PRZEGLĄD ELEKTROTECHNICZNY

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Mathematical and virtual modeling of operating modes of electrohydraulic units with automated electric drive

Matematyczne i wirtualne modelowanie trybów pracy urządzeń elektrohydraulicznych z automatycznym napędem elektrycznym

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Abstract: The physical, mathematical and virtual models of the electrohydraulic unit was developed to expand the range of experimental and theoretical research of the operating modes of electromechanical and hydraulic equipment, and high-quality training of electrical engineering specialists. To reduce dynamic loads in the hydraulic system and improve the efficiency of the electrohydraulic unit, a control system based on a frequency-controlled electric drive of a centrifugal pump and pipeline fittings was proposed.

Keywords: mathematical model, virtual laboratory model, electrohydraulic unit, variable-frequency electric drive, electromechanical system

Streszczenie: W artykule przedstawiono wyniki opracowanych modeli fizycznych, matematycznych i wirtualnych układu elektrohydraulicznego, celem poszerzenia zakresu badań eksperymentalnych i teoretycznych z uwzględnieniem trybów pracy urządzeń elektromechanicznych i hydraulicznych oraz zapewnienia wysokiej jakości szkolenia specjalistów z branży elektrotechnicznej. Aby zmniejszyć obciążenia dynamiczne w układzie hydraulicznym i poprawić sprawność układu elektrohydraulicznego, zaproponowano układ sterowania oparty na sterowanym częstotliwościowo napędzie elektrycznym pompy odśrodkowej i armatury rurociągowej.

Słowa kluczowe: model matematyczny, wirtualny model laboratoryjny, jednostka elektrohydrauliczna, napęd elektryczny o zmiennej częstotliwości, układ elektromechaniczny

Introduction

One of the largest consumers of electricity in both the industrial and municipal sectors are electromechanical systems (EMS) of electrohydraulic units (EHU), which combine objects of various physical nature with certain constant and variable characteristics [1], [2]. The electric drive, pumps, shut-off valves, and pipeline network must be considered as interconnected electromechanical and hydraulic elements, the operating mode of which depends on the consumer's work schedule, which varies over time. EHUs are characterized by rather low controllability in non-stationary modes, which is caused by different schemes for connecting pumping units with a regulated and unregulated electric drive (ED), the complex geometric configuration of the pipeline network, the operation of hydraulic equipment, the development of nonlinear hydrodynamic processes in the hydraulic system, etc. This leads to increased vibrations of the equipment, significant fluctuations in the torque on the pump shaft, pressure surges in the pipeline and, as a result, to a reduction in the service life of electromechanical and hydraulic equipment, and considerable financial costs for eliminating accidents.

As experience shows [3]–[5] the implementation of automated electric drive systems in electrohydraulic units based on frequency converters ensures high energy efficiency of the electromechanical system.

It allows to significantly reduce the consumption of electrical energy, and also helps to eliminate excessive pressure increase in pipeline networks, which, accordingly, leads to the elimination of water hammer, reduction of bursts of main pipelines, and fluid savings.

Taking into account the above, it is relevant to research the operating modes of electrohydraulic units with a regulated electric drive when changing the technological parameters of the consumer based on mathematical and virtual laboratory models. It allows to substantiate the choice of theoretical methods and technical solutions to ensure energy-efficient and reliable operation of electro-hydraulic complexes for various purposes.

Research method and results

In order to research the operating modes of the automated electric drive of the electrohydraulic unit, a physical laboratory model of a small-scale experimental unit was developed (Fig. 1). It includes: two centrifugal pumps equipped with a variable-frequency electric drive; a branched pipeline system containing horizontal and vertical sections with installed shut-off, regulating and protective valves; receiving tanks; frequency converters; a system of control and measuring equipment based on current, voltage, rotation frequency, pressure and discharge sensors; a device for connecting control and measuring and executive equipment with a computer based on analog-to digital (ADC) and digital-to-analog (DAC) converters.

Fig. 1. General view of EHU physical laboratory model

The electrohydraulic plant operates on the principle of a circulation system, where a tank with greater capacity is the receiving and output capacity. Back pressure in the hydraulic system is created by a second tank (of smaller capacity) installed at the highest point of the pipeline network. Engineering performance of the electrohydraulic equipment is shown in Table 1.

