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Identification of electrohydraulic complex parameters using instantaneous power components

Abstract. *It is proved that identification of electrohydraulic complex parameters is to be based on equations of power balance of all the components of power channel instantaneous power. An electrohydraulic complex equivalent circuit with division of parameters into active resistance and inductive reactance is proposed, which makes it possible to take into consideration inertial loss of head in the pipeline. A sufficient number of identification equations for determination of the hydrosystem necessary parameters are obtained. It is pointed out that the offered energy method can be used to solve problems of identification of parameters of electrohydraulic complexes with group operation of pump units with controlled and uncontrolled pump electric drive.*

Streszczenie. *Przedstawiono metodę identyfikacji parametrów złożonego układu elektrohydraulicznego bazującą na równaniach bilansu mocy. System hydrauliczny jest reprezentowany przez rezystancję i indukcyjność. Zaproponowana metoda może służyć do analizy systemu złożonego z pomp sterowanych elektrycznie.* ***Identyfikacja złożonego systemu elektrohydraulicznego bazująca na chwilowych składowych mocy***

Keywords: electrohydraulic complex, instantaneous power, equations of power balance, identification system, equivalent circuit.
Słowa kluczowe: system elektrohydrauliczny, moc chwilowa, bilans mocy

Introduction

Conditions causing occurrence of nonstationary hydrodynamic processes often take place in the practice of electrohydraulic complexes (EHC) operation. This, in its turn, results in time variations of the main parameters of pump units and pipeline network: head, discharge, efficiency, hydraulic resistance of the pump and hydraulic network [1].

Any variation in EHC operation condition causes redistribution of power at the elements of power channel: electric power supplied to the mechanism shaft, mechanical power of the electric motor, hydraulic power at the pump output, in pipeline network and at the consumer [2, 3].

The above said conditions the topicality of the problems of increasing the power efficiency of operating pumping facilities functioning by means of creating control systems on the basis of power models able to reflect correctly complicated power processes taking place in hydraulic tracts of turbomechanisms and pipeline networks when liquid flow rate and variation of water consumption schedule are regulated.

Instantaneous power method based on formulating equation of instantaneous power signal harmonic components power balance [2–4] has been widely spread recently in solving problems of identification of electromechanical devices parameters. Application of instantaneous power method most completely reflects the pattern of power transformation processes in systems of any physical nature, with signals of arbitrary form, as it is based on the energy conservation law [5].

Purpose of the work is substantiation of the possibility of application of power criterion based on instantaneous power components to solution of the problem of identifying parameters of electrohydraulic complex presented by an equivalent circuit.

Research method

Fig. 1 contains a functional diagram of EHC parameters identification system. It includes: a pump (*P*) with a drive induction motor (*IM*), a frequency converter (*FC*) with integrated control system (*CS*), a pipeline network, a consumer (*C*), a regulated stopcock (*S*), pressure sensors (*PS*), discharge sensors (*DS*), a tachometer generator (*TG*), block of test action formation (*BTAF*), a calculation block (*CB*) containing a block of power model, a block of frequency analysis (*BFA*) and a block of identification (*BI*).

Signals of head $H(t)$, discharge $Q(t)$ and rotation speed $\omega(t)$ of drive motor come to *BPM* where determination of instantaneous power $P_1(t)$ on the pump unit, hydraulic machine output $P_p(t)$, in the pipeline network $P_n(t)$ and at the consumer $P_c(t)$ takes place. Instantaneous power signals decomposition into a constant and an alternating (cosine and sine) components is performed in *BFA* with the use of mathematical analysis method based on Fourier series [3, 4]. A system of identification equations is formed in *BI*. Its solution allows determination of EHC parameters: active hydraulic resistances of the pump, the pipeline and the consumer, inductive reactance and static head in the hydraulic network.

To solve the problem of *BTAF* identification a test harmonic action is provided. It comes to the input of frequency converter control system. In the above analyzed system (Fig. 1) a voltage signal including a constant U_0, V, and a variable U_{var}, V, components is the test assigning action:

$$U_{zad}(t)=U_0+U_{var}\cos(\Omega t-\varphi) \tag{1}$$

where $\Omega=2\pi f$ – circular frequency, s^{-1}; f – frequency of input signal variation, Hz; φ – angle of phase shift in relation to the origin of coordinates, degrees.

