PRZEGLĄD ELEKTROTECHNICZNY

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Organ Stowarzyszenia Elektryków Polskich • Wydawnictwo SIGMA-NOT Sp. z o.o.

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doi:10.15199/48.2018.01.01

The automation of the procedure of the electrohydraulic complex power harmonic analysis

***Abstract**. A possibility of application of the method for the harmonic analysis of power signals in the non-stationary modes of electrohydraulic complexes operation is demonstrated. To automate the procedure of power harmonic analysis an energy analyzer is created. It enables the research of the electrohydraulic complex power processes when they change in real time with preservation of all information about the initial power-forming signals. It is obtained that the wave processes in the pipeline in non-stationary modes are accompanied by increase of the power signals variable components, especially, their low-frequency component. It is proposed to use the indices based on determination of the power root-mean-square values to assess the energy conversion processes in the electrohydraulic complex.*

Streszczenie.** W pracy zademonstrowano możliwość aplikacji metody analizy harmonicznych sygnałów mocy w niestacjonarnych modach układów elektrohydraulicznych. Do zautomatyzowania procesu stworzono procedurę harmonicznej analizy mocy w analizatorach energii. Umożliwia to badanie procesów w układach elektrohydraulicznych w czasie realnym, podczas ich zmiany z zachowaniem wszystkich informacji o początkowych sygnałach. Otrzymano, że niestacjonarne procesy falowe w rurociągu stowarzyszone są ze wzrostem składników sygnałów mocy, specjalnie tych o niskiej częstotliwości. Zaproponowano wykorzystanie indeksów bazujących na określeniu wartości skutecznej w celu oszacowania procesów przemiany energetycznej w układzie elektrohydraulicznym. **(Automatyzacja procedur analiz harmonicznych układu elektrohydraulicznego)

Keywords: electrohydraulic complex, non-stationary processes, power, energy analyzer, energy controllability.
Słowa kluczowe: układ elektrohydrauliczny, procesy niestacjonarne, moc, energia, analizator energii, sterowalność energii

Introduction

Electrohydraulic complexes (EHC) represent a complicated energy conversion system. When the modes of EHC operation change, the conditions for occurrence of such non-stationary hydrodynamic processes as: head pulsations, surges, cavitation oscillations, etc. are created [1–3]. The analysis [1, 2] revealed that EHCs are characterized by low controllability of electrohydraulic equipment in non-stationary operation modes. It results in occurrence of various emergency situations. Moreover, the conventional methods to EHC equipment control in emergency situations solve only local problems and work when a breakage really takes place. Papers [4, 5] contain the proof of the direct relation of EHC controllability and the processes of energy consumption or generation in the power channel. In this case time-variable power component characterizes the process of energy exchange between the EHC elements and results in reduction of its energy controllability.

Taking the above said into consideration, the automation of the procedure of the harmonic analysis of the processes of energy conversion in EHC power channel is relevant. It enables to determine the technological contour nonlinear processes influence on the hydrosystem energy modes.

Research method

When various non-stationary processes occur in the pipeline system, energy processes in EHC are of the character of periodic steady oscillations of power at the analyzed time interval [6, 7]. So, cavitation processes occurrence in the hydrosystem results in periodic time variation of the head and discharge. It, in its turn, changes the load condition of PU operation which results in the variation of the electric current and, consequently, the electromagnetic power supplied to the motor stator windings. The above said allows presentation of the signals of voltage and current, head and discharge by a generalized Fourier series and also provides approximation of the signals of power (electrical, hydraulic one) in a form of harmonic components sum.

So, time signals of voltage and current of the electric motor phase *A* can be presented by relations of the form [7–9]:

$$u_A(t)=\sum_{n=1}^{N}U_n\cos(\Omega_n t-\varphi_n)=\sum_{n=1}^{N}U_{na}\cos(\Omega_n t)+\sum_{n=1}^{N}U_{nb}\sin(\Omega_n t); \quad (1)$$

$$i_A(t)=\sum_{m=1}^{M}I_m\cos(\Omega_m t-\psi_m)=\sum_{m=1}^{M}I_{ma}\cos(\Omega_m t)+\sum_{m=1}^{M}I_{mb}\sin(\Omega_m t) \quad (2)$$

where n,m – numbers of voltage and current harmonics, respectively; N,M – quantity of voltage and current harmonic components; φ,ψ – phase angles of voltage and current signals, respectively; Ω_n,Ω_m – circular frequencies of voltage and current signals variation, respectively; $U_{na}=U_n\cos\varphi_n$, $U_{nb}=U_n\sin\varphi_n$, $I_{ma}=I_m\cos\psi_m$, $I_{mb}=I_m\sin\psi_m$ – orthogonal cosine and sine components of voltage and current signal, respectively.