Such a physical model of the EHU EMS allows solving a whole range of research and applied problems: to study the static and dynamic characteristics of the operation of pumping units operating on a real hydraulic network with backpressure during throttling and frequency regulation; to analyze the energy processes occurring in the EHU power channel, assess the impact of the development of non-stationary processes (cavitation, surge oscillations, water hammer) on the electrical, electromechanical and technological parameters of electro-hydraulic equipment; analyze the impact of the control rate and the closing trajectory of pipeline valves with an adjustable electric drive on dynamic loads in the hydraulic system etc.

Table 1. The engineering performance of the laboratory stand equipment

Parameter name	Parameter value
Rated power, W	830
Rated voltage, V	380
Rated current, A	1.7
Mains frequency, Hz	50
Rotation frequency, rpm	2900
Maximum discharge, m³/hour	8
Maximum head, m	22
Rated power, W	550

The development of virtual models of an electrohydraulic unit with an automated electric drive is based on a mathematical description of the static and dynamic characteristics of the physical equipment used. So, the main operating characteristics of pumps are described by dependences of the type [6]–[8]:

$$H_p = A_2 \nu^2 + B_2 \nu Q_p + C_2 Q_p^{\,2} \tag{1}$$

$$N_p = A_3 \nu^2 Q_p + B_3 \nu Q_p^{\,2} + D_3 \nu^3 \tag{2}$$

where:
H_p – head at the pump output, m;
Q – pump capacity, m³/s;
N_p – power consumed by the pump, W;
A_2, B_2, C_2, A_3, B_3, D_3 – approximation coefficients of pump published data;
$\nu = \omega_i / \omega_n$ – relative rotation velocity of pump impeller;
ω_i / ω_n – pump current and nominal angular velocity, respectively, s^{-1}.

Pumping unit dynamic properties are taken into account by a transfer function of the type:

$$W_p(s) = \frac{Q_p(s)}{H_p(s) - \Delta H(s)} = \frac{k_p}{T_p s + 1} \tag{3}$$

where:
$k_p = Q_p / H_p$ – pump proportionality coefficient;

$T_p = 4(D_2 - D_1) \Big/ \Omega z \ln \frac{D_2}{D_1}$ – pump time constant, s;

ΔH – head losses in the pipeline, m;

D_1, D_2 – input and output diameters, respectively, of the pump impeller circular grid, m;

Ω – liquid relative velocity in the inter-blade space of the circular grid, m/s;

z – number of circular grid blades.

Induction motor (IM) model is represented by a differential equation system in the form of flux linkages in coordinate system "u ,v ,0":

$$(4)\quad \begin{cases} \frac{d\psi_{1u}}{dt} = -\frac{R_1}{L_1\sigma}\psi_{1u} + \frac{R_1 L_m}{L_1 L_2 \sigma}\psi_{2u} + \omega_{0e}\psi_{1v} + U_{1m}; \\ \frac{d\psi_{1v}}{dt} = -\frac{R_1}{L_1\sigma}\psi_{1v} + \frac{R_1 L_m}{L_1 L_2 \sigma}\psi_{2v} - \omega_{0e}\psi_{1u}; \\ \frac{d\psi_{2u}}{dt} = -\frac{R_2'}{L_2\sigma}\psi_{2u} + \frac{R_2' L_m}{L_1 L_2 \sigma}\psi_{1u} + \omega_{2e}\psi_{2v}; \\ \frac{d\psi_{2v}}{dt} = -\frac{R_2'}{L_2\sigma}\psi_{2v} + \frac{R_2' L_m}{L_1 L_2 \sigma}\psi_{1v} - \omega_{2e}\psi_{2u}; \\ M = \frac{3}{2} p_n \frac{L_m}{L_1 L_2 \sigma}(\psi_{1v}\psi_{2u} - \psi_{1u}\psi_{2v}) \end{cases}$$

where:

M – electromagnetic moment, Nm²;

p_n – number of poles pairs;

L_m – stator and rotor windings mutual inductance, Hn;

Ψ – magnetic flux, Vb;

L_1, L_2 – stator and rotor inductance, respectively, Hn;

R_1, R_2 – stator and rotor active resistance, respectively, Om.