Formation of test signal of (1) forms makes it possible to obtain the required number of components in the instantaneous power signal.

Time variation of voltage supplied to the stator windings, in its turn, causes change of relative rotation frequency:

$$\nu(t)=\nu_0+\nu_m\cos(\Omega t-\psi)= =\nu_0+\nu_a\cos(\Omega t)+\nu_b\sin(\Omega t) \tag{2}$$

where ν_0, ν_m – amplitude of the constant and the variable components of rotation frequency signal, respectively; ν_a, ν_b – orthogonal cosine and sine components of relative rotation frequency signal, respectively; ψ – angle of signal phase shift, degrees.

Then discharge at the pump unit output is a time function of the form:

$$Q(t)=Q_n\nu(t)=Q_0+Q_a\cos(\Omega t)+Q_b\sin(\Omega t) \tag{3}$$

where Q_0, Q_a, Q_b – amplitude values of constant and orthogonal cosine and sine components of discharge signal, respectively m^3/s; Q_n – discharge nominal value, m^3/s.

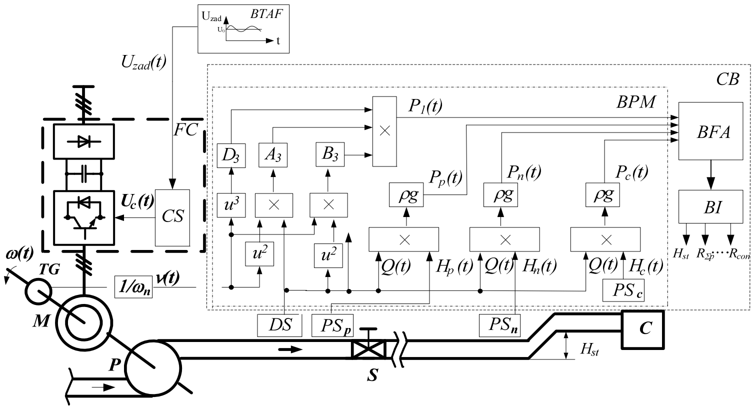


Fig. 1. Functional diagram of electrohydraulic complex parameters identification system

Fig. 2 contains an EHC equivalent electric circuit. In this case pump unit (*PU*) is represented by a hydraulic power source $H_0\nu^2(t)$, m, and a nonlinear active resistance $R_{\Sigma p}=\alpha Q(t)$, kg/m^4s, where H_0 – head, m, developed by the pump at zero supply; $\nu(t)=\omega_i(t)/\omega_n$ – relative rotation frequency; $\omega_i(t),\omega_n$ – current and nominal values of angular velocity, respectively, s^{-1}; α – approximation coefficient taking into consideration viscous forces between liquid layers, between the liquid and the channel walls, which results in power dissipation in the form of heat.

Losses of power in a pipeline containing a source of static back pressure H_{st} are taken into account by an equivalent active and inductive load [4]:

(4) $$Z_n(j\omega)=R_{net}+jL_{net}=\delta/Q(t)+j\gamma\nu(t)$$

where R_{net}, L_{net} – pipeline active and inductive hydraulic resistances, respectively, kg/m^4s; $\delta=0.0034l^4\mu/d^8g^4$, $\gamma=\rho l\beta$ – approximation coefficients taking into consideration liquid characteristic features and geometric parameters of the pump and pipeline hydraulic track; l – length of the pipeline flow section, m; μ – kinematic viscosity, m^2/c; d – pipeline diameter, m; ρ – medium density, kg/m^3; $\beta=1.33$ – correction factor; g – gravitational acceleration, m/c^2.

The consumer is represented by time-invariable active resistance R_{con}, kg/m^4s.

