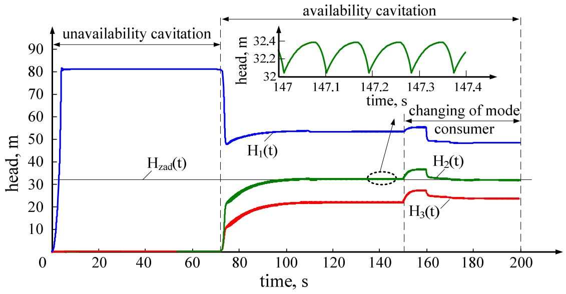

Fig. 5. PC head variation curves

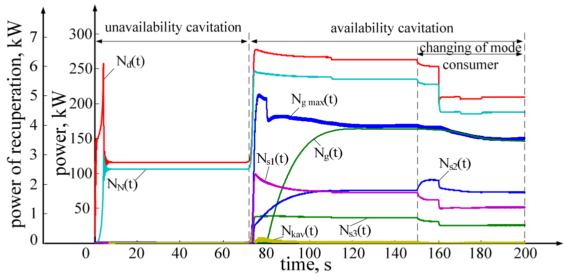

Fig. 6. PC elements power variation curves

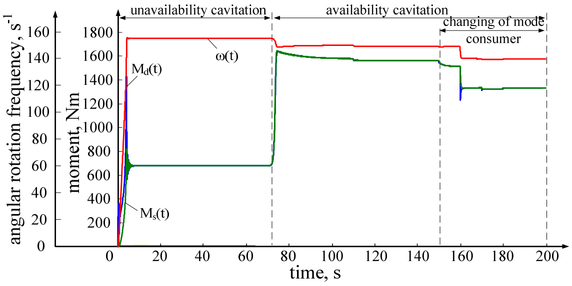

Fig. 7. Moment variation curves and ED angular rotation frequency variation curves

Thus, the proposed structure of ACS of PC ED enables provision of stabilization of pressure at the consumer, minimum power losses caused by cavitation processes in the pipeline and maximum value of recuperated power of gas-vapor mixture.

Use of instantaneous power method proposed in papers [5, 6] for diagnostics and identification of electro-mechanical system parameters the possibility to analyze power losses at all the elements of power channel of the electrohydraulic system on the basic of the developed model of PC ED ACS. It its turn, it will allow assessment of PC efficiency during development to nonlinear hydrodynamic processes in the pipeline.

Conclusions

It has been proved that control of cavitation processes in a hydraulic system can be performed by means of controlled electric drive of the pump complex. It is realized by variation of pump rotation frequency with the aim of regulation of process variables (pressure or flow rate) and simultaneous control of occurrence of cavitation areas in the hydraulic system.

An electromechanical device for recuperation of gas-vapor mixture energy generated at development of cavitation processes in the pipeline, practically entirely reducing head losses in the pipeline network due to cavitation, has been proposed.

A structure of the system of automatic control of the electric drive of the pump complex with an electromechanical device for recuperation of gas-vapor mixture energy, making it possible to minimize power losses due to cavitation and simultaneously recuperate gas-vapor mixture energy at stabilization of the process variable at the consumer, has been substantiated.

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