Pipeline network hydraulic characteristic is of a nonlinear type and is determined by values of static H_{st} and dynamic H_{dyn} heads:

$$(5)\qquad H_{net} = H_{st} + H_{dyn} = H_{st} + R_{net}Q^2$$

where R_{net} – pipeline hydraulic resistance depending on pipeline length, diameter, wall material, properties of the pumped liquid, s²/m⁵.

To describe wave processes in hydraulic networks the principles of electric-hydraulic analogy are applicable, as equations of wave distribution in pipes are similar in their form to the laws of electromagnetic waves distribution:

$$(6)\quad \begin{cases} \frac{\partial H_{net}}{\partial x} + \frac{1}{gS}\frac{\partial Q}{\partial t} + \frac{\lambda}{d}\frac{1}{S^2}\frac{Q|Q|}{2g} = 0 \\ \frac{\partial H_{net}}{\partial t} + \frac{c^2}{gS}\frac{\partial Q}{\partial x} = 0 \end{cases}$$

where:

$S = \pi d^2/4$ – cross-section area, m²;

d – pipeline diameter, m;

λ – pipeline resistance dimensionless coefficient;

c – velocity of sound propagation in the medium, m/s (for water c = 1450 m/s).

Lock-control valves installed in delivery pump branches are designed for smooth change of the amount of the pumped medium and are characterized by a certain rate of opening/closing.

Pipeline valves in pumping complexes present elements with nonlinear hydraulic characteristic. Considerable increase of hydraulic resistance coefficient ξ occurs at certain critical value β_{cr} of opening/closing degree. A stopcock hydraulic resistance coefficient is described by a function of the form:

$$(7)\qquad \xi = A\left((1/\beta)-1\right)^C + B\left((1/\beta)-1\right)^D + \xi_0$$

where

C, B, C, D, – coefficients of approximation of pipeline valves hydraulic characteristic;

ξ_0 – coefficient of hydraulic resistance when valves are completely open β = 1.

In expression (7) parameter β depends on valve control rate, which influences the character of transient processes in EHU. It's worth mentioning that the ABCD coefficient values were determined by fitting a polynomial to the measurement data obtained from a physical laboratory model. This method allows for greater functional resolution and is commonly used to model nonlinear relationships in various fields of science and technology.

The use of computer simulators, virtual laboratory stands or trainers as an alternative tool for studying the operating modes of physical equipment by simulating it on virtual models has been an effective means of training engineering and technical personnel in the electromechanical field recently [12]–[14].

The virtual laboratory model (VLM) of the EHU proposed in the paper includes a set of instrumental and modeling tools for researching the characteristics of electrohydraulic equipment both in normal modes and in emergency situations. Fig. 2 shows a graphical interface and virtual models of the EHU VLM developed using the software package LabVIEW. The main window of the VLM interface contains a simulation model block (SMB), which displays the operation of one pumping unit with a variable-frequency electric drive on the pipeline network; a control and management panel (CMP) of the EHU parameters; a main menu (MM), which is intended for selecting training tasks and saving the training result in the form of a report; a characteristics display block (CDB) of the EHU operating modes. The virtual models of EHU elements