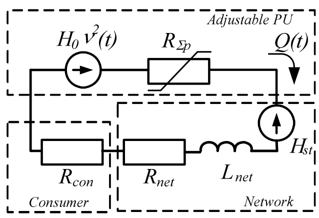


Fig. 2. EHC equivalent circuit

Such an approach based on electrohydraulic analogy principle [6] can be applied to more complicated EHC technological schemes. Fig. 3 a, b shows equivalent circuits taking into account pump parallel and series connection, respectively; Fig. 3 c – cavitation processes in pipeline network are taken into consideration by means of introducing additional cavitation circuit where $H_{kav}\mu(t)$ – generator of cavitation self-oscillations, m; R_{kav},L_{kav} – elements taking into account the growth of pipeline hydrodynamic resistance because of a blub in the liquid flow, kg/m^4s.

Development of an electrohydraulic complex power model

The general equation of power balance for the above given equivalent circuit of EHC is determined by the expression:

(5) $$p_{in}(t)=p_{st}(t)+p_{R_p}(t)+p_{R_{net}}(t)+p_{L_{net}}(t)+p_{R_{con}}(t)$$

where $p_{in}(t)=H_0\nu^2(t)Q(t)$ – instantaneous hydraulic power at the pump unit input; $p_{st}(t)=H_{st}Q(t)$ – pipeline network hydraulic power consumed to overcome back pressure; $p_{R_p}(t)=R_pQ^3(t)=\alpha Q^4(t)$ – power at pump active resistance; $p_{R_{net}}(t)=R_{net}Q^3(t)=\delta Q^2(t)$ – power at pipeline active resistance; $p_{L_{net}}(t)=L_{net}Q(t)\frac{d}{dt}\left(Q^2(t)\right)=$ $=\gamma Q_n\nu^2(t)\frac{d}{dt}\left(Q^2(t)\right)$ – power at pipeline reactance; $p_{R_{con}}(t)=R_{con}Q^3(t)$ – instantaneous hydraulic power at consumer active resistance.

Instantaneous power at the pump unit shaft:

(6) $$\begin{aligned}p_{in}(t)&=H_0\nu^2(t)Q(t)=\\&=H_0(\nu_0+\nu_a\cos(\Omega t)+\nu_b\sin(\Omega t))^2\times\\&\times(Q_0+Q_a\cos(\Omega t)+Q_b\sin(\Omega t))=P_{in\,0}+P_{in\,1a}\cos(\Omega t)+\\&+P_{in\,1b}\sin(\Omega t)+P_{in\,2a}\cos(2\Omega t)+P_{in\,2b}\sin(2\Omega t)+\\&+P_{in\,3a}\cos(3\Omega t)+P_{in\,3b}\sin(3\Omega t)\end{aligned}$$

where:

$P_{in0}=H_0Q_0\nu_0^2+H_0Q_0\nu_a^2/2+H_0Q_0\nu_b^2/2+H_0Q_a\nu_0\nu_a+$ $+H_0Q_b\nu_0\nu_b$ – constant component of instantaneous hydraulic power signal;

$P_{in\,1a}=2H_0Q_0\nu_0\nu_a+H_0Q_a\nu_0^2+3H_0Q_a\nu_a^2/4+H_0Q_a\nu_b^2/4+$ $H_0Q_b\nu_a\nu_b/2$ – cosine component of power first harmonic;

$P_{in\,1b}=H_0Q_b\nu_0^2+H_0Q_b\nu_a^2/4+3H_0Q_b\nu_b^2/4+2H_0Q_0\nu_0\nu_b+$ $+H_0Q_a\nu_a\nu_b/2$ – sine component of instantaneous hydraulic power first harmonic at the pump input;

$P_{in\,2a}=H_0Q_0\nu_a^2/2-H_0Q_0\nu_b^2/2+H_0Q_a\nu_0\nu_a-H_0Q_b\nu_0\nu_b$ – cosine component of hydraulic power second harmonic at pump unit input;

$P_{in\,2b}=H_0Q_0\nu_a\nu_b+H_0Q_b\nu_0\nu_a+H_0Q_a\nu_0\nu_b$ – sine component of instantaneous power second harmonic;

