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MATHEMATICAL MODEL OF RELIABILITY AND EFFICIENCY OF PUMPING UNIT OF AN OIL PUMPING STATION

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МАТЕМАТИЧНА МОДЕЛЬ НАДІЙНОСТІ ТА ЕФЕКТИВНОСТІ РОБОТИ НАСОСНОГО АГРЕГАТА НАФТОПЕРЕКАЧУВАЛЬНОЇ СТАНЦІЇ

Purpose. Developing a mathematical model for the efficiency and reliability of the pumping unit (PU) of the oil pumping station (OPS) on the basis of the per-unit system and the methodology of the system approach which contains the electric, hydraulic and mechanical subsystems and reflects the energy inputs and outputs of the centrifugal pump (CP) and synchronous motor (SM).

Methodology. Mathematical models of PU of OPS are developed which are synthesized on the basis of a system approach taking into account the impact of their operating modes on reliability and efficiency parameters of the SM and CP. This allows determining the optimal operation modes of PU OPS and to develop measures for their implementation.

Findings. Based on a systematic approach a model which is a unified system of subsystems with different physical nature was formed. The mathematical model of efficiency and reliability parameters of SM and CP was formalized as polynomials and values of their coefficients were calculated. It was clarified that the extreme values of efficiency and reliability are achieved for different flow rate values. That requires the use of multi-objective optimization studies.

Originality. Based on the systematic approach, a mathematical model of PU of OPS was formalized which makes it possible to take into account the effect of changes of operating mode of PU on performance and reliability parameters of SM and CP. It is clarified that the extreme values of efficiency and reliability parameters of SM and CP are achieved for different flow rate values.

Practical value. Mathematical models that allow estimating the impact of changes of flow rate of OPS on the performance and reliability parameters of SM and CP to select the best operating mode without expensive field experiments are developed.

Keywords: *synchronous motor, centrifugal pump, mathematical model, reliability, efficiency, optimization*

Introduction. For now lowering of power consumption is a global development priority in energy policy in Ukraine and in the world. OPS pipelines which are equipped with PU are complex energy-intensive facilities, consisting usually of CP driven by SM. The present-day world politic and economic situation has resulted in the fact that the PUs of OPS often operate in underloaded mode which caused a sharp decline in their efficiency and reliability parameters. That is why particularly important is solving the problem of implementation of optimal multipurpose control of PU aimed at improving those parameters, which in turn requires developing a complex mathematical model of OPS based on a systematic approach. That model should be able to show correctly the complex interdependent connections between OPS's subsystems of different physical nature.

Analysis of the recent research. The most efficient operating mode of CP is determined considering its efficiency value [1]. However, it was also proposed to take into account the reliability of SM behavior [2] for a comprehensive analysis of its functioning, which makes it possible to reduce the cost of repairs and maintenance. In addition, the SM drive of CP is usually chosen so that its nominal parameters match optimal parameters of the pump [3]. Thus, the non-optimal operating mode of CP causes a reduction of efficiency of SM such as impairment of its efficiency and power factor and appearance of additional losses in the elements of power supply. According to [3] PU performance parameters such as efficiency of PU and SM can reach maximal values for different flow rates of oil Q different from those shown in documents. However, this does not include the impact of changes of reliability parameters of the PU. A systematic approach for optimizing behavior of PU by the criteria of efficiency and reliability of CP and SM respectively is proposed in [4]. However, their functional dependence on the volume flow rate of PU was not established.

Unsolved aspects of the problem. To achieve this goal it is necessary to solve the following tasks: to develop a mathematical model of reliability and efficiency; to investigate the impact of operating mode on the effective-

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ness and reliability of SM and CP; to formalize mathematical models of efficiency and reliability in the form of third degree polynomials and calculate their numerical values for PU "СТД-2500-2 and НМ-3600-230".

Presentation of the main research. The operating mode of pipeline depends on oil flow rate transported in it. Therefore, the performance and reliability of OPS should be determined, depending on oil flow rate Q_{OPS}.

OPS of pipelines is a complex system (Fig. 1), consisting of mutually connected electrical and hydraulic subsystems, energy exchange between them is conducted by PU shafts. N_{SW} and N_{RW} are input power capacity of stator winding and rotor (excitation) winding of SM respectively; N_{Sh} is PU shaft horsepower.