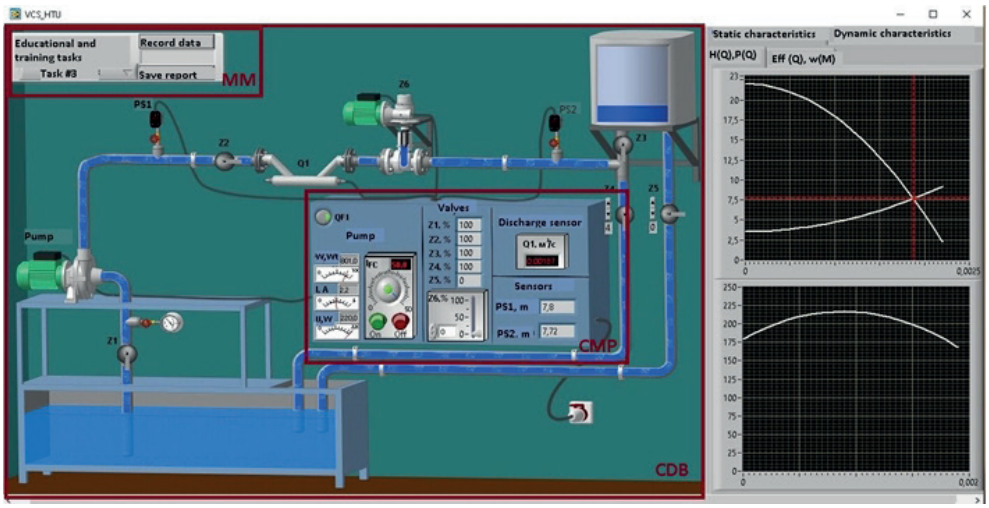

Fig. 2. The main window of the EHU VLM interface

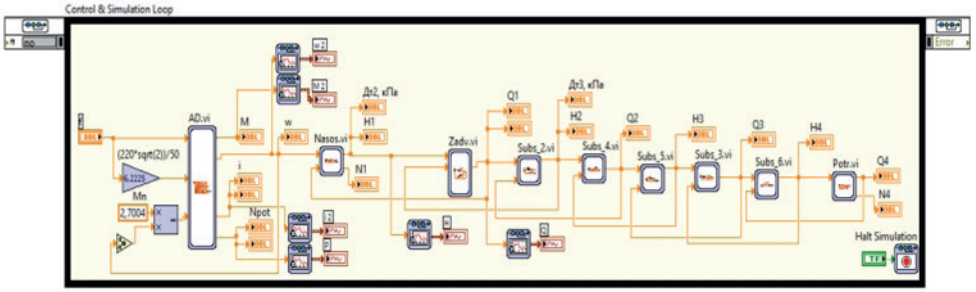

Fig. 3. The block diagram of the virtual model "Pipeline"

represented by corresponding block diagrams in the LabVIEW environment (Figs. 3–6).

One of the ways to reduce dynamic loads in the EHU pipeline network is to control the opening/closing rate of the control valve installed in the head branch of the pipeline network.

For this purpose, a pipeline valve control system was developed in the LabVIEW programming environment, the structure of the graphical interface of which is presented in Fig. 7. The graphical interface panel consists of four blocks.

The block "Setting the hydro-transport plant parameters" (***I***), Fig. 7 contains windows in which the IM parameters, the type of pipeline valve is selected (stopcock, single-seat valve, disc valve) and the voltage frequency of the power supply network of ED valve are set.

The block "Setting the parameters of valves hydraulic characteristics" (***II***), Fig. 7 consists of windows, in which: parameters- of the hydraulic characteristic are set; a table containing the said value of hydraulic resistance S and degree β of opening for the pipeline valves; a window reflecting the polynomial dependence of the hydraulic characteristic of the shut-off and control valves (stopcock, single-seat valve or disc gate); windows for setting approximation coefficients A, B, C, D, So.

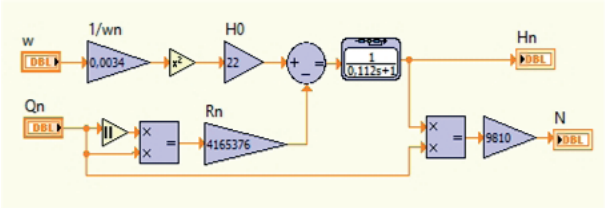

Fig. 4. The block diagram of the virtual model "Pump"

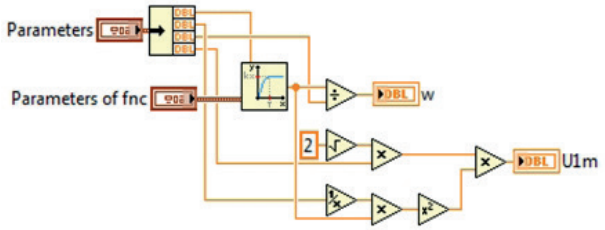

Fig. 5. The block diagram of the virtual model "Frequency converter"