$P_{in\,3a}=H_0Q_a\nu_a^2/4-H_0Q_a\nu_b^2/4-H_0Q_b\nu_a\nu_b/2$ – cosine component of instantaneous hydraulic power third harmonic at pump input;

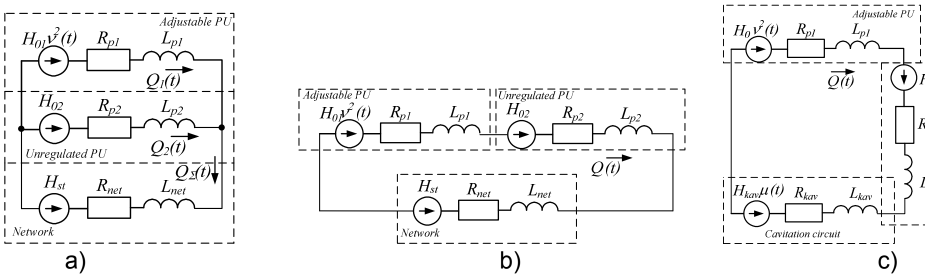


Fig.3. Equivalent circuits of operating pump units connected in parallel (a) and in series (b), taking cavitation into account (c)

$P_{in\ 3b} = H_0 Q_b \nu_a^2/4 + H_0 Q_a \nu_a \nu_b/2 - H_0 Q_b \nu_b^2/4$ – sine component of instantaneous hydraulic power third harmonic at pump input.

Expressions for determination of instantaneous power at the rest of the elements of EHC power channel are obtained in a similar way.

Then energy balance equation system for constant and harmonic components of instantaneous power at the elements of EHC power channel is of the form:

$$
\left.
\begin{aligned}
&P_{in\,0} = P_{st\ 0} + P_{R_p 0} + P_{R_{net} 0} + P_{L_{net} 0} + P_{R_{con} 0};\\
&P_{in\,1a} = P_{st\ 1a} + P_{R_p 1a} + P_{R_{net} 1a} + P_{L_{net} 1a} + P_{R_{con} 1a};\\
&P_{in\,1b} = P_{st\ 1b} + P_{R_p 1b} + P_{R_{net} 1b} + P_{L_{net} 1b} + P_{R_{con} 1b};\\
&P_{in\,2a} = P_{R_p 2a} + P_{R_{net} 2a} + P_{L_{net} 2a} + P_{R_{con} 2a};\\
&P_{in\,2b} = P_{R_p 2b} + P_{R_{net} 2b} + P_{L_{net} 2b} + P_{R_{con} 2b};\\
&P_{in\,3a} = P_{R_p 3a} + P_{L_{net} 3a} + P_{R_{con} 3a};\\
&P_{in\,3b} = P_{R_p 3b} + P_{L_{net} 3b} + P_{R_{con} 3b};\\
&0 = P_{R_p 4a} + P_{L_{net} 4a};\\
&0 = P_{R_p 4b} + P_{L_{net} 4b}
\end{aligned}
\right\} \qquad (7)
$$

where $P_{in\,0}, P_{st\ 0}, P_{R_p 0}, P_{R_{net} 0}, P_{L_{net} 0}, P_{R_{con} 0}$ – constant components of instantaneous power at the pump unit shaft, power necessary to overcome back pressure, instantaneous powers at the pump active resistance, at the pipeline active resistance and inductive reactance and active resistance at the consumer, respectively;

$P_{in\,1a}, P_{st\ 1a}, P_{R_p 1a}, P_{R_{net} 1a}, P_{L_{net} 1a}, P_{R_{con} 1a}, P_{in\,2a}, P_{R_p 2a}, P_{R_{net} 2a}, P_{L_{net} 2a}, P_{R_{con} 2a}, P_{in\,3a}, P_{R_p 3a}, P_{L_{net} 3a}, P_{R_{con} 3a}, P_{R_p 4a}, P_{L_{net} 4a}$ – amplitude values of cosine component of instantaneous power 1st – 4th harmonics at the corresponding EHC elements;

$P_{in\,1b}, P_{st\ 1b}, P_{R_p 1b}, P_{R_{net} 1b}, P_{L_{net} 1b}, P_{R_{con} 1b}, P_{in\,2b}, P_{R_p 2b}, P_{R_{net} 2b}, P_{L_{net} 2b}, P_{R_{con} 2b}, P_{in\,3b}, P_{R_p 3b}, P_{L_{net} 3b}, P_{R_{con} 3b}, P_{R_p 4b}, P_{L_n 4b}$ – amplitude values of sine component of instantaneous power 1st – 4th harmonics at the corresponding EHC elements.

