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Power criterion in problems of leakage identification in hydrotransport complex

***Abstract**. The use of power criterion obtained on the basis of frequency analysis of hydraulic power signal in the problems of leakage identification is substantiated. It is shown that leakage formation in a pipeline system is accompanied by distortion of hydraulic power signal, appearance of higher order harmonics, growth of instantaneous power sine component. It is offered to use power distortion nonlinear coefficient as information index when a leakage in the hydrosystem is identified.*

Streszczenie.** W pracy uzasadniono użycie kryterium mocy otrzymane na bazie analizy częstotliwości hydraulicznego sygnału mocy w problemach identyfikacji upływu. Pokazano, że formowanie upływności w systemie rurociągowym jest stowarzyszone z zaburzeniem hydraulicznego sygnału mocy, obecności harmonicznych wyższego rzędu, wzrost mocy chwilowej w harmonicznej podstawowej. Zaoferowano użycie nieliniowego współczynnika zaburzenia mocy jako wskaźnika informacyjnego kiedy identyfikowany jest upływ w hydrosystemie. **(Kryterium mocy w problemach identyfikacji upływu systemach hydrotransportowych).

Keywords: hydrotransport complex, leakage, mathematic model, hydraulic power, power processes.
Słowa kluczowe: system hydrotransportowy, upływ, model matematyczny, moc hydrauliczna, procesy mocowe.

Introduction

In the process of operation of hydrotransport complexes (HTC) of public and industrial water supply systems, oil-transfer stations, etc. conditions under which technological parameters (head and flow) exceed their overload capacities are possible. As a result of this, various contingencies: hydraulic impacts, leakages, cavitations, surge, etc. may occur [1].

The most common undesirable phenomena include pipeline network leakages conditioned by unsatisfactory technical state of the water-mains, increased dynamic loads when pump parameters are regulated, abrupt actuation of protective fittings, illegal liquid withdrawal, etc.

Existing methods of diagnostics of leakages and liquid unaccounted flow use the values of head and flow, their derivatives, and vibroacoustic indices as controlled parameters [2]. The mentioned methods are rather complicated to realize, require installation of expensive equipment and do not provide exact and unambiguous result in finding the leakage.

The analysis has shown that presence of leakage in HTC pipeline network results not only in distortion of head and hydraulic power signals form, but also in the change of power indices: consumed and hydraulic power, HTC efficiency, etc. Hydraulic power $P_h(t)$ is determined by the product of head $H(t)$ and flow $Q(t)$ at pump output, sections of pipeline network, the consumer. Frequency analysis of instantaneous hydraulic power $P_h(t)$ makes it possible to single out information characteristics typical of a HTC particular emergency state.

Application of power criterion most completely reflects the processes of power consumption, transference and transformation between the source (pump) and the consumer (pipeline network with liquid withdrawal devices) under both static and dynamic operation conditions. In this connection it is expedient to use the instantaneous power method [3] characterized by high information value and efficiency when power transformation processes are analyzed. Such an approach is widely used in the problems of electric motor parameter identification, diagnostics of electromechanical systems technical state and provides the possibility to analyze power processes not only in electric, but also in other systems: mechanical, electromechanical, hydraulic, etc., where initial power forming signals may be of a complicated character (periodic or nonperiodic) [4].

Problem statement

Analysis of power processes in hydrotransport complex and substantiation of the use of power criterion in the problems of leakage identification in the pipeline network.

Research method

A functional diagram of the system of HTC pipeline network leakage identification (Fig.1) includes: a pump with a drive induction motor (*IM*), a frequency converter (*FC*), a pipeline network with *n* number of sections, controlled stopcocks ($S_1 \ldots S_n$) with electric drives ($ED_1 \ldots ED_n$), pressure sensors (*PS*), flow sensors (*FS*), voltage sensors (*VS*), current sensors (*CS*) and control system (*CSYS*) containing power model block (*PMB*), control block (*CB*).