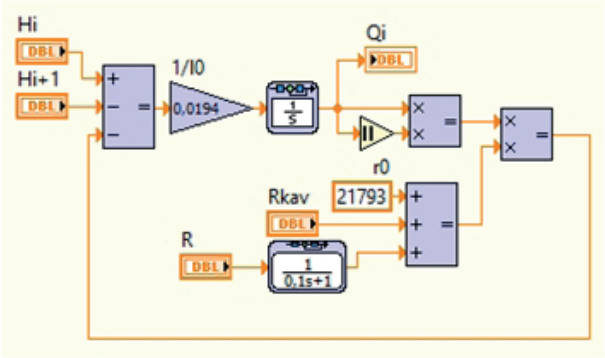

Fig. 6. The block diagram of the virtual model "Stopcock"

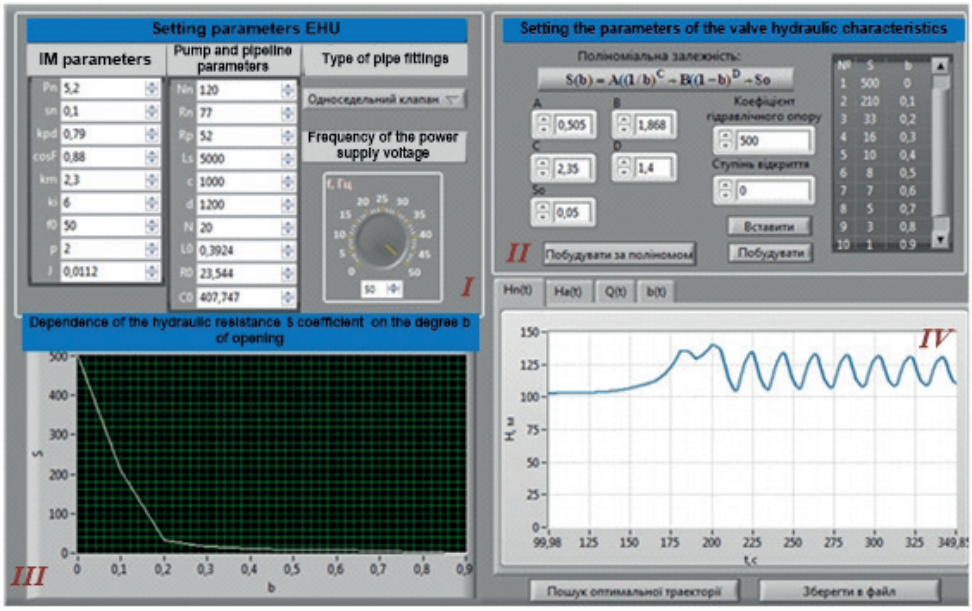

Fig. 7. The main window of the VLM "Dynamic Load Reduction System"

The block "Dependence of coefficient S of hydraulic resistance on degree β of opening" (***III***), Fig. 7 – displays the hydraulic characteristics of the pipeline valves in a graphical form.

The block for displaying transient processes (***IV***), Fig. 7 occurring in the hydro-transport plant: curves of head change $H_p(t)$ at the pump outlet and $H_{zas}(t)$ at the valves, discharge $Q(t)$ in the consumer's network, and the rate of valve control β (t).

As an example, the curve of the change in pressure at the pump outlet with an uneven valve closing rate is shown on the right in Fig. 7.

Conclusions.

The developed approach, which combines physical, mathematical and virtual modeling, has proven its effectiveness in researching the operating modes of electrohydraulic complexes and in studying electromechanical and hydraulic characteristics. It has been shown that a real physical laboratory stand of an electrohydraulic plant is the prototype of the developed virtual models. The developed virtual laboratory models are a set of tools that makes it possible to simulate both stationary (normal) and non-stationary (emergency) operating modes of electro-hydraulic equipment, various ways to start pumping units, change the geometric configuration of pipelines, and set the pump operating mode to backpressure. The proposed virtual models are a basic platform for training engineering personnel both in industrial and municipal enterprises, and future specialists in the electromechanical field of higher education institutions.

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