To determine five unknown EHC parameters (active hydraulic resistances of the pump, pipeline and consumer, inductive reactance and static head in the hydronet) five first identification equations of system (7) are used. They reflect the pattern of power balance among the most important components of instantaneous power in EHC power channel.

Their solution enabled obtaining the following analytical expressions for determination of EHC equivalent circuit parameters:

static head

$$
\begin{aligned}
H_{st} = {} & H_0\left(\nu_0^2 + \nu_a^2/2 + \nu_b^2/2 + Q_a\nu_0\nu_a/Q_0 + Q_b\nu_0\nu_b/Q_0\right) - \\
& - R_{con}\left(Q_0^2 + Q_a^2/2 - Q_b^2/2\right) - \alpha\left(0.375Q_a^4/Q_0 - 1.5Q_a^2Q_b^2/Q_0 - \right.\\
& \left. - Q_0^3 - 3Q_0Q_a^2 - 0{,}375Q_b^4/Q_0 - 3Q_0Q_b^2\right) + \gamma\left(2Q_n\nu_0^2 - \right.\\
& - Q_nQ_a\nu_0^2/Q_0 + Q_n\nu_a^2 + Q_n\nu_b^2 - Q_nQ_aQ_b\nu_a^2\Omega/2Q_0 + \\
& + Q_nQ_a\nu_a\nu_b\Omega/2Q_0 - 2Q_nQ_b\nu_0\nu_a\Omega - Q_n\Omega\nu_0\nu_b/Q_0 + \\
& + Q_nQ_aQ_b\nu_b^2\Omega/2Q_0 - Q_nQ_a\nu_b^2/2Q_0 + \\
& \left. + Q_nQ_b^2\Omega\nu_a\nu_b/2Q_0\right) + \delta\left(-Q_0 - Q_a^2/Q_0 - Qb/Q_0\right);
\end{aligned}
$$

approximation coefficients included in expressions for determination of the pump and pipeline network active resistance and inductive reactance

$$
\begin{aligned}
\alpha = {} & \left[H_0\left(Q_0\nu_0\nu_a + Q_a\nu_0^2 + 0.75Q_a\nu_a^2 + 0{,}25Q_a\nu_b^2 + \right.\right.\\
& \left. + 0{,}5Q_b\nu_a\nu_b\right) - H_{st}Q_a - 2\delta Q_0Q_a - \gamma\left(2Q_nQ_aQ_b\nu_0\nu_a\Omega - \right.\\
& - Q_nQ_a^2\nu_0\nu_b\Omega - Q_nQ_0Q_a\nu_a\nu_b\Omega + 2Q_nQ_0Q_b\nu_0^2\Omega + \\
& \left. + 0.5Q_nQ_0Q_b\nu_b^2\Omega + 1.5Q_nQ_0Q_b\nu_a^2\Omega + Q_nQ_b^2\nu_0\nu_b\Omega\right) - \\
& \left. - R_{con}\left(3Q_0^2Q_a + 0.75Q_a^3 + 0.75Q_aQ_b^2\right)\right] \Big/ \left[Q_0Q_a\left(3Q_b^2 + 3Q_a^2 + 4Q_0^2\right)\right];
\end{aligned}
$$

