Volume 8, Number 1, 2022 49

Modelling the Modes of System of Asynchronous Centrifugal Units of Multi-Unit Pumping Station with Serial Connection of Pumps

Vladyslav Lysiak*, Mykhailo Oliinyk

Lviv Polytechnic National University, 12 S. Bandera St., Lviv, 79013, Ukraine

Received: January 18, 2022. Revised: February 18, 2022. Accepted: March 25, 2022.

© 2022 Authors. Published by Lviv Polytechnic National University.

Abstract

Based on the current regulations on pipeline transport, the need for a systematic approach to the study of processes occurring in the technological complexes of pumping stations of the main pipelines and their power supply systems is shown. The development of effective control systems for such complexes in order to reduce energy consumption involves a comprehensive analysis of current modes and forecasting of both steady-state and dynamic modes by simultaneously studying their subsystems as a whole The replacement of obsolete centrifugal pumps of multi-unit pumping stations with main and booster pumps with the modern types with a significantly higher efficiency increases the importance of energy saving potential in dynamic modes. The scientific research results regarding modelling of pumping stations and their electrical complexes are analysed. It is shown that the generally accepted approach is not always sufficient for the effective study of the influence of subsystems of different physical nature of pumping stations on the power supply system and the mutual influence of these subsystems on each other. A formalized mathematical model of the system of asynchronous centrifugal units of a multi-unit pumping station with serial connection of pumps is built, its verification is carried out and the prospects of its use are discussed.

Keywords: asynchronous motor; pumping station; centrifugal pump; pipeline; model.

1. Definition of the research problem selected for the study

Pumping stations (PS) of the main oil and water pipelines are powerful consumers of significant amounts of electricity. The main pipelines (PL) and PS are transit facilities that allow large amounts of fluid to be transferred to distribution pipelines. Ukraine has one of the world's biggest oil pipelines. According to the Law of Ukraine "On Pipeline Transport" [1], "the main pipeline is a technological complex that operates as a single system and which includes a separate pipeline with all facilities and structures connected with it by a single technological process, or several pipelines through which the transit, interstate and interregional supplies of transportation products to consumers are carried out, or other pipelines designed and built in accordance with the state construction requirements for main pipelines". The diagnostic and testing procedures are also described here, and the basic requirements for design, reliability and uninterrupted safe operation of the main pipelines, their diagnostics and defectoscopy are given in [2], [3]. Conducting physical experiments with transient processes is difficult for a number of reasons [4]; only diagnostics and defectoscopy strictly regulated in [1], as well as data of operating modes, which are usually quasi steady-state [5], are actually available. However, the development of effective control systems for such complexes in order to reduce energy consumption involves a comprehensive analysis of current modes and forecasting of both steady-state and dynamic [6] modes by simultaneously studying their subsystems as a whole [1]. One of the ways to solve this problem is the development of hybrid models consisting of a digital model of the power unit and a physical model of the information and signal control system [7].

* Corresponding author. Email address: vladyslav.h.lysiak@lpnu.ua

This paper should be cited as: V. Lysiak, M. Oliinyk. Modelling the modes of system of asynchronous centrifugal units of multi-unit pumping station with serial connection of pumps. Energy Engineering and Control Systems, 2022, Vol. 8, No. 1, pp. 49 – 56. https://doi.org/10.23939/jeecs2022.01.049

Usually, in order to ensure an uninterrupted transportation of fluid under the condition of changeable needs in its quantity, PS are equipped with farms of buffer reservoirs of the required volume. The powerful main centrifugal pumps (CP), which create the required fluid pressure with a given capacity (flow rate), are very sensitive to the damaging effect of possible cavitation processes on the surface of the blades [8]. Therefore, they need to maintain a cavitation reserve, i.e. a certain stable excess pressure at the inlet over the entire performance range. This pressure is created by booster units connected in series with the main CPs, which directly intake the fluid from the accumulators and supply it to the inlet of the main CPs. The booster CPs of the multi-unit PSs have a lower nominal pressure and power, but the same nominal capacity as the main ones. The analysis of works [9], [10] shows that the feasibility of using a controlled electric drive of CP on multi-unit PSs depends not only on the form of the technological schedule of the hydraulic load, but also on the efficiency of the CPs themselves. Recently, obsolete CPs with a low efficiency (75-80%) are being replaced everywhere by modern units with a significantly higher value of this indicator (up to 90%), as a result of which the energy saving potential increases in dynamic modes.

Given the above, it can be concluded that the development of available new and improvement of existing low-cost tools for studying the operating modes of powerful multi-unit PSs is relevant.