According to the law of conservation of energy using system of equations (1), let us write the capacity balance equations for the i-th PU

$$N_{H_{out}i} = N_{H_{in}i} + N_{RWi} + 3N_{SW} . \tag{1}$$

Within studied technological area of OPS a consistent combination of three CPs (pumping system "pump to pump") is usually used, which defines equal values of flow rate Q_{OPS} for them. In this scheme the output hydraulic power $N_{H_{out}i}$ of previous flow on CP will be equal to the input $N_{H_{in}(i+1)}$ of the next CP $N_{H_{out}i} = N_{H_{in}(i+1)}$, while the hydraulic input power of the first PU and output power of the third PU are input $N_{H_{in}1} = N^{OPS}_{H_{in}}$ and output $N_{H_{out}3} = N^{OPS}_{H_{out}}$ hydraulic power of OPC respectively.

The structural and functional scheme of a separate PU which reflects the energy inputs and outputs of CP and SM is shown in Fig. 2. The motor itself is energy supplied by dual channels:

- to three phase stator windings of SM (Power $3N_{SW}$). Energy parameters are values of voltage U_{SW} and electric current I_{SW};
- to the rotor windings (power N_{RW}). Energy parameters are voltage U_{RW} and current field I_{RW} (direct current with frequency $f_{RW} = 0$).

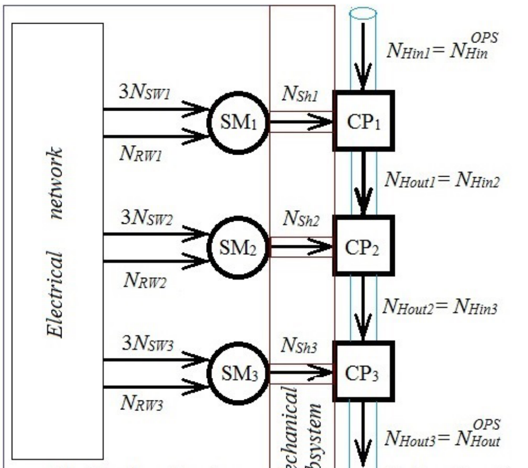

Fig. 1. Structural and functional scheme of an oil pumping station

Mechanical energy output from SM N_{Sh} occurs through the shaft of PU and simultaneously it is an entrance to the CP with energy parameters of torque M and angular velocity ω_R. Power supply by dual channels is also typical for CP. Besides of aforementioned mechanical energy, the pump is also supplied with fluid through the inlet nozzle. Hydraulic power N_{Hin} of the fluid is characterized by suction pressure H_{in} and volumetric flow rate Q_{in}. It is obvious that through the discharge pipe of CP effective hydraulic power N_{Hout} is obtained. Energy parameters are output pressure H_{out} and flow rate Q_{out}. It should also be noted that quantities obtained by multiplying of power parameter (U_{SW}, U_{RW}, M, H_{in}, H_{out}) by velocity parameter (I_{SW}, I_{RW}, ω_R, Q_{in}, Q_{out}) show the power of energy flow N.

To simplify the analysis process, let us consider that the hydraulic input power is zero (suction pressure is ignored $H_{in} = 0$). In this case, a pressure difference H_V obtained by mechanical energy of the drive is equal to the absolute value of output pressure of the pump $H_V = H_{out} - H_{in}$. This approach is generally considered in experimental research of CP characteristics depending on its flow rate which is the same for all the pumps $Q_{OPS} = Q_{out} = Q_V$ [1] if PU of OPS are connected in series.

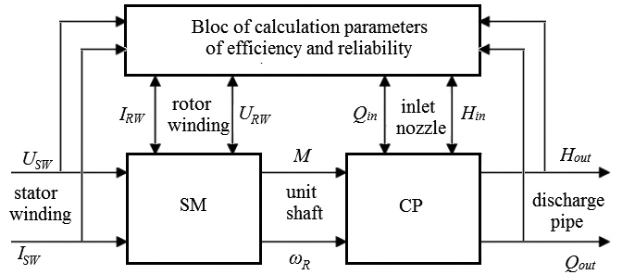

Fig. 2. Structural and functional scheme of a pump unit

The efficiency and reliability of the PU of OPS directly depend on flow rate of the station Q_V and methods of its regulation, that is why coefficients of efficiency (η_{SM}, η_{CP}) and reliability (γ_{SM}, γ_{CP}) of SM and CP are values for assessing these criteria according to [4].