The time function of phase *A* electric power taking into account (1), (2) is of the form [7, 8]:

$$p_{el\,A}(t)=u_A(t)i_A(t)=$$

(3) $$=\left(\sum_{n=1}^{N}U_{na}\cos(\Omega_n t)+\sum_{n=1}^{N}U_{nb}\sin(\Omega_n t)\right)\times$$
$$\times\left(\sum_{m=1}^{M}I_{ma}\cos(\Omega_m t)+\sum_{m=1}^{M}I_{mb}\sin(\Omega_m t)\right).$$

Then the three-phase total electric power supplied to the electric motor stator windings is equal to the sum of powers of separate phases:

(4) $$p_{el}(t)=p_{el\,A}(t)+p_{el\,B}(t)+p_{el\,C}(t)= \\ =u_A(t)i_A(t)+u_B(t)i_B(t)+u_C(t)i_C(t)$$

where $p_{el\,B}(t), p_{el\,C}(t)$ – time functions of the power of phases *B* and *C*, respectively; $u_B(t), u_C(t), i_B(t), i_C(t)$ – phase voltages and currents, respectively.

After transformation of the power signal in the frequency domain the following will be obtained [7, 9]:

(5) $$p_{el}(t)=\sum_{k=1}^{K}P_{k0}+\sum_{k=1}^{K}P_{ka}\cos(\Omega_k t)+\sum_{k=1}^{K}P_{kb}\sin(\Omega_k t)$$

where $\sum_{k=1}^{K}P_{k0}$ – total constant power component; $\sum_{k=1}^{K}P_{ka}$, $\sum_{k=1}^{K}P_{kb}$ – amplitude value of the total cosine and sine power components, respectively; Ω_k – angular frequency of the *k*-th power harmonic $(\Omega_k=|\Omega_n\pm\Omega_m|)$; *K* – quantity of power harmonic components.

As mentioned above, EHC non-stationary operating modes cause occurrence of various wave processes in the pipeline. They are characterized by periodic time variation of the head $H(t)$ and discharge $Q(t)$:

(6) $$H(t)=\sum_{j=1}^{J}H_{j\,0}+\sum_{j=1}^{J}H_j\cos(\Omega_j t-\delta_j)= \\ =\sum_{j=1}^{J}H_{j\,0}+\sum_{j=1}^{J}H_{j\,a}\cos(\Omega_j t)+\sum_{j=1}^{J}H_{j\,b}\sin(\Omega_j t);$$

(7) $$Q(t)=\sum_{l=1}^{L}Q_{l0}+\sum_{l=1}^{L}Q_l\cos(\Omega_l t-\gamma)= \\ =\sum_{l=1}^{L}Q_{l0}+\sum_{l=1}^{L}Q_{la}\cos(\Omega_l t)+\sum_{l=1}^{L}Q_{lb}\sin(\Omega_l t)$$

where $j,\ l$ – number of the harmonics of the head and discharge signals, respectively; $J,\ L$ – quantity of the harmonics of the head and discharge signals, respectively; $H_{j\,0}, H_j$, $Q_{l\,0}, Q_l$ – amplitude values of the constant and variable components of the head and discharge signals, respectively; $H_{j\,a}=H_j\cos\delta;\ H_b=H_j\sin\delta$, $Q_{l\,a}=Q_l\cos\gamma;\ \ Q_{l\,b}=Q_l\sin\gamma$ – orthogonal cosine and sine components of the head and discharge signals, respectively; Ω_j, Ω_l – circular frequency of the head and discharge signals, respectively; δ, γ – angles of shift of the head and discharge signals in relation to the origin of coordinates, respectively.