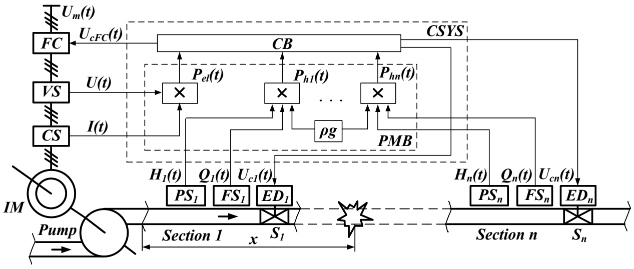

Fig. 1. Functional diagram of the system of leakage identification in HTC: $U(t)$, $I(t)$ – signals of voltage and current, respectively; $U_{cFC}(t)$, $U_{c1}(t)$, $U_{cn}(t)$ – signals of control of frequency converter, electric drives of the first and the n-th stopcocks, respectively

PMB calculates instantaneous power $P_{el}(t)$ at the output of frequency converter, pump $P_{hp}(t)$ and pipeline network sections $P_{h1}(t),..,P_{hn}(t)$. Application of Fourier series theory enables presentation of power signals by trigonometric sums and singling out instantaneous power components: constant and variable (cosine and sine) components [3]. Frequency analysis of instantaneous power signals in a hydrosystem without a leakage and in its presence provides a possibility to evaluate the degree of damage and its location.

HTC refer to objects with distributed parameters, and processes taking place therein are described by means of telegraph equation method [1]. A pipeline network is a long line in which head and flow can change continuously at different cross sections, which is conditioned by route water consumption sources and the ones concentrated at particular points. Telegraph equations are solved by means of finite elements method allowing one to present a pipeline network as a finite number of quadripoles, and pressure and productivity within the section are assumed to be constant. For *i*-th quadripole equations of head and flow are of the form [1]:

$$(1)\qquad \begin{cases} H_i - H_{i-1} + l_0 l_s \dfrac{dQ_i}{dt} + r_0 l_s Q_i \left|Q_i\right| = 0; \\ \dfrac{dH_i}{dt} + c_0 \dfrac{1}{l_s}\left(Q_i - Q_{i-1}\right) = 0 \end{cases}$$

where $H_i, Q_i, H_{i-1}, Q_{i-1}$ – head and productivity at the output and input of *i*-th quadripole, respectively, m, m^3/s; $r_0 = \dfrac{\lambda}{S^2 d}\dfrac{1}{2g}$ – pipeline hydraulic resistance reduced to a length unit, s^2/m^6; λ – hydraulic friction coefficient; S – pipeline cross section area, m^2; d – pipeline diameter, m; l_s – section length, m; g – gravitational acceleration, m/c^2; *c* = 1400 m/c – speed of propagation of sound in liquids; $c_0 = c^2/Sg$, $l_0 = 1/Sg$ – shock wave propagation speed and pipeline unit segment length reduced to a unit of pipeline cross section area, 1/m, s^2/m^3, respectively.

Pump unit work is described by a head-flow characteristic of the following form:

$$(2)\qquad H_p = A_2 \nu^2 + B_2 \nu Q_s + C_2 Q_s^{\,2}$$

where A_2, B_2, C_2 – are approximation coefficients depending on turbomechanism design features and determined according to its nameplate *H*(*Q*) characteristic; $\nu = n_i / n_n$ – pump impeller relative rotation frequency; n_i, n_n – current and nominal values of pump impeller rotation frequency, respectively, rad/s; H_p – head at pump output, m; Q_s – fixed withdrawal at the pipeline end cross section, m^3/s.

Inertia processes in the pump unit are taken into account by a transfer function of the form:

$$(3)\qquad W_p(p) = \frac{1}{T_p p + 1}$$

where $T_p = J_n \omega_n / M_n$ – pump time constant, s; M_n – nominal torque at the pump shaft, Nm; J_n – pump nominal inertia moment, kgm^2.

Hydraulic power in the system is equal to:

$$(4)\qquad P_h(t) = \rho g H_p(t) Q_s(t)$$

where ρ – fluid density, kg/m^3.

A HTC simplified technological diagram and a mathematical model block diagram for analysis of power processes in pipeline network with a leakage are shown in Fig. 2, a and Fig. 2, b, respectively. The following equipment parameters are assumed in modeling:

pump unit with nominal head H_n = 50 m and flow Q_n = 0.055 m^3/s;

pipeline network 2000 m long and d=0.24 m across;

consumer characterized by a fixed fluid withdrawal at the end of the pipeline network;

leakage-forming block providing the possibility of presenting a constant leakage $Q_l = const$ or a time-variable leakage $Q_l = f(t)$.