To build a mathematical model we apply a per-unit system which makes it possible to simplify the analysis of operating modes of electric and hydraulic machines and find common patterns of their behavior in various modes. The main feature of this system is that it is possible to obtain general dependences which emphasize the analogy of physical processes.

Such basic values as voltage U_{bas}, active power (on the shaft) N^{SM}_{bas}, electric current I_{bas} and impedance Z_{bas} are considered as new units of measurement for SM, as shown in (2). Two first values are randomly selected or selected among of nominal operating modes, while the other two are defined out of known ratios

$$\begin{cases} I_{bas} = \dfrac{N^{SM}_{bas}}{\sqrt{3}U_{bas}\cos\phi} \\ Z_{bas} = \dfrac{U^2_{bas}\cos\phi}{N_{bas}} \end{cases}, \tag{2}$$

where φ is phase angle shift between the voltage and electric current vectors.

Similar for CP, basic values are considered pressure H_{bas}, flow rate Q_{bas}, power N_{bas}^{CP}, and resistance R_{bas}. Ratio between those basic values is shown in (3)

$$\begin{cases} N_{bas}^{CP} = \rho g H_{bas} Q_{bas} \\ R_{bas} = \dfrac{\rho g H_{bas}}{Q_{bas}} \end{cases}, \tag{3}$$

where ρ and g are fluid density and gravitational acceleration respectively.

Let us combine the basic mode and nominal mode and note that in the per-unit system (for incompressible fluid) dimensionless pressure values P and H are equal

$$P_* = \frac{\rho g H}{\rho g H_{bas}} = \frac{H}{H_{bas}} = H_* .$$

In order to pass to the system of dimensional units, per unit values are multiplied by the base values. Further calculations will be done in the per-unit system and the index "*" will be ignored.

All studies will be conducted with three PUs connected in series and consisting of pairs of SM-CP "СТД-2500-2" and "НМ-3600-230". The parameters are given in the Table 1 and Table 2.

Table 1

Catalog of nominal parameters of synchronous motor СТД-2500-2

N^{nom} kW	$\cos\varphi^{nom}$	U^{nom}, V	n^{nom}, r/m	I^{nom}, A	η^{nom} %	x_d, %
2500	0.9	6000	3000	276	97.4	154.5

Table 2

Catalog of nominal parameters of the main pump НМ-3600-230

H_V^{nom}, m	Q_V^{nom}, m³/h	N_{Sh}^{nom}, kW	n^{nom}, r/m	η^{nom}	η_{mech}^{nom}	n_S
230	3600	2593	3000	0.87	0.968	131

The coefficient of SM efficiency η_{SM} is shown in (4) [5] (power N_{RW} is ignored)

$$\eta_{SM} = \left[1 + \frac{(1-\eta_{SM}^{nom})}{2\eta_{SM}^{nom} k_l}(1+k_l^2)\right]^{-1}, \tag{4}$$

where η_{SM}^{nom} is motor efficiency at nominal load; k_l is the SM load factor which is the ratio of SM shaft power N_{SM} to its nominal power N_{SM}^{nom}. It is shown in (5)

$$k_l = \frac{N_{SM}}{N_{SM}^{nom}}. \tag{5}$$

However, the shaft mechanical power of SM depends on flow rate Q_V of CP [1], as shown in (6)

$$\Delta N_{SM} = N_{Sh} = \frac{\rho g Q_V H_V}{\eta_{CP}}, \tag{6}$$

where η_{CP} is efficiency of CP. Formulas (4—6) allow us to find out how efficiency parameter η_{SM} depends on flow rate Q_V (Fig. 3).

Fig. 3 shows congruence of dependence of the coefficient of efficiency η_{SM} of motor СТД-2500-2 on flow rate Q_V calculated using the formulas (4—6) (curve 1) and obtained in an experimental study (curve 2) [6].