2. Analysis of the recent studies and publications on the problem

An intrinsic connection between the electromechanical and hydraulic subsystems of PSs of the main pipelines and their power supply systems requires a systematic approach to the study of processes occurring in such technological complexes, as well as to their modelling. However, in most works dedicated to this issue, the emphasis is usually laid on deepening the mathematical description of only one separate subsystem: either hydraulic [11], [12] or electromechanical [13], [14], [15]. The ways to optimize energy and other integrated indicators of the modes of PS power complexes on the basis of objective functions are proposed in [16], [17], which gives only a general picture (a more detailed mathematical description of PS subsystems is given in [18]). The simulation models (for example, [12], [19]) provide more details on a number of coordinates of the mode, but do not reflect the essence of the physical processes. In the works [20], [21], each of the subsystems of a single electrically driven asynchronous pumping unit in dynamic modes is described in sufficient detail, but the issue of modelling their joint operation, which is typical for multi-unit PSs, is not resolved.

3. Aim of the research

The aim of the paper is to develop a mathematical model of the dynamic modes of the system of asynchronous centrifugal units (ACU) of a multi-unit pumping station with serial connection of pumps, which will allow studying both the influence of subsystems of different physical nature on the power supply system and the mutual influence of these subsystems on each other, while operating the internal parameters of the separate structural elements.

4. Results and their discussion

The model of a saturated asynchronous motor (AM) and the CP model, the feature of which is the identification of its parameters by the geometric dimensions of the CP structural elements and physical properties of the working fluid, created in the *d-q* coordinates connected with the common shaft, proposed in [21], are taken as the basis. Fig. 1 shows a generalized diagram of the hydraulic connections of ACU of a multi-unit PS.

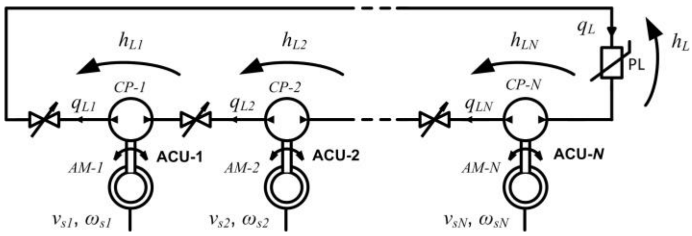

Fig.1. Generalized diagram of hydraulic connections of ACU of a multi-unit PS.

According to the diagram in Fig. 1, the symbol N indicates the total number of ACUs of a multi-unit PS with a serial connection of CP hydraulic paths and the index i indicates the serial number of ACU, AM and CP. The generalized model of the ACU system of a multi-unit PS with a serial connection of CP hydraulic paths is represented by equations (1)-(7), supplemented by expressions (8), (9). The small bold symbols indicate the complex variables (real and imaginary parts correspond to *d-q* coordinates).

The equations (1)-(3) describe the state of each individual (*i*-th) ACU (total number of equations is $10\cdot N$), in particular:

- equation (1) is written in a matrix-vector form; it describes the state of electromagnetic (4 equations with complex variables for each AM) and hydraulic (4 equations with complex variables for each CP) subsystems of ACU, i=1...N, the total number of equations is $8\cdot N$;
- equation (2) sets the collinearity of the vectors of pressure and volumetric flow rate of the working fluid at the outlet of each individual CP (1 equation for each CP), i=1...N, the total number of equations is N;
- equation (3) of the AM rotor movement establishes the connection of the electromagnetic and hydraulic subsystems of each specific ACU with an absolutely rigid common shaft, i=1...N, the total number of equations is N

The equations (4)-(6) describe the serial connection of CP hydraulic paths of all ACUs and PLs (total number of equations is N+1), in particular:

- equation (4) defines the equality of volumetric flow rate of the working fluid of all CPs connected in series by hydraulic paths (1 equation for the *i*-th and *i*+1st CP), i=1...N-1, the total number of equations is N-1;
- equation (5) sets the equality of volumetric flow rates of the working fluid at the PL inlet and random of CPs connected in series by hydraulic paths (1 equation for PL and random separate CP), i is arbitrary in the range from 1 to N, the total number of equations is 1;
- equation (6) sets the equality of the working fluid pressure at the PL inlet and the sum of the working fluid pressure of all CPs connected in series by hydraulic paths (1 equation for PL and arbitrary *i*-th of separate CP), i=1...N, the total number of equations is 1.

The equation (7) describes the state of PL (total number of equations is 1).

Thus, the generalized model of the system of ACU of a multi-unit PS with CP hydraulic paths connected in series consists of $11\cdot N + 2$ equations (including 8 equations in the complex form). The above expressions include relative values of coordinates and parameters; the exception is the total moment of inertia of ACU J_Σ, kg·m^2, as well as the basic values [21], marked with the index *b*.