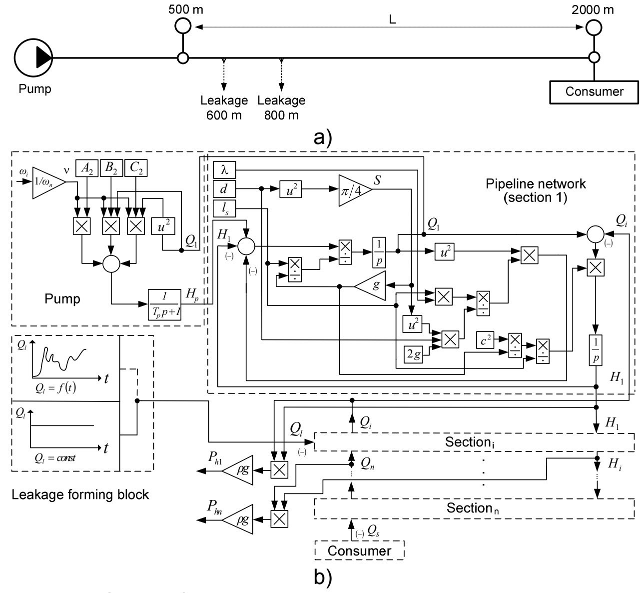

Fig. 2. HTC simplified technological diagram (a) and mathematical model block diagram (b)

Research results

Modeling resulted in obtaining hydraulic power $P_h(t)$ variation curves at the control point at the distance of 500 m from the pump when a leakage with volume flow of 10% of the nominal one occurs at the distance of 600 and 800 m from the pump (Fig. 3, Fig. 4, a).

It was found out that a sudden appearance of a leakage in the pipeline network (Fig. 4, a) is accompanied by distortion of hydraulic power signals. The closer the leakage is situated to the measurement point, the more explicit the signal $P_h(t)$ distortion connected with the leakage is. When the leakage location is removed from the measurement point, signal and delay time $P_{h600}(t)$ and $P_{h800}(t)$ (phase shift between two nearest analyzed curves) is increased, vibrations decrease and harmonic composition of hydraulic power signals changes.

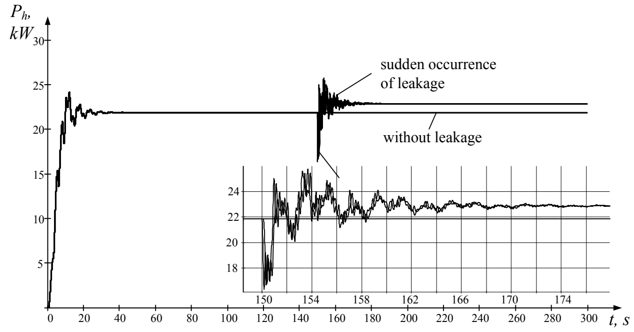

Fig. 3. Curves of hydraulic power change when a sudden leakage occurs in the pipeline network

Fig. 4,b shows spectra of hydraulic power signals with the period of time $T_{pe} = 2L/c$ for signal decomposition, where L – distance from the measurement point to the end of the pipeline, m (Fig. 2, a).

For the considered case $T_{pe} = 2.14$, which corresponds to the time of propagation of the pressure wave from the measurement point (500 m) to the end of the pipeline and backwards (Fig. 4, a). Analysis of the amplitude spectra of signals $P_{h600}(t)$ and $P_{h800}(t)$ showed the presence of higher order harmonics 1, 2,..,12 at a sudden occurrence of a leakage.

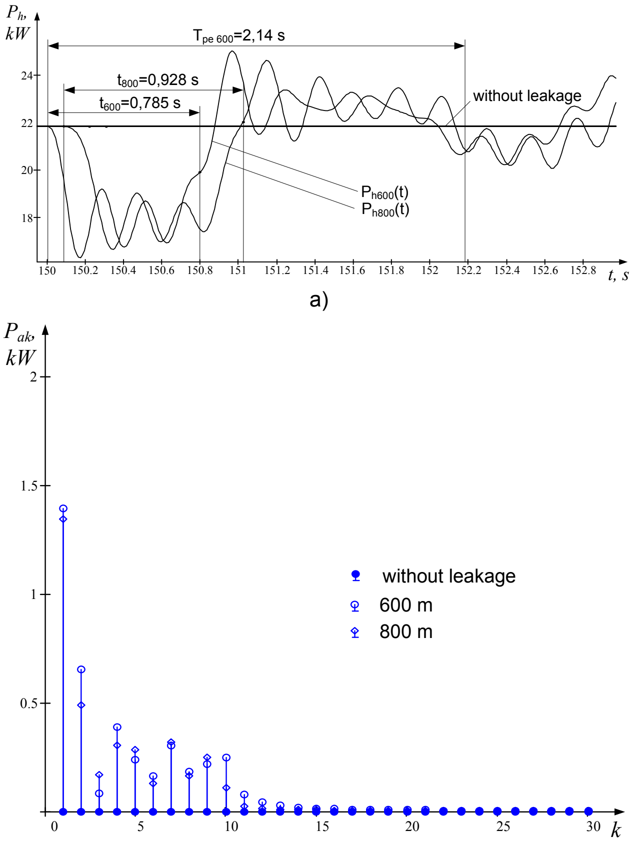

Fig.4. Curves of hydraulic power change at a sudden occurrence of leakage at the distance of 600 and 800 m from the pump (a) and their amplitude spectra (b)