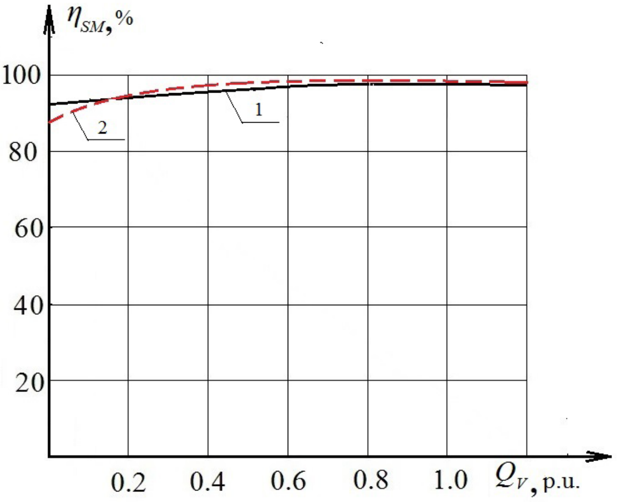

Fig. 3. Motor efficiency η_{SM} versus flow rate Q_V:
1 — calculated using the formula (8); 2 — obtained in an experimental study (curve 2) [6]

Obviously, SE performance value η_{SM} depends on the performance of CP η_{CP}, which, in turn, also depends on the flow rate value Q_V. This requires a mathematical model of CP to build its energy performance characteristics, taking into account the physical properties of the liquid.

Mathematical models of CP are usually based on stochastic empirical formulas, which makes it more difficult to find out interrelations between the structural elements of CP. Currently in modeling of hydraulic machines there are new approaches related to the Kirchhoff theory of circles, which is the basis of electric machines theory. In particular, in the [7, 8] on the basis of electrohydraulic analogy there was developed a complex graphic model of CP as an equivalent electric circuit (Fig. 4) with active and inductive (inertial) elements, which takes into account structural features and properties of the fluid.

Concepts of passive linear parameters of CP such as hydraulic resistance r_{eq} and hydraulic inductance x_{eq} were used to build an equivalent circuit: hydraulic resistance of pipeline — r_{load}; outlet pressure of CP impeller — $\rho g H_{eq}$.

Table 3 includes the results of calculating of dimensionless parameters of equivalent circuit for CP OPS.

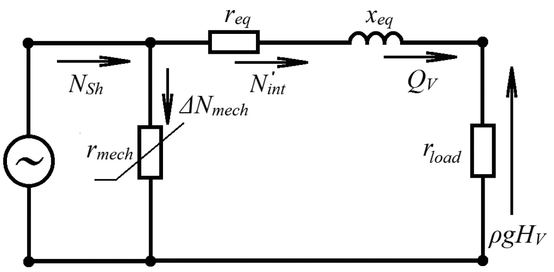

Fig. 4. Equivalent complex circuit of a centrifugal pump

Table 3

Estimated parameters of the main pump HM-3600-230

γ_l^{nom}	ΔN_{mech}^{idle}	ΔN_{mech}^{nom}	$\Delta N_{\text{int}}^{'idle}$	H_{eq}	x_{eq}	r_{eq}
1.085	0.44	0.04	0.041	1.227	0.707	0.0029

Nonlinear active resistance in modeling of mechanical losses determined by the (7)

$$r_{mech} = \frac{H_{eq}^2}{\Delta N_{mech}^{\text{const}} + \Delta N_{mech}^{\text{var}}}. \tag{7}$$

In addition, expression (8) for consumed power N_{Sh} by SM as the sum of the internal power N_{int}' and power of mechanical losses ΔN_{mech} is illustrated by the equivalent circuit of CP (Fig. 4)

$$N_{Sh} = N_{\text{int}}' + \Delta N_{mech}. \tag{8}$$

The research made it possible to present a model of mechanical losses in the CP in the equation (9) (Fig. 5) [8]

$$\Delta N_{mech} = \Delta N_{mech}^{\text{const}} + \Delta N_{mech}^{\text{var}}. \tag{9}$$

The constant component (at a constant speed of rotation of the wheel) of these losses $\Delta N_{mech}^{\text{const}}$ shows the power capacity of irreversible dissipative losses of disk friction, friction in bearings and shaft seal friction independent of flow rate. It is equal to the value of mechanical power losses in nominal operating mode of CP ΔN_{mech}^{nom}, which is typically less than 5.7 % of the total power consumption of CP and taking into account the laws of similarity [1] is defined in the per-unit system as shown in (10)

$$\Delta N_{mech}^{\text{const}} = \Delta N_{mech}^{nom} = \frac{1 - \eta_{mech}^{nom}}{\eta_{CP}^{nom}}, \tag{10}$$

where η_{CP}^{nom} and η_{mech}^{nom} are coefficient of efficiency and mechanical coefficient of efficiency of CP in nominal operating mode respectively.