$$\overline{\mathbf{D}_i} = \breve{\mathbf{P}}_i \times \overline{\mathbf{Q}_i} + \overline{\mathbf{P}_{0i}} \times \mathbf{h}_{0i} + \overline{\mathbf{V}_i} \;; \tag{1}$$

$$h_{L_i d} q_{33_i q} - h_{L_i q} q_{33_i d} = 0 \;; \tag{2}$$

$$d\omega_{r_i}/dt = \left(T_{am.b_i}\left(\psi_{\delta_i d} i_{s_i q} - \psi_{\delta_i q} i_{sd}\right) - T_{cp.b_i} H_{0.nom_i} \omega_{r_i} \frac{\omega_{am.b_i}}{\omega_{cp.b_i}} \sqrt{\left(q_{11_i d} + q_{44_i d}\right)^2 + \left(q_{11_i q} + q_{44_i q}\right)^2} - \Delta T_{m0_i} \omega_{r_i}^2 \right) \Big/ \left(J_{\Sigma_i} \omega_{am.b_i} \right); \tag{3}$$

$$\left(q_{b_i}/q_{b_{i+1}}\right)^2 \left(q_{33_i d}^2 + q_{33_i q}^2\right) = \left(q_{33_{i+1} d}^2 + q_{33_{i+1} q}^2\right); \tag{4}$$

$$q_L = \left(q_{b_i}/q_b\right)\sqrt{q_{33_i d}^2 + q_{33_i q}^2} \;; \tag{5}$$

$$h_{L\Sigma} = \sum_{i=1}^{N} \frac{h_{b_i}}{h_b} \sqrt{h_{Ld_i}^2 + h_{Lq_i}^2} \;; \tag{6}$$

$$dq_L/dt = -\left(r_L/L_L\right) q_L + \left(1/L_L\right) h_{L\Sigma} - \left(1/L_L\right) h_{st} \;; \tag{7}$$

$$\mathbf{h}_{0_i} = \omega_{r_i}^2 H_{0.\mathrm{nom}_i} \left(\omega_{b_i}/\omega_{cp.b_i}\right)^2 \left(\cos\left(\omega_{r_i}\omega_{b_i} t + \Psi_{0cp_i}\right) + j\sin\left(\omega_{r_i}\omega_{b_i} t + \Psi_{0cp_i}\right)\right); \tag{8}$$

$$R_{m_i}\left(\psi_{\delta_i}\right)=\left(0.82+0.148\cdot\left(\psi_{\delta d_i}^2+\psi_{\delta q_i}^2\right)+0.044\cdot\left(\psi_{\delta d_i}^2+\psi_{\delta q_i}^2\right)^4\right)\Big/\left(x_{\sigma_i}+x_{a_i}\right), \qquad (9)$$

where t is the time; $\breve{\mathbf{P}}_i$ is the matrix of ACU parameters (its full form is given in Table 1); $\overline{\mathbf{Q}_i}=\left(\mathbf{q}_{11i},\ \mathbf{q}_{22i},\ \mathbf{q}_{33i},\ \mathbf{q}_{44i},\ \mathbf{i}_{s_i},\ \mathbf{i}_{r_i},\ \mathbf{e}_{\delta_i},\ \boldsymbol{\psi}_{\delta_i}\right)_t$ is the column vector of ACU mode coordinates; $\overline{\mathbf{P}_{0i}}=\left(-1/L_{11_i},\ -1/L_{21_i},\ -1/L_{31_i},\ 1/L_{mech_i},\ 0,\ 0,\ 0,\ 0\right)_t$ is the matrix of parameters of CP mechanical energy losses; $\overline{\mathbf{D}_i}=\left(d\mathbf{q}_{11_i}/dt,\ d\mathbf{q}_{22_i}/dt,\ d\mathbf{q}_{33_i}/dt,\ d\mathbf{q}_{44_i}/dt,\ d\mathbf{i}_{s_i}/dt,\ d\mathbf{i}_{r_i}/dt,\ d\boldsymbol{\psi}_{\delta_i}/dt,\ 0\right)_t$ is the column vector of the first derivatives of the ACU mode coordinates; $\overline{\mathbf{V}_i}=\left(0,\ 0,\ 0,\ 0,\ \mathbf{v}_{s_i}/L_{s_i},\ 0,\ 0,\ 0\right)_t$ is the column vector of ACU coercive forces; ω_{ri}, ω_{si} is the angular frequency of the ACU common shaft and angular frequency of the AM stator winding voltage; h_{st} is the PL static back pressure; $\mathbf{i}_{si}$, $\mathbf{i}_{ri}$, $\mathbf{v}_{si}$ is the stator current, rotor current reduced to the stator and AM stator winding voltage; $\boldsymbol{\psi}_{\delta i}$ is the flux linkage from the magnetic flux of the air gap of AM reduced to the stator; $L_{\sigma si}$, R_{si} are the leakage inductance and resistance of AM stator winding; $L_{\sigma ri}$, R_{ri} are the leakage inductance and resistance of AM rotor winding reduced to the stator; R_{ai} is the equivalent resistance to account for active energy losses in the AM core; $R_{m_i}\left(\psi_{\delta_i}\right)$ is the static nonlinear magnetic resistance of the AM main magnetic circuit given in the form of a polynomial (x_{ai}, $x_{\sigma\text{i}}$ are relative nominal values of AM magnetization and scattering inductances); $\mathbf{h}_{0_i}$ is the fictitious pressure of the idealized CP ($H_{0.nomi}$ is the nominal value, Ψ_{0cpi} is arbitrary); $\mathbf{q}_{11_i}$, $\mathbf{q}_{22_i}$, $\mathbf{q}_{33_i}$, $\mathbf{q}_{44_i}$ are the fictitious CP output; $h_{L_i}=\sqrt{h_{Ld_i}^2+h_{Lq_i}^2}$ is the effective head of the real CP; $q_{L_i}=\sqrt{q_{33d_i}^2+q_{33q_i}^2}$ is the effective volumetric flow rate of fluid of the real CP; $h_{L\Sigma}$ is the total head of all CPs at the PL inlet; h_{st} is the PL static back pressure; L_L, r_L is the PL hydraulic inductance and hydraulic resistance; $r_{mech_i}\left(q_{L_i}\right)$ is the equivalent hydraulic resistance [22] to take into account the CP mechanical energy losses; $\Delta T_{0\text{i}}$ is the equivalent torque to account for mechanical losses in ACU bearings; $J_{\Sigma\text{i}}$ is the total moment of ACU inertia, kg·m^2.