Under such conditions the synthesis of the hydraulic power time function at the EHC i-th element by a generalized Fourier series is justified:

(8) $$p_{h\,i}(t)=\rho g H_i(t)Q_i(t)= \\ =\sum_{r=1}^{R}P_{rh0\,i}+\sum_{r=1}^{R}P_{rha\,i}\cos(\Omega_r t)+\sum_{r=1}^{R}P_{rhb\,i}\sin(\Omega_r t)$$

where $g=$ 9.81 m/s^2 – gravitational acceleration; ρ – liquid density; $H_i(t)$ – head signal; $r,\ R$ – number and quantity of the hydraulic power signal harmonics, respectively; $P_{rh\,0\,i}, P_{rha\ i}, P_{rhb\ i}$ – amplitude values of the constant and orthogonal cosine and sine components of hydraulic power, respectively; Ω_r – circular frequency of the hydraulic power signals.

The effective power obtained as a root-mean-square value of the time function of power (electric, hydraulic) at the *i*- th element of EHC energy conversion serves as a measure of assessment of the quality of energy processes in EHC [9]:

(9) $$P_{ei}=\sqrt{1/T\int_0^T p_{h\,i}^2(t)dt}= \\ =\sqrt{\left(\sum_{r=1}^{R}P_{rh0i}\right)^2+\left(\sum_{r=1}^{R}P_{rhai}\right)^2\Big/2+\left(\sum_{r=1}^{R}P_{rhbi}\right)^2\Big/2}.$$

For the comparative assessment of the energy conversion processes in various modes of the EHC operation a coefficient of energy controllability is proposed [4, 5]:

(10) $$k_{pc}=P_{e\,i\,id}\big/P_{e\,i\,r}$$

where $P_{e\,i\,id}, P_{e\,i\,r}$ – effective power in an ideal (in the absence of non-stationary hydrodynamic processes) and real (at their occurrence) systems at the *i*-th element of energy conversion, respectively.

It should be noted that it is possible to assess energy controllability of both separate elements on the basis of $P_{e\,hi\,id}$ and $P_{e\,hi\,r}$, and the whole system, using the values of effective input electric power in an ideal $P_{eel\,id}$ and real $P_{eel\,r}$ EHC for the analysis.

Development of the energy analyzer structure

The analysis of EHC energy processes in non-stationary operating modes was performed on the basis of the laboratory physical model described in [6].

For the generation and frequency analysis of electrical (current, voltage), technological (head, discharge) and energy (electric and hydraulic power) signals the structure of the controlling and measuring block (CMB) of the laboratory plant contains an energy analyzer software module. It includes: a block 1 of processing the input signals coming directly from the sensors; a block 2 of generation of the time function of the power obtained by multiplication of the initial signals; a signal spectrum analyzer 3 enabling representation of the curves of currents and voltages, heads and discharges and also power signals by a trigonometric series in the form of a sum of constant and harmonic (cosine and sine) components.