In addition, in the CP there are variable losses γ_l^{nom} caused by deviation of the nominal operating mode, accompanied by impact collision of fluid with the working surface of the blades. They are considered as mechanical losses because they reflect dissipative heating processes in CP. These losses are represented as a quadratic function as shown in (11)

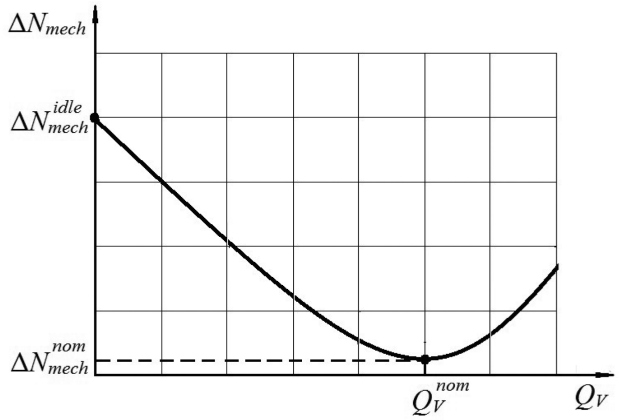

Fig. 5. Dependence of mechanical loss ΔN_{mech} of centrifugal pump on flow rate Q_V

$$\Delta N_{mech}^{\text{var}} = \left(\Delta N_{mech}^{idle} - \Delta N_{mech}^{nom}\right)\left(Q_V - 1\right)^2, \tag{11}$$

where ΔN_{mech}^{idle} is relative value of mechanical losses in the idle mode, which can be determined using a scalar model of CP [7] as shown in (12)

$$\Delta N_{mech}^{idle} = \frac{1 - \gamma_l^{nom} ctg \gamma_l^{nom}}{\eta_{CP}^{nom}} - \Delta N_{\text{int}}^{'idle}, \tag{12}$$

where γ_l^{nom} is nominal angle of CP load, which at first approximation depends on a specific speed coefficient n_s of CP [7] as shown in (13)

$$\gamma_l^{nom} \approx 0.475\left(1 + \frac{n_s}{100}\right), \tag{13}$$

where N_{int}' and $\Delta N_{\text{int}}^{'idle}$ are values of internal power of CP in the current mode and idle mode [8].

Obviously, non-impact flow of fluid in the impeller of CP $\Delta N_{mech}^{\text{var}} = 0$ occurs in the nominal operating mode only. This approach is due to the fact that a change of pressure losses of CP increases almost linearly when deviation from the non-impact mode happens, which determines the change in power losses for parabolic law of the second grade [8].

Table 3 includes calculated dimensionless parameter values γ_l^{nom}, ΔN_{mech}^{idle}, ΔN_{mech}^{nom} and $\Delta N_{\text{int}}^{'idle}$ with basic nominal parameters of main pump HM-3600-230.

Formulas (6–13) show analytical dependence of power consumption of CP N_{Sh} and efficiency of CP on flow rate Q_V. Figs. 6, 7 show a good match between these characteristics, designed for the pump HM-3600-230 with its experimental specifications [8].

The complex mathematical model of SM should enable to estimate the reliability of OPS behavior to control its operating modes. However, the lack of sufficient statistic data on the frequency and causes of SM failure in different conditions and flow rates does not let to determine

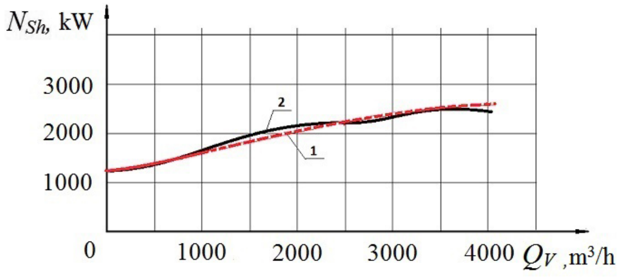

Fig. 6. Comparison of power consumption N_{Sh} at different flow rate values Q_V of the main pump HM-3600-230:

1 – calculated on a model of motor; 2 – obtained in an experimental way [8]

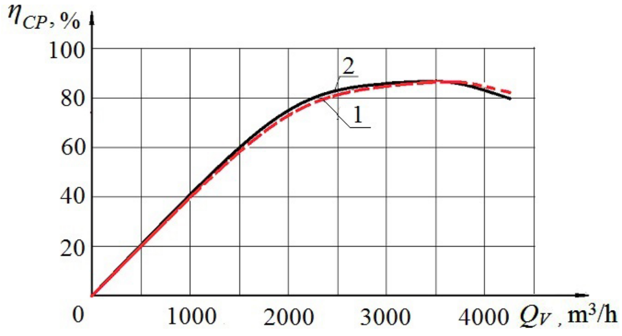

Fig. 7. Comparison of coefficient of efficiency η_{CP} at different flow rate values Q_V of the main pump HM-3600-230:

1 – calculated on a model of motor; 2 – obtained in an experimental way [8]

the reliability parameters of the motor. Due to this fact we choose SE static stability factor as a reliability parameter of SE γ_{SM}, which, as shown in (14), depends on the pump power consumption N_{Sh} from the shaft [9]

$$\gamma_{SM}=\frac{N_{SM}^{\max}}{N_{Sh}}-1, \qquad (14)$$

where $N_{SM}^{\max}$ is the maximum value of electromagnetic power of SM determined by the formula (15)

$$N_{SM}^{\max}=\frac{E_{SM}^{nom}(\alpha_1 I_f^2+\alpha_2 I_f+\alpha_3)U_{SW}}{x_d}, \qquad (15)$$

where x_d is synchronous inductance of SM; E_{SM}^{nom} is electromotive force value in the nominal operating mode [9], as shown in (16); α_1, α_2, α_3 are approximation coefficients of the machine idle operating mode characteristic. This characteristic is a dependency of the electromotive force on field current of SD.

$$E_{SM}^{nom}=\sqrt{(1+x_d\sin\phi)^2+(x_d\cos\phi)^2}. \qquad (16)$$

Considering formula (6) equation for γ_{SM} is shown in (17)

$$\gamma_{SM}=\frac{E_{SM}^{nom}(c_1 I_f^2+c_2 I_f+c_3)U_{SW}\eta_{CP}}{\rho g Q_V H_V x_d}-1. \qquad (17)$$

Obviously, the reliability parameter of SM depends on the efficiency of CP η_{CP}, which is determined by the method given above. Figs. 8, 10 illustrate the equation (17) for PU “СТД-2500-2” and “HM-3600-230”. Since $\gamma_{SM}=\infty$ in the idle operating mode, for clarity the parameter is normalized (changes in range from 0 to 1) by dividing by its maximum value $\gamma_{SM\,0.1}$ at $Q_V = 0.1$

$$\gamma'_{SM}=\frac{\gamma_{SM}}{\gamma_{SM\,0,1}}.$$

In order to formalize the model of CP reliability we use the parameter γ_{CP}, which depends not only on duration of work of the pump, but also on its operating mode [2] (Fig. 9), which is determined by flow rate Q_V. Work of CP when flow rate is not optimal, causes a significant reduction of reliability of the pump. Mechanical problems occur such as failure of bearings, mechanical seals, shaft breakage and increased vibration and so on.

Reliability of CP should be considered in three operating modes [2]: 1) operating when flow rate is minimal when starting the pump; 2) underloaded operating mode. In the area 2.1 cavitation is possible; in areas 2.2 and 2.3 recirculation of flow in inlet and outlet of the impeller is possible. As a consequence a significant reduction in the reliability of the pump occurs; 3) overloaded operating mode, which is characterized by the growing energy consumption, reducing of efficiency and instability of SM.

According to Figs. 8, 9 scale of reliability parameters of SE and CP varies from 0 to 100 % (or from 0 to 1 in the per-unit system). The value equal to 1 indicates the best operating mode for PU, defined by minimum value of vibration, temperature of bearing and other parameters on which a durability of CP and SE depends. Thus, the value equal to 1 does not mean endless time of work without failures, but values of reliability parameters of

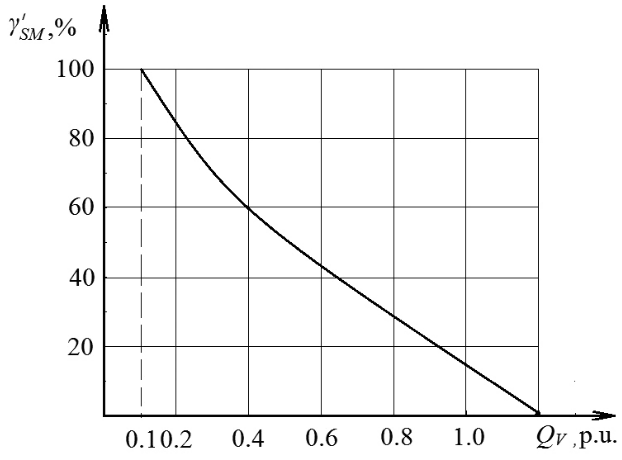

Fig. 8. Calculated dependence of reliability of the electric motor СТД-2500-2 on flow rate of the pump HM-3600-230