Table 1 shows the full view of $\breve{\mathbf{P}}_i$ matrix of CP and AM parameters of i-th ACU. The columns 1...8 of the table correspond to the components of $\overline{\mathbf{Q}_i}$ column vector of the mode coordinates, and rows 1..8 correspond to the separate equations of the i-th ACU compactly written in the matrix-vector form (1).

Table 1. Matrix $\breve{\mathbf{P}}_i$ of CP та AM parameters of i-th ACU

	1	2	3	4	5	6	7	8
1	$\frac{r_{11_i}}{L'_{11_i}}-\frac{r_{21_i}}{L'_{12_i}}$	$\frac{r_{22_i}}{L'_{12_i}}-\frac{r_{32_i}}{L'_{13_i}}$	$\frac{r_{33_i}}{L'_{13_i}}-\frac{r_{23_i}}{L'_{12_i}}$	0	0	0	0	0
2	$\frac{r_{11_i}}{L'_{21_i}}-\frac{r_{21_i}}{L'_{22_i}}$	$\frac{r_{22_i}}{L'_{22_i}}-\frac{r_{32_i}}{L'_{23_i}}$	$\frac{r_{33_i}}{L'_{23_i}}-\frac{r_{23_i}}{L'_{22_i}}$	0	0	0	0	0
3	$\frac{r_{11_i}}{L'_{31_i}}-\frac{r_{21_i}}{L'_{32_i}}$	$\frac{r_{22_i}}{L'_{32_i}}-\frac{r_{32_i}}{L'_{33_i}}$	$\frac{r_{33_i}}{L'_{33_i}}-\frac{r_{23_i}}{L'_{32_i}}$	0	0	0	0	0
4	0	0	0	$\frac{-r_{mech_i}\left(q_{L_i}\right)}{L_{mech_i}}$	0	0	0	0
5	0	0	0	0	$\frac{-R_{s_i}}{L_{s_i}}-j\omega_{s_i}$	0	$\frac{-1}{L_{s_i}}$	$\frac{-j\omega_{s_i}}{L_{s_i}}$
6	0	0	0	0	0	$\frac{-\omega_{s_i}R_{r_i}}{L_{r_i}}-j\left(\omega_{s_i}-\omega_{r_i}\right)$	$\frac{-\omega_{s_i}}{L_{r_i}}$	$\frac{j\left(\omega_{s_i}-\omega_{r_i}\right)}{L_{r_i}}$
7	0	0	0	0	0	0	1	0
8	0	0	0	0	1	1	0	$-R_{m_i}\left(\psi_{\delta_i}\right)-\frac{j\omega_{s_i}}{R_{a_i}}$

The expressions of the equivalent hydraulic inductance $L'_{11_i} = \left(L_{12_i} L_{21_i} \big/ \left(L^2_{11_i} L''_i\right) - 1\big/L_{11_i}\right)^{-1}$, $L'_{22_i} = L''_i$; $L'_{33_i} = \left(L_{32_i} L_{23_i} \big/ \left(L^2_{33_i} L''_i\right) - 1\big/L_{33_i}\right)^{-1}$, $L'_{12_i} = L'_{21_i} = L_{11_i} L''_i \big/ L_{12_i}$, $L'_{13_i} = L'_{31_i} = L_{11_i} L_{33_i} L''_i \big/ \left(L_{12_i} L_{23_i}\right)$, $L'_{23_i} = L'_{32_i} = = L_{33_i} L''_i \big/ L_{23_i}$, $L''_i = L_{12_i} L_{21_i} \big/ L_{11_i} - L_{22_i} + L_{23_i} L_{32_i} \big/ L_{33_i}$, $L_{11i}=L_{t.nomi}+L_{\mu H.nomi}+L_{\mu Q.nomi}$, $L_{12i}=L_{21i}=L_{\mu Q.nomi}$, $L_{23i}=L_{32i}=L_{\Delta Q.nomi}$, $L_{33i}=L_{\Delta Q.nomi}+L_{\Delta H.nomi}$, $L_{22i}=L_{\mu Q.nomi}+L_{\Delta Q.nomi}$ and equivalent hydraulic resistance $r_{11i}=r_{12i}=R_{\mu Q.nomi}$, $r_{22i}=r_{23i}=R_{\Delta Q.nomi}$, $r_{33i}=R_{\Delta Q.nomi}+R_{\Delta H.nomi}$ include the corresponding nominal calculated [20] parameters of CP $L_{t.nomi}$, $L_{\mu H.nomi}$, $L_{\mu Q.nomi}$, $L_{\Delta Q.nomi}$, $L_{\Delta H.nomi}$, $R_{\mu Q.nomi}$, $R_{\Delta Q.nomi}$, $R_{\Delta H.nomi}$.