The above said is confirmed by the growth of the coefficient of power signal nonlinear distortions $k_{Ph} = \sqrt{\sum_{k=2}^{k=20} (P_{hk}/P_{h1})^2}$. When there is no leakage, k_{Phwl} = 0.00024; when the leakage is at the distance of 800 m from the pump, k_{Ph800} = 0.698; when the leakage is at the distance of 600 m from the pump, k_{Ph600} = 0.807. The obtained results are connected with appearance of alternating-sign components in power signal $P_h(t)$:

cosine component $P_{hka} = \frac{1}{T_{pe}} \int_0^{T_{pe}} P_h(t) cos(k\Omega t) dt$;

sine component $P_{hkb} = \frac{1}{T_{pe}} \int_0^{T_{pe}} P_h(t) sin(k\Omega t) dt$

where k – power harmonic number; Ω – signal circular frequency.

Fig. 5 contains amplitude spectra of cosine and sine components of hydraulic power in the presence of a leakage in the pipeline network. The analysis showed that the leakage volume increases, the value of instantaneous power sine component grows, which is conditioned by the processes of hydraulic energy dissipation from the pipeline as a result of leakage.

The distance from the control point of the pipeline network to the place of leakage is determined by dependence [1]:

(5) $$x = tc - x_{500}$$

where t – time of propagation of pressure wave from the control measurement point to the leakage and backwards, s; x_{500} – location of measurement point (in this case 500 m).

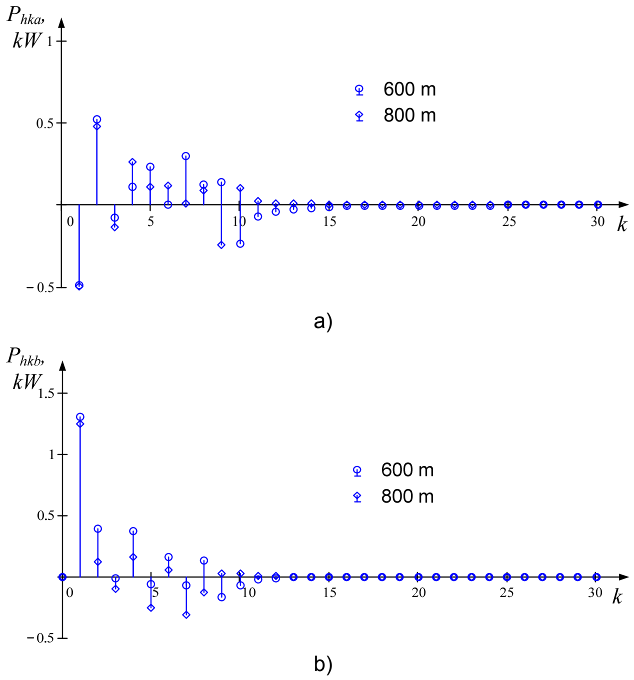

Fig.5. Amplitude spectra of cosine (a) and sine (b) components of hydraulic power at a sudden occurrence of a leakage at the distance of 600 and 800 m from the pump

Obviously, transient processes conditioned by leakage in the pipeline network complicate in the presence of forking and local resistances in the hydraulic system, airlocks, gravity sections, appearance of several simultaneous breaks in the pipeline, etc. A complicated character of leakage variation results in growth of hydraulic power sine component, increase of its efficient value. Qualitative evaluation of signal $P_h(t)$ implies formation of a clear system of identification features allowing one to determine the nature of the contingency with sufficient accuracy.

Experimental verification

To confirm the results of mathematic modeling experimental research of power processes in HTC in the presence of a leakage in the hydrosystem was carried out.

A HTC physical model (Fig. 6) includes two centrifugal pumps, equal as to their diameters, 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.

A sudden appearance of leakage in the pipeline network was provided by an abrupt turning on a tap installed between two measurement points: at the pump output – $P_{h1}(t)$ and at the end of the pipeline network – $P_{h2}(t)$. Tap turning on was accompanied by free outflow of the liquid out of the systems. Curves of hydraulic power change at measurement points are shown in Fig. 7.