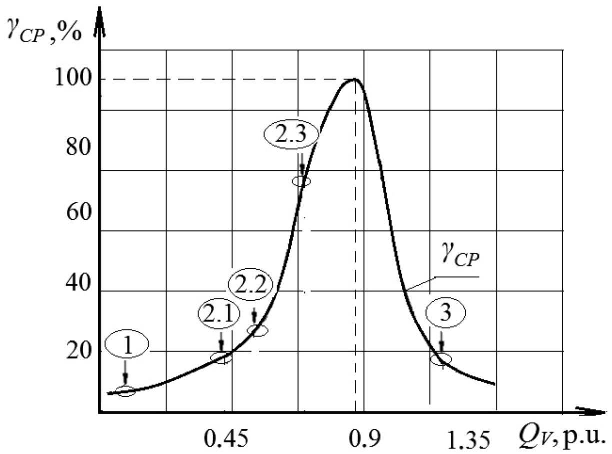

Fig. 9. Dependence of the reliability parameter of centrifugal pump γ_{CP} on flow rate Q_V

CP and SE less than 1 cause a decrease in their durability. Zero values of parameters γ'_{SM} and γ_{CP} do not mean failure of PU, but indicate that these conditions should be avoided [10].

We obtained four parameters of efficiency and reliability of PU. Their dependence on flow rate Q_V can be represented as graphic (Fig. 10). In addition, these dependencies can be approximated by polynomials of the third grade as shown in (18)

$$\left.\begin{aligned} \eta_{SM} &= a_1 Q_V^3 + a_2 Q_V^2 + a_3 Q_V + a_4 \\ \eta_{CP} &= b_1 Q_V^3 + b_2 Q_V^2 + b_3 Q_V + b_4 \\ \gamma'_{SM} &= c_1 Q_V^3 + c_2 Q_V^2 + c_3 Q_V + c_4 \\ \gamma_{CP} &= d_1 Q_V^3 + d_2 Q_V^2 + d_3 Q_V + d_4 \end{aligned}\right\}. \tag{18}$$

Coefficients for the motor "СТД-3200-2" and pump "НМ-3600-230" are represented in Tables 4 and 5 respectively. Obviously, during the pumping of fluid, maximum values of efficiency and reliability parameters should be reached. However, this cannot be achieved simultaneously (Fig. 10), because extreme values of these parameters are achieved for different values of flow rate Q_V. Thus, in the future it will be necessary to solve the problem of PU operating modes optimal control on the criteria of efficiency and reliability involving methodologies of multi-optimization (optimization block of structural and functional scheme shown in Fig. 2).

Conclusions.

1. Modeling of operating modes of PU of OPS should be based on a systematic approach and using efficiency and reliability parameters of SM and CP.

2. Mathematical models of efficiency and reliability as polynomials of the third grade are formalized and their values for PU "СТД-2500-2" and "НМ-3600-230" are calculated.

3. Extreme values of parameters of efficiency and reliability of SM and CP are achieved at different flow rate values, which requires multi-objective optimization studies for finding the best operating mode of PU.

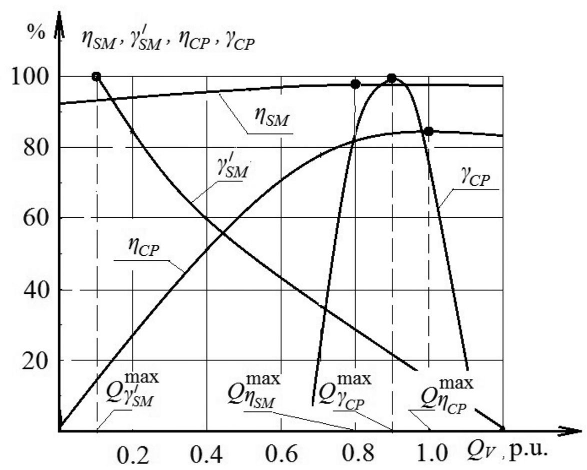

Fig. 10. Efficiency and reliability parameters of SM (η_{SM}, γ'_{SM}) and CP (η_{CP}, γ_{CP}) at different flow rate values Q_V of PU "СТД-2500-2" and "НМ-3600-230"