To test the efficiency and correctness of the model, it was adapted to a 2-unit ACU system, which consists of the main (first) and booster (second) units, the CP hydraulic paths of which are connected in series and operate for a common pipeline. The test calculations were performed in the Mathcad system. The parameters of the units selected for the test calculations are shown in Tables 2...5. The CP moment of inertia is taken into account in the amount of 15% of the AM moment of inertia.

Table 2. Parameters of AM-1 of 4AN355M6U3 type of ACU-1 booster unit

P_{nom}, kW	η_{nom},	$V_{s.nom}$, V	n_{nom}, rpm	$\cos\varphi_{nom}$,	p_0	T_{max*}	T_{min*}	T_{s*}	I_{s*}	J_{am}, kg·m^2
250	0.935	380	985	0.9	3	2.2	0.9	1.4	7	9.5

Table 3. Parameters of AM-2 of 4A3MB-1600/6000У2-5 type of ACU-2 main unit

P_{nom}, kW	η_{nom},	$V_{s.nom}$, V	n_{nom}, rpm	$\cos\varphi_{nom}$,	p_0	T_{max*}	T_{min*}	T_{s*}	I_{s*}	J_{am}, kg·m^2
1600	0,961	6300	2979	0,9	1	2.6	0.7	1.9	6	31.0

Table 4. Parameters of booster CP-1 of 14НДс-Н type of ACU-1 booster unit

H_{nom}, m	Q_{nom}, m^3/h	η_{nom},	n_{nom}, rpm	$P_{hydr\cdot nom}$, kW	$H_{0.nom*}$	$R_{\Delta Q*}$	$L_{\Delta Q*}$	$R_{\Delta H*}$	$L_{\Delta H*}$	L_{t*}	$L_{\mu H*}$	$L_{\mu Q*}$	R_{mech*}	L_{mech*}
45	1260	0.809	980	154	1.302	29.47	9.49	$6.627\cdot10^{-4}$	0.4144	0.00876	0.0352	0.2375	7.180	0.02287

Table 5. Parameters of main CP-2 of QG300-2-100b type of ACU-2 main unit

H_{nom}, m	Q_{nom}, m^3/h	η_{nom},	n_{nom}, rpm	$P_{hydr\cdot nom}$, kW	$H_{0.nom*}$	$R_{\Delta Q*}$	$L_{\Delta Q*}$	$R_{\Delta H*}$	$L_{\Delta H*}$	L_{t*}	$L_{\mu H*}$	$L_{\mu Q*}$	R_{mech*}	L_{mech*}
428	800	0.745	2980	932	2.641	43.89	15.12	$5.897\cdot10^{-5}$	0.4675	1.03311	0.3122	2.3111	20.377	0.00436

At the time t = 0.1 s, the AM-1 of ACU-1 was switched on and after its acceleration at the time t = 2.0 s, the AM-2 of ACU-2 was switched on (direct start, hydraulic valves of CP of units were closed). From t=5.0 to t=5.5 s, the hydraulic valve of CP-1 of ACU-1 was smoothly opened, and from t=15.0 s to t=15.5 s, the hydraulic valve of CP-2 of ACU-2 was smoothly opened. At the time t = 22.0 s for 0.1 s, an emergency situation was simulated (complete break of PL), and from t = 22.0 s to t = 25.5 s, a smooth simultaneous closing of CP valves of both units was simulated. The main results are presented in Fig. 2...11.

The correctness of the model is confirmed by the convergence of the coordinates of the nominal and limit steady-state modes obtained on the model and the main nominal mode data of AM and CP. For this purpose, the figures were supplemented with the corresponding nominal mode data of CP (nominal and maximum pressure in the mode of the fully closed hydraulic valve at the outlet and volumetric flows in the mode of complete break of the pipeline), the amplitude values of the rated current calculated according to the nominal data of AM, the nominal values of electromagnetic torques at the rated frequencies and powers as well as the rated rotational speed of AM and CP.

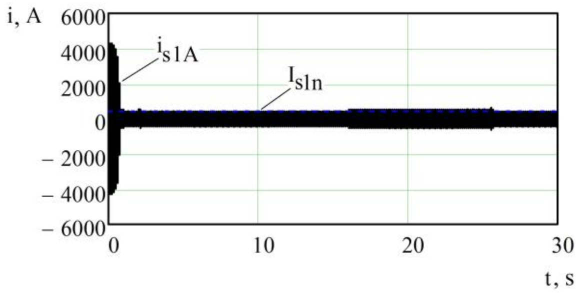

Fig.2. Phase A current of AM-1 stator.