$$
\begin{aligned}
\delta = {} & H_0\left(0.5\nu_0^2/Q_0 + 0.125\nu_a^2/Q_0 + 0.375\nu_b^2/Q_0 + \nu_0\nu_b/Q_b + \right.\\
& \left. + 0.25Q_a\nu_a\nu_b/Q_0Q_b\right) - 0.5H_{st}/Q_0 - \alpha\left(1.5Q_a^2 + 1.5Q_b^2 + 2Q_0^2\right) - \\
& - \gamma\left(-0.5Q_nQ_a^2\nu_0\nu_a\Omega/Q_0Q_b + 0.5Q_nQ_b\nu_0\nu_a\Omega/Q_0 - \right.\\
& - 0.25Q_nQ_a\nu_a^2\Omega/Q_b - 0.75Q_nQ_a\nu_b^2\Omega/Q_b - Q_nQ_a\nu_0\nu_b\Omega/Q_0 + \\
& \left. + 0.5Q_n\nu_a\nu_b\Omega - Q_nQ_a\nu_0^2\Omega/Q_b\right) - R_{con}\left(1.5Q_0 + \right.\\
& \left. + 0.375Q_a^2/Q_0 + 0.375Q_b^2/Q_0\right);
\end{aligned}
$$

$$
\begin{aligned}
\gamma = {} & H_0\left(0.5Q_0\nu_a^2 - 0.5Q_0\nu_b^2 + Q_a\nu_0\nu_a - Q_b\nu_0\nu_b\right) + \alpha\left(1.5Q_a^2Q_b^2 - \right.\\
& \left. - 3Q_0^2Q_a^2 + 3Q_0^2Q_b^2 - 0.5Q_a^4 + 0.5Q_b^4\right) + \delta\left(0.5Q_a^2 + 0.5Q_b^2\right) - \\
& - R_{con}\left(1.5Q_0Q_a^2 + 1.5Q_0Q_b^2\right) \big/ Q_bQ_n \times \left(2Q_a\nu_0^2 + 2Q_0Q_a\nu_0\nu_b + \right.\\
& \left. + 2Q_0\nu_0\nu_a + Q_a\nu_a^2 + Q_a\nu_b^2\right);
\end{aligned}
$$

active hydraulic resistance of the consumer

$$
\begin{aligned}
R_{con} = {} & H_0\left(0.33\nu_a\nu_b/Q_aQ_b + 0.33\nu_0\nu_a/Q_0Q_a + 0.33\nu_0\nu_b/Q_0Q_b\right) + \\
& + \alpha\left(-0.33Q_b^2/Q_0 - 2Q_0 - 0.33Q_a^2/Q_0\right) - 0.33\delta/Q_0 + \\
& + \gamma\left(-0.66Q_n\nu_0\nu_b\Omega/Q_a + 0.33Q_nQ_a\nu_0^2\Omega/Q_0Q_b - \right.\\
& - 0.33Q_nQ_b\nu_0^2\Omega/Q_0Q_a + 0.17Q_nQ_a\nu_a^2\Omega/Q_0Q_b - \\
& - 0.17Q_nQ_b\nu_b^2\Omega/Q_0Q_a + 0.67Q_n\nu_0\nu_a\Omega/Q_b + \\
& + 0.17Q_nQ_a\nu_b^2\Omega/Q_0Q_b - 0.17Q_nQ_b\nu_a^2\Omega/Q_0Q_a .
\end{aligned}
$$

Experimental verification

Theoretical results are confirmed on the basis of EHC laboratory facility (Fig. 4) including two centrifugal pumps, equal as to centrifugal pump parameters, with drive induction motors; forked pipeline network with locking and regulating fittings installed therealong; a receiving tank; frequency converters to change rotation frequency of pump drive motors; measuring devices (current, voltage, rotation frequency, pressure and flow sensors). Technical parameters of electric motors and pumps installed on the physical model are given in tables 1, 2.