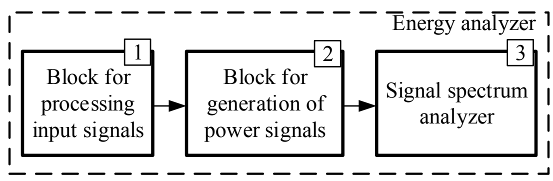

Fig. 1. Energy analyzer structure

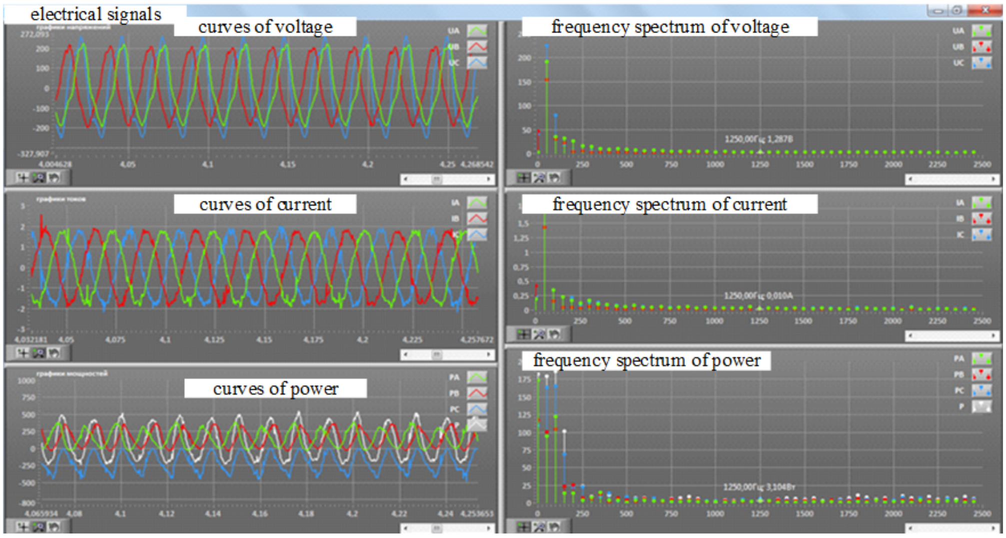

Fig. 2. Window mapping the electrical signals and their spectra during the development of cavitation in the hydrosystem

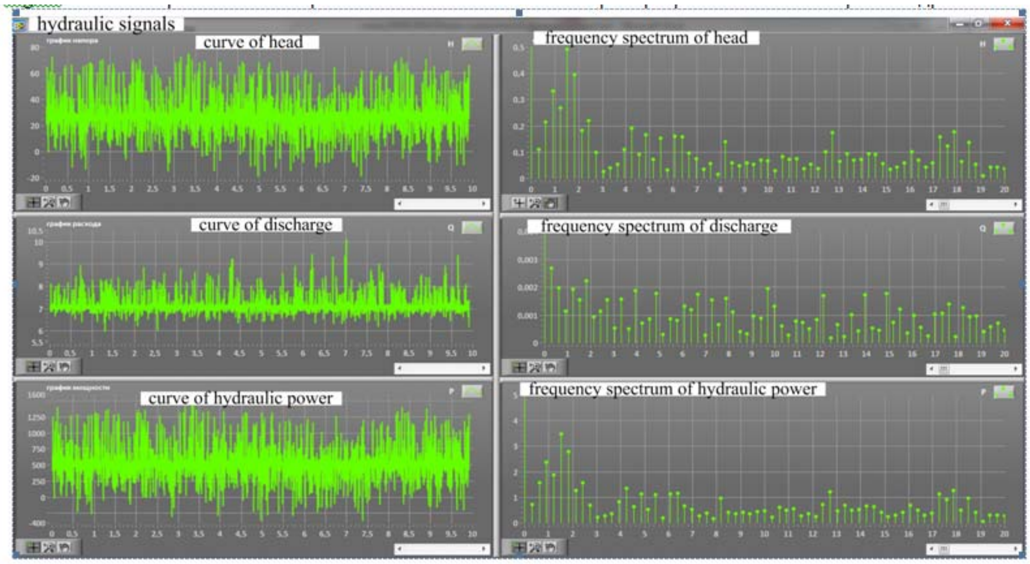

Fig. 3. Window mapping the hydraulic signals and their spectra during the development of cavitation in the hydrosystem