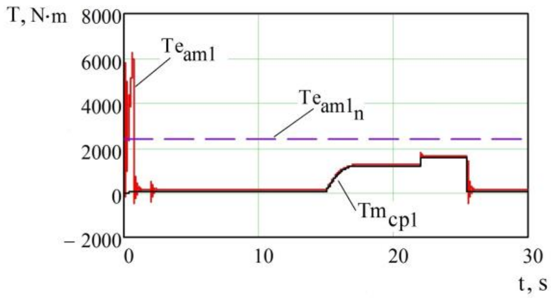

Fig.3. AM-1 electromagnetic torque and mechanical moment and CP-1 mechanical moment of resistance.

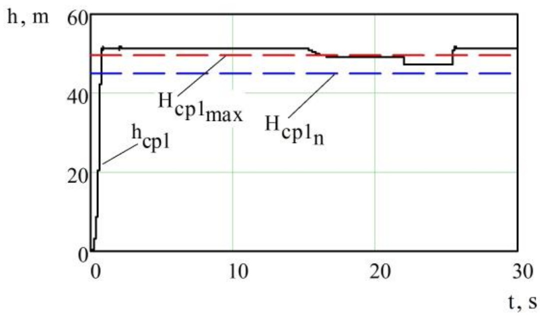

Fig.4. Working fluid head at CP-1 outlet.

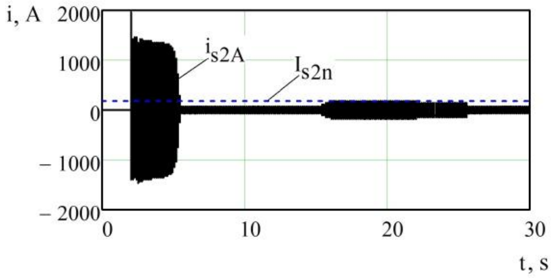

Fig.5. Phase A current of AM-2 stator.

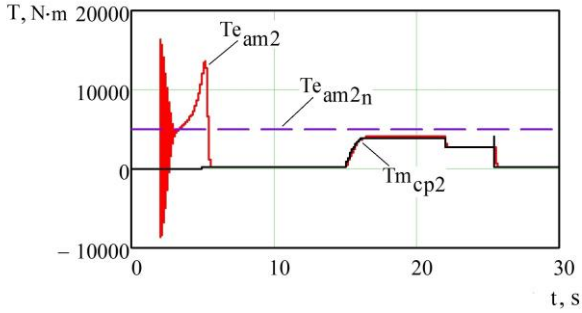

Fig.6. AM-2 electromagnetic torque and mechanical moment and CP-2 mechanical moment of resistance.

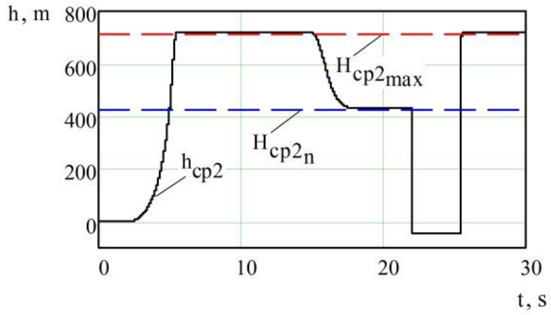

Fig.7. Working fluid head at CP-2 outlet.

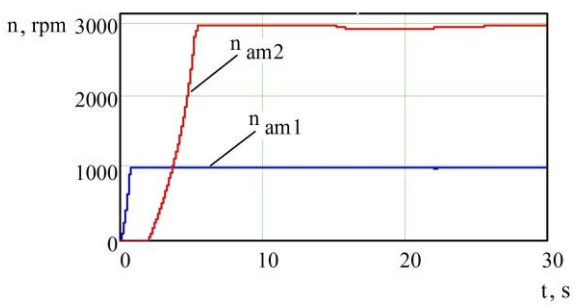

Fig.8. Rotational speed of ACU-1 common shaft and ACU-2 common shaft.

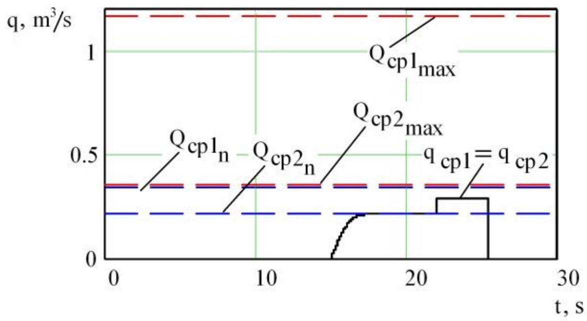

Fig.9. Volumetric flow rate of working fluid at CP-1, CP-2 outlet and PL inlet.