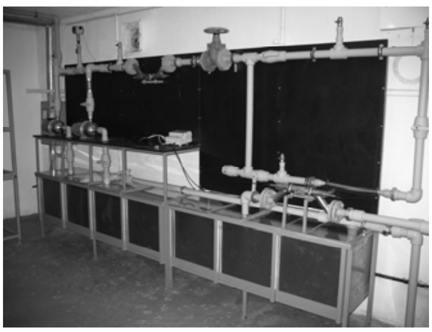


Fig. 4. General view of EHC physical model

Table 1. Motor engineering performance

Parameter name	Parameter value
Rated power [W]	830
Rated voltage [V]	380
Mains frequency [Hz]	50
Rotation frequency [rpm]	2900

Table 2. Pump and pipeline engineering performance

Parameter name	Value
Maximum discharge [m^3/h]	8
Maximum head [m]	20.8
Power [W]	550
Nominal head [m]	18
Pipeline diameter [m]	0.04
Pipeline length [m]	6

Variation curves of discharge, head, power on the pump unit shaft, hydraulic power at its output and in the pipeline network are shown in Fig. 5.

In this case test assigning action supplied to the input of experimental hydrotransport facility FC control system is of the form:

$$U_{zad}(t) = U_0 + U_{var}\cos(\Omega t - \varphi) = \\ = 3.5 + 1.5\cos(\Omega t - 15^\circ)$$

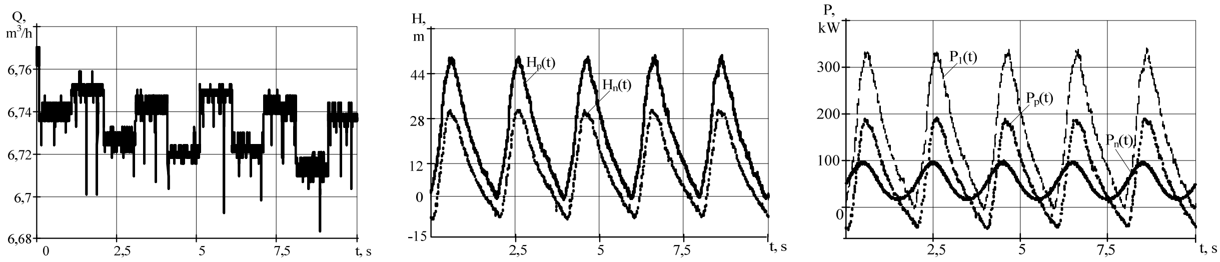
where $\Omega = 3.14$ s^{-1}, $f = 0.5$ Hz.

Use of the analyzed power models (5), (6) and frequency analysis of the obtained signals of instantaneous power made it possible to create a system of identification equations of the form (7).

EHC parameters obtained using the proposed power method and experimental researches are shown in Table 3. The analysis demonstrated that the error of parameters calculated on the basis of power method is (5-7)%.

Table 3. EHC parameters

EHC parameters	Method of determination	
	Theoretical	Experimental
H_{st}, m	0.35	0.33
α	$9.19 \cdot 10^7$	$9.68 \cdot 10^7$
δ	89.236	84.98
γ	$7.98 \cdot 10^3$	$7.5 \cdot 10^3$
R_{con}, $kg/m^4 s$	$1.405 \cdot 10^7$	$1.489 \cdot 10^7$



a) b) c)

Fig. 5. Experimental curves of hydrotransport facility parameters variation:

a) – discharge $Q(t)$; b) – head $H_p(t)$ at the output of the pump unit and in the pipeline network $H_n(t)$;

c) – power $P_1(t)$ at the pump unit shaft, at the output of hydraulic machine $P_p(t)$ and in the pipeline network $H_n(t)$

Conclusions

The use of instantaneous power method for identification of operating electrohydraulic complexes parameters has been substantiated. It has been demonstrated that identification is to be based on equations of power balance of instantaneous power components of all the elements of electrohydraulic complex power channel.

Presentation of the electrohydraulic complex by an equivalent circuit with division of parameters into active resistance and inductive reactance made it possible to obtain a sufficient number of identification equations for determination of the necessary parameters of the hydrosystem.

The proposed power method can be used for solutions to problems concerning identification of parameters for more complicated equivalent circuits of the hydrotransport complexes, the problems taking into consideration group operation of pump units with pump controlled and uncontrolled electric drive, cavitation processes in pipeline network, technological nonlinearities showing when equipment operation conditions change.

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