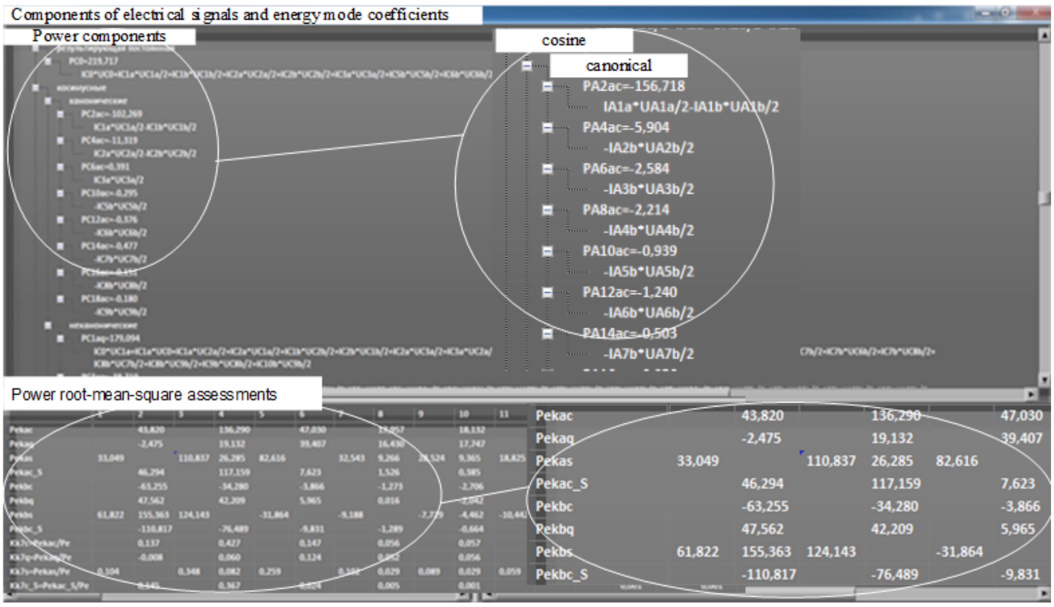

Fig. 4. Window mapping the orthogonal components of voltage, current and power and their root-mean-square assessments

The spectrum analyzer allows representation of the time signals of electrical parameters (current, voltage and power) in a three-phase system, total electromagnetic power supplied to the electric motor stator (Fig. 2), as well as signals of hydraulic parameters (head, discharge and power) both at the output of the pumping unit and in the pipeline network (Fig. 3). The frequency characteristic of the obtained curves is reflected by the spectra (amplitude, phase ones) for different components (cosine or sine) of the analyzed signals (Fig. 2, 3).

The possibilities of the energy analyzer include generation of mathematical functions describing harmonic components of power in the form of the product of the initial signal orthogonal harmonic components forming power as well as their root-mean-square assessments (Fig. 4).

By way of example, Figs. 2, 3 contain curves of variation of phase voltages, currents and phase powers as well as curves of head, discharge and hydraulic power at the pump output during development of cavitation processes in the system with the frequency of $f_{kav} = 0.3$ Hz. The harmonic analysis of the signals of head $H_p(t)$ and hydraulic power $p_{hp}(t)$ at the pump output revealed that cavitation oscillations are accompanied by the occurrence of head and power variable low-frequency components (Fig. 3). Table 1 shows the values of effective power and energy controllability coefficient for the different degrees of cavitation n_{kav} development, where $n_{kav} = V_{cur}/V_0$, V_0, V_{cur} – the initial and current values of the volume of the cavitation cavity, respectively; $P_{e\,el}$, $P_{e\,p}$, P_{econ} – the effective value of electric and hydraulic powers at the pump output and at the consumer, respectively. The analysis of the obtained results revealed that great values n_{kav} result in the growth of the root-mean-square value of power and, consequently, in the deterioration of EHC energy controllability coefficient k_{pc}

Table 1. Values of effective power and energy controllability coefficient

Degree of development of cavitation	$P_{e\,el}$, VA	$P_{e\,p}$, VA	P_{econ}, VA	k_{pc}
$n_{kav1} = 3.7$	216.937	51.82	38.402	1.0
$n_{kav2} = 7$	225.976	51.433	38.41	0.96
$n_{kav3} = 19.7$	341.063	51.468	38.419	0.636
$n_{kav4} = 26$	467.647	51.893	38.461	0.464
$n_{kav5} = 31.3$	478.89	51.457	38.469	0.452

Conclusions

It has been demonstrated that the use of the method for (electrical, hydraulic) power signals harmonic analysis makes it possible to assess the energy conversion processes in the electrohydraulic complex in the non-stationary modes of its operation.

The automation of the procedure of the electrohydraulic complex power frequency analysis enables the research of the energy processes during their variation in real time with preservation of complete information about the initial signals forming power.

The use of the indices based on determination of root-mean-square values of power both at separate elements and in the whole system has been justified for the assessment of the energy conversion processes and energy controllability of the electrohydraulic complex.

It has been obtained that when nonlinear hydrodynamic processes occur, the power variable components, especially their low-frequency component, increase in the technological contour of the electrohydraulic complex. It results in the growth of the effective value of power and, consequently, in the decrease of the energy controllability of the electrohydraulic system. The above said deserves special attention in the problems of creation of the systems of control and protection of electrohydraulic equipment in non-stationary modes of operation.

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