Table 4

Estimated values of coefficients of approximation of efficiency and reliability polynomials for the electric motor "СТД-2500-2", which drives the pump "НМ-3600-230"

Parameter	Value of coefficient of approximation			
Efficiency of SM, η_{SM}	a_1	a_2	a_3	a_4
	5.556	-19.673	21.819	90.11
Reliability of SM, γ'_{SM}	c_1	c_2	c_3	c_4
	-53.316	148.435	-192.465	117.801

Table 5

Estimated values of coefficients of approximation of efficiency and reliability polynomials for the pump НМ-3600-230, driven by the electric motor "СТД-2500-2"

Parameter	Value of coefficient of approximation			
Efficiency of CP, η_{CP}	b_1	b_2	b_3	b_4
	-24.306	-33.929	143.234	1.381
Reliability of CP, γ_{CP}	d_1	d_2	d_3	d_4
	1333	-5971	7455	-2743

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Мета. Створення математичної моделі ефективності й надійності роботи насосного агрегата (НА) нафтоперекачувальної станції (НПС) на основі системи відносних одиниць і методології системного підходу, що містить електричну, гідравлічну й механічну підсистеми та відображає енергетичні входи-виходи відцентрового насоса (ВН) і синхронного двигуна (СД).

Методика. Розроблені математичні моделі НА НПС як об’єкта керування, синтезовані на основі системного підходу з урахуванням впливу їх режимів роботи на надійність і ефективність СД та ВН. Це дало змогу визначити оптимальні режими роботи НА НПС і розробити заходи для їх реалізації.

Результати. На основі системного підходу сформована модель НА НПС як єдиної системи з підсистемами різної фізичної природи. Математична модель ефективності й надійності СД і ВН формалізована у вигляді поліномів, розраховані числові значення їх коефіцієнтів. Встановлено, що екстремальні значення показників ефективності й надійності досягаються за різних значень витратного навантаження, що вимагає залучення методів багатокритеріальної оптимізації.

Наукова новизна. На основі системного підходу формалізована математична модель НА НПС, що дає можливість урахувати вплив зміни режиму роботи НА на показники ефективності й надійності роботи СД і ВН. Встановлено, що екстремальні значення показників ефективності й надійності СД і ВН досягаються за різних значень витратного навантаження.

Практична значимість. Створення математичних моделей, що дозволяють оцінити вплив зміни витратного навантаження НПС на показники ефективності й надійності роботи СД і ВН з метою вибору оптимального режиму роботи НА НПС без проведення дорогих натурних експериментів.

Ключові слова: *синхронний двигун, відцентровий насос, математична модель, надійність, ефективність, оптимізація*

Цель. Создание математической модели эффективности и надежности работы насосного агрегата (НА) нефтеперекачивающей станции (НПС) на основе системы относительных единиц и методологии системного подхода, которая содержит электрическую, гидравлическую и механическую подсистемы и отражает энергетические входы-выходы центробежного насоса (ЦН) и синхронного двигателя (СД).

Методика. Разработаны математические модели НА НПС как объекта управления, синтезированные на основе системного подхода с учетом влияния их режимов работы на надежность и эффективность СД и ЦН. Это позволило определить оптимальные режимы работы НА НПС и разработать меры по их реализации.

Результаты. На основе системного подхода сформирована модель НА НПС как единой системы с подсистемами различной физической природы. Математическая модель эффективности и надежности СД и ЦН формализована в виде полиномов, рассчитаны числовые значения их коэффициентов. Установлено, что экстремальные значения показателей эффективности и надежности достигаются при разных значениях расходной нагрузки, что требует привлечения методов многокритериальной оптимизации.

Научная новизна. На основе системного подхода формализована математическую модель НА НПС, которая дает возможность учесть влияние изменения режима работы НА на показатели эффективности и надежности работы СД и ЦН. Установлено, что экстремальные значения показателей эффективности и надежности СД и ЦН достигаются при разных значениях расходной нагрузки.

Практическая значимость. Создание математических моделей, которые позволяют оценить влияние изменения расходной нагрузки НПС на показатели эффективности и надежности работы СД и ЦН с целью выбора оптимального режима работы НА НПС без проведения дорогостоящих натурных экспериментов.

Ключевые слова: *синхронный двигатель, центробежный насос, математическая модель, надежность, эффективность, оптимизация*

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