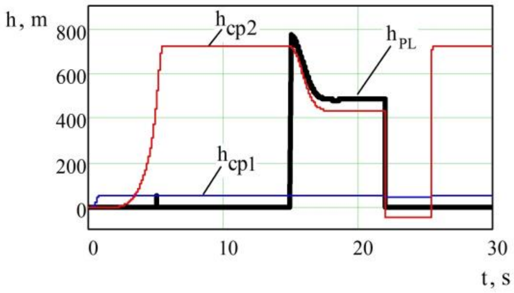

Fig.10. CP-1 and CP-2 working fluid head at PL inlet.

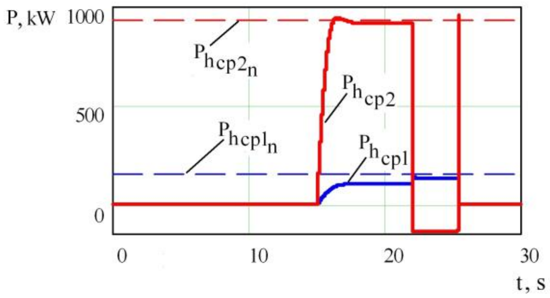

Fig. 11. CP-1 and CP-2 net and rated hydraulic power.

5. Conclusion

A mathematical model of the system of asynchronous centrifugal units of a multi-unit pumping station with serial connection of pumps is presented. The model is an effective tool for studying the influence of subsystems of different physical nature of pumping stations on the power supply system and the mutual influence of these subsystems on each other in order to improve the energy efficiency. The use in the model of the hydraulic subsystem of the parameters that depend on the geometric dimensions of the structural elements of the pumps and the physical properties of working fluid allows taking into account the operational change in the characteristics of the hydraulic subsystem and its impact on the modes. The modular principle and formalization of the matrix-vector form of writing the equations of the model make it possible to adapt it for the analysis of various electrical complexes for fluid transportation and automate the formation of equations, significantly expanding possible applications. Supplementing the developed digital model with a physical model of the information and signal control system can create an effective tool for a comprehensive analysis of current modes and forecasting of both steady-state and dynamic modes of such complexes without conducting physical experiments on power equipment.

References

[1] On Pipeline Transport: Law of Ukraine No. 192/96-BP of 15.05.1996 (as of 13.01.2011) // Gazette of the Supreme Council of Ukraine. – 1996. – No. 29. Art. 139. – https://zakon.rada.gov.ua/laws/show/192/96-вр#Text. (in Ukrainian)

[2] On Approval of the Safety Rules for the Operation of Main Oil Pipelines: Order of the State Committee of Ukraine for Industrial Safety, Labour Protection and Mining Supervision of 19.12.2007 under No. 1389/14656 // Gazette of the Supreme Council of Ukraine. – 1996. – No. 29. Art. 139. – https://zakon.rada.gov.ua/laws/show/z1389-07#Text. (in Ukrainian)

[3] DBN B.2.5-74: 2013 Water supply. External networks and structures. Basic design provisions. - Valid from 01.01.2014. - Kyiv: Ministry of Regional Development of Ukraine, 2013. - V, p. 172: Fig., Table. - (State building norms of Ukraine). – https://dbn.co.ua/load/normativy/dbn/1-1-0-1084. (in Ukrainian)

[4] Fedorov A.V. System of uninterrupted power supply of processing facilities of the oil and gas complex: Abstract of Cand. Tech. Sci. Dissertation in the specialty 05.09.03 – Electrotechnical Complexes and Systems. – St. Petersburg, 2016. — p. 20 (in Russian)

[5] Lysiak V.H. Modelling the steady-state modes of electrical grids with synchronous electric drive of hydraulic load / V.H. Lysiak, M.Y. Oliinyk, M.B. Sabat, Y.L. Shelekh // Electric Power and Electromechanical Systems. – 2019. – Issue 1, Number 1, 2019. – pp. 36–45. (in Ukrainian)

[6] Mukani Eme Boris. Modes of operation of power supply systems for oil and gas fields: Abstract of Cand. Tech. Sci. Dissertation in the specialty 05.09.03 - Electrotechnical Complexes and Systems. - Moscow, 2011. - p.165 (in Russian)

[7] K. Ou et al., "MMC-HVDC Simulation and Testing Based on Real-Time Digital Simulator and Physical Control System," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 4, pp. 1109-1116, Dec. 2014.

[8] Zaher M. A. Centrifugal Pump Technology and Pump Cavitation. // CreateSpace Independent Publishing Platform, 2015. – p. 242

[9] Yaremak I.I., Kostyshyn V.S. (2020). Control of electrohydraulic complex modes based on systematic approach. Scientific Bulletin of National Forestry University of Ukraine, 30(3), 83-88. https://doi.org/10.36930/40300314. (in Ukrainian.)

[10] Mukhortov I.S. Improving the energy efficiency of a group of electric drives of reservoir pressure maintenance systems: Abstract of Cand. Tech. Sci. Dissertation in the specialty 05.09.03 – Electrotechnical Complexes and Systems. – Samara, 2014.- 25. (in Russian)

[11] Kostyshyn, Volodymyr & Yaremak, Iryna & Kurlyak, P.O. (2020). Creation of object-oriented model of centrifugal pump on the basis of electro-hydrodynamic analogy method. Scientific Bulletin of National Mining University. 2019, No. 6. 72-79. 10.29202/nvngu/2019-6/11

[12] Andrushchak S.V., Besedin P.V. Mathematical and simulation modelling of the process of transportation and dosing of sludge // Economics. Informatics, 2016. - No.16 (237). – pp. 115-122. (in Russian)

[13] Kutsyk A.S. Mathematical model of the system "frequency-controlled electric drive - pump - water supply network" / A.S. Kutsyk, A.O. Lozynskyi, O.F. Kinchur // Bulletin of Lviv Polytechnic National University. Electrical Power and Electromechanical Systems. 2015.– No. 834.– pp. 48–55. (in Ukrainian)

[14] Yin Luo, Shouqi Yuan, Hui Sun,Yihang Guo. Energy-saving control model of inverter for centrifugal pump systems / Advances in Mechanical Engineering, 2015, 7(7), pp. 1–12.

[15] Lozynskyi A. O. The research of efficiency of the use of neuropredictor in the control system of water-supply pump electric drive / A. O. Lozynskyi, A. S. Kutsyk, O. F. Kinchur // Scientific Bulletin of National Mining University. - 2017. - No. 1. - p. 93-99.

[16] Leznov B.S. Application of adjustable electric drive in pumping units of water supply and water disposal systems / B.S. Leznov // Ecological systems: Electronic journal of energy service company. - Kremenchuk, 2010. - No. 11. - pp. 9-12. (in English)

[17] Yaremak I.I. Multi-purpose optimization of steady-state modes of operation of electrically driven oil pumping stations / I.I. Yaremak, V.S. Kostyshyn // Bulletin of Kremenchuk Mykhailo Ostrohradskyi National University. - 2018. - Issue 1. - pp. 15-21. (in Ukrainian)

[18] Kostyshyn V.S. Mathematical model of reliability and efficiency of pumping unit of an oil pumping station / V.S. Kostyshyn, I.I. Yaremak // Scientific Bulletin of National Mining University. - 2017. - No. 5. - p. 62-68.

[19] Misiunas D. Burst Detection and Location in Pipelines and Pipe Networks with Application in Water Distribution Systems / D. Misiunas // Department of Industrial Electrical Engineering and Automation Lund University. – Sweden : Lund, 2004. – ISBN 91-88934-30-6. – Mode of access: http://www.iea.lth.se/publications/Theses/LTH-IEA-1038.pdf.

[20] Kostyshyn V.S. Investigation of dynamic modes of operation of electrically driven centrifugal pumping units with the help of their computer-oriented Bond Graph models / V.S. Kostyshyn, P.O. Kurlyak // Bulletin of Vynnytsia Polytechnic Institute. - 2012. - No. 2. - pp. 148-153. (in Ukrainian)

[21] Lysiak V.H. Modelling the dynamic operating modes of asynchronous electric drive with centrifugal pump load / V.H. Lysiak, M.Y. Oliinyk // Bulletin of Pryazovskyi State Technical University: Collection of scientific papers. Issue 42. - Mariupol: Pryazovskyi State Technical University, State Higher Educational Institution, 2021. – pp. 113–121. (in Ukrainian)

[22] Kostyshyn V.S., Kurlyak P.O. Simulation of performance characteristics of centrifugal pumps by the electro-hydrodynamic analogy method. Journal of Hydrocarbon Power Engineering, 2015, vol. 2, no. 1, pp. 24-31.

Моделювання режимів системи асинхронних відцентрових агрегатів багатоагрегатної помпової станції з послідовним сполученням помп

Владислав Лисяк, Михайло Олійник

Національний університет «Львівська політехніка», вул. С. Бандери, 12, м. Львів, 79013, Україна

Анотація

На підставі чинних нормативних документів щодо трубопровідного транспорту показано необхідність системного підходу до вивчення процесів, які відбуваються в технологічних комплексах помпових станцій магістральних трубопроводів та їхніх систем електропостачання. Розроблення ефективних систем керування такими комплексами з метою зменшення енергоспоживання передбачає всебічний аналіз поточних та прогнозування як усталених, так і динамічних режимів шляхом одночасного дослідження їхніх підсистем як єдиного цілого. Заміна застарілих відцентрових помп багатоагрегатних помпових станцій з основними та підпірними помпами на сучасні моделі зі суттєво вищим к.к.д. збільшує вагомість потенціалу енергоощадності в динамічних режимах. Проаналізовано наукові розробки, які стосуються моделювання помпових станцій та їхніх електротехнічних комплексів. Показано, що загальноприйнятий підхід не завжди достатній для ефективного дослідження впливу підсистем різної фізичної природи помпових станцій на систему електропостачання та взаємного впливу цих підсистем одна на одну. Побудовано формалізовану математичну модель системи асинхронних відцентрових агрегатів багатоагрегатної помпової станції з послідовним сполученням помп, здійснено її верифікацію та запропоновано перспективи її використання.

Ключові слова: асинхронний двигун; помпова станція; відцентрова помпа; трубопровід; модель.