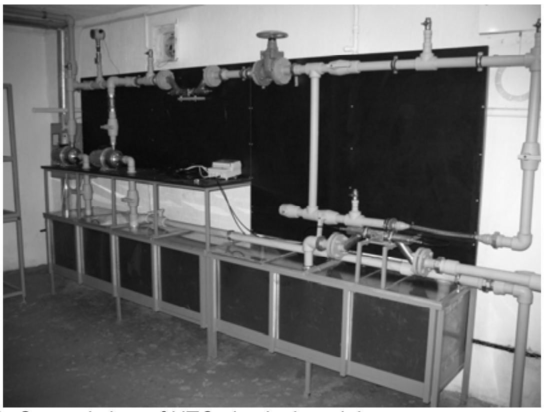

Fig. 6. General view of HTC physical model

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. Engineering performance of centrifugal pumps

Parameter name	Parameter value
Maximum discharge [m^3/hour]	8
Maximum head [m]	22
Rated power [W]	550

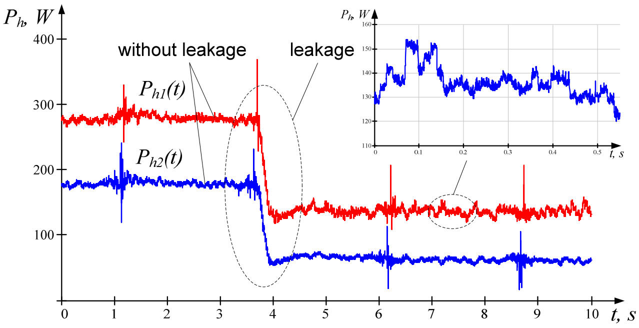

Fig. 7. Experimental curves of hydraulic power change at sudden occurrence of leakage

The analysis of power $P_{h1}(t)$ amplitude spectra (Fig. 8) showed growth of harmonics 1, 2,..,20 as well as decrease of constant component when a leakage appears. Presence of small amplitude power harmonics in a system without leakage is connected with hydraulic noise (turbulent phenomena) conditioned by a forked structure of the pipeline network. The value of the coefficient of power nonlinear distortions for the case of operation without leakage k_{Phwl} = 0.081, when a leakage appears – k_{Phl} = 0.308. The obtained result confirms a complicated character of energy exchanging processes in a hydrosystem with a leakage, which is described above.

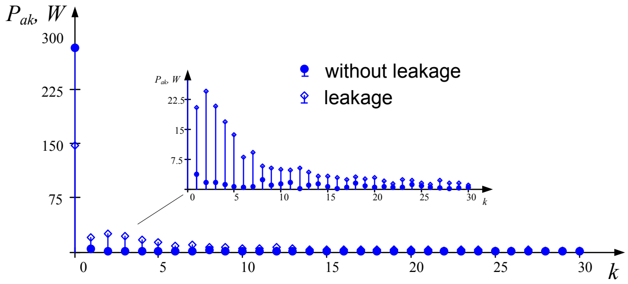

Fig. 8. Hydraulic power amplitude spectrum at a sudden occurrence of a leakage

Conclusions

A structure of leakage identification system for a hydrotransport complex has been offered. The system structure is based on the use of a power criterion – hydraulic power signals frequency analysis. It has been shown that an abrupt occurrence of a leakage in the hydrosystem results in a significant change of the form of hydraulic power signal, appearance of higher order harmonics, growth of alternating-sign (sine) component of hydraulic power. It has been proposed to use power nonlinear distortion coefficient, whose value grows when a leakage in the hydrosystem appears, as one of information indices. The above said is conditioned by variation of energy exchanging processes in the pipeline system. The obtained result is fundamental during creating systems of emergency state control in a hydrotransport complex to prevent development of contingency situations and improve the reliability of operation of electric and hydraulic equipment.

REFERENCES

[1] Vishnevskii K.P. Transient processes in water supply head systems. – M.: Agropromizdat, 1986. – 135 p. (in Russian)

[2] Golianov A.A. Analysis of pipeline leakage detection methods // Transport and oil products storage. – 2002. No.11. – P. 5–14 (in Russian)

[3] Rod'kin D. I., Resolving the power of polyharmonic signals into components, *Russian Electrical Engineering*, 2003, no. 74 (3), pp. 39-44.

[4] Zagirnyak M., Rod'kin D., Korenkova T., "Enhachement of instantaneous power method in the problems of estimation of electromechanical complexes power controllability", Przeglad Elektrotechniczny (Electrical review), 2011, № 12b, pp. 208 